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Railway Traction and Power System Energy Optimisation

Ning Zhao
Birmingham Centre for Railway Research and Education

Background

- Energy consumption is becoming a critical 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.

Objectives

- Identify an optimal train trajectory using the developed tram simulator based on a tram route
- Implement the optimal train trajectory on a service tram in a fields test to evaluate and identify the optimisation results;
- Develop a detailed multi-train simulator of the train route that includes the vehicles, power supply network system and track alignment;
- Use the multi-train simulator to identify optimal infrastructure design and operational methods.

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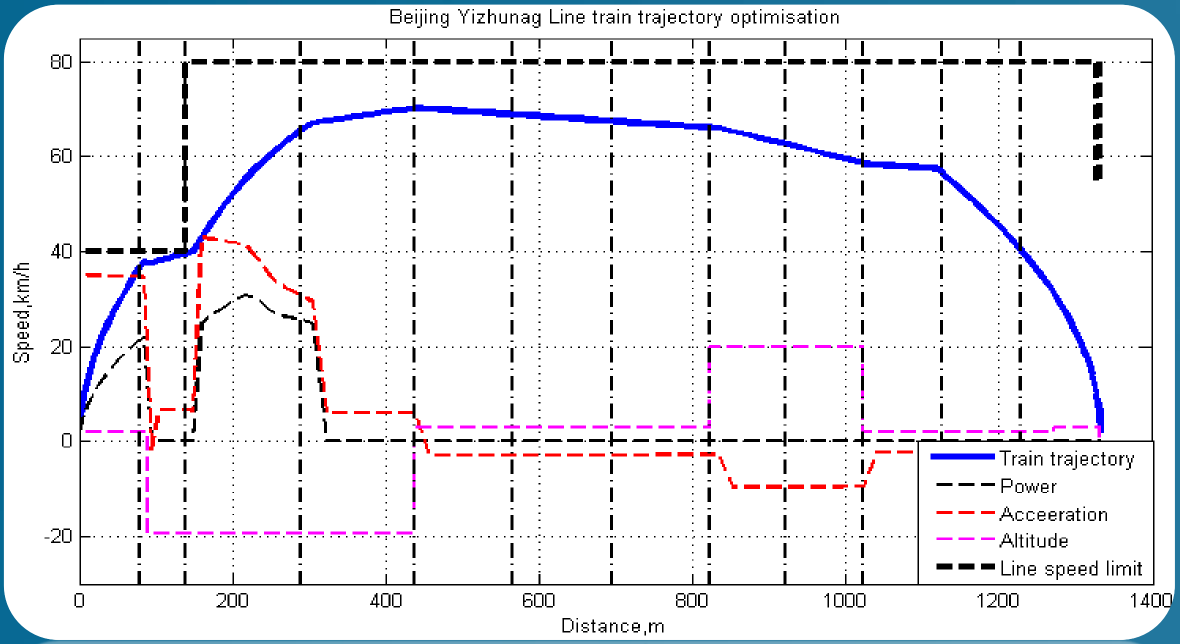
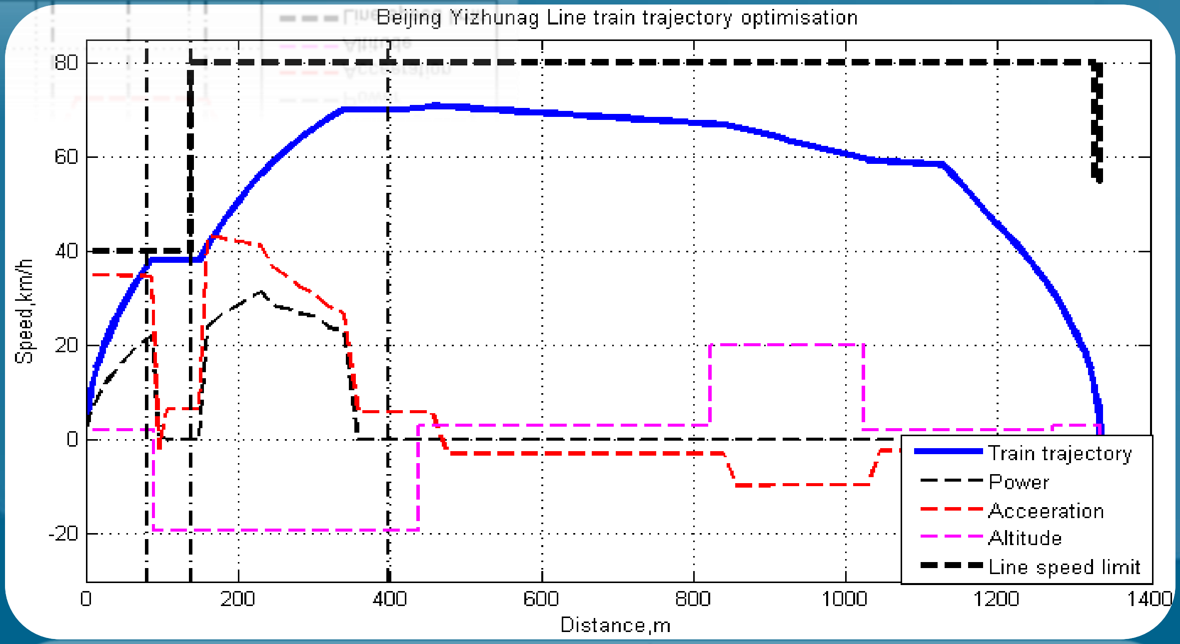
Objective 1: Single train trajectory optimisation

- **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;**
- **A number of algorithms have been implemented and evaluated in the optimisation for different scenarios.**



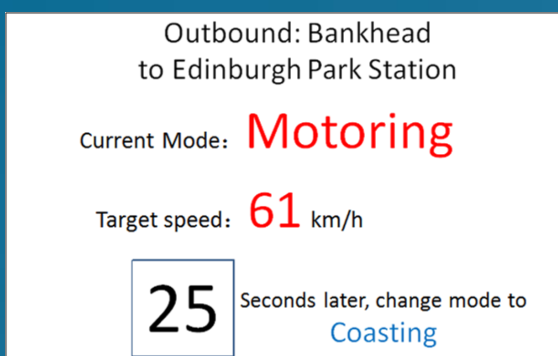
Optimisation for ATO systems

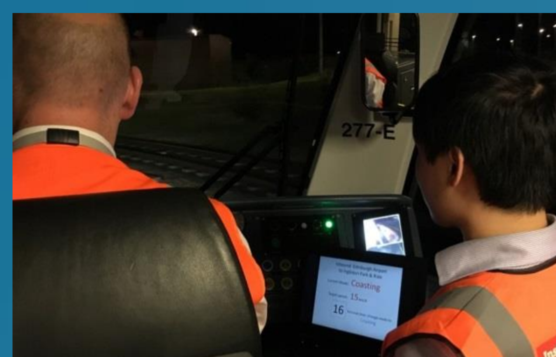
Optimisation for human driving systems



Objective 2: Field test on single train trajectory optimisation

In order to evaluate the performance of the optimised single tram trajectory, a field test is expected to be taken. A Driver Adversity System (DAS) has be developed special for this propose. The DAS will include the optimisation results that achieved in the Objective 1.





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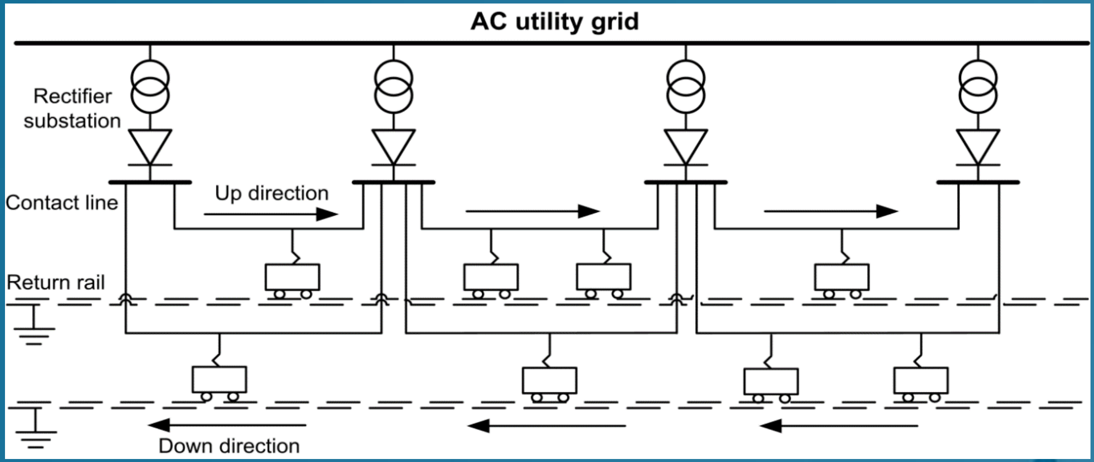
Objective 3: Power network simulator development

- Simulate the detailed movement of railway vehicles around an AC or DC powered railway network;
- Calculate the substation power and the vehicle power consumptions;



- Analyse the overall energy consumed when specific timetables are operated;
- Allow the modification of the behaviour of trains within the simulation;
- Identify and quantify energy losses.

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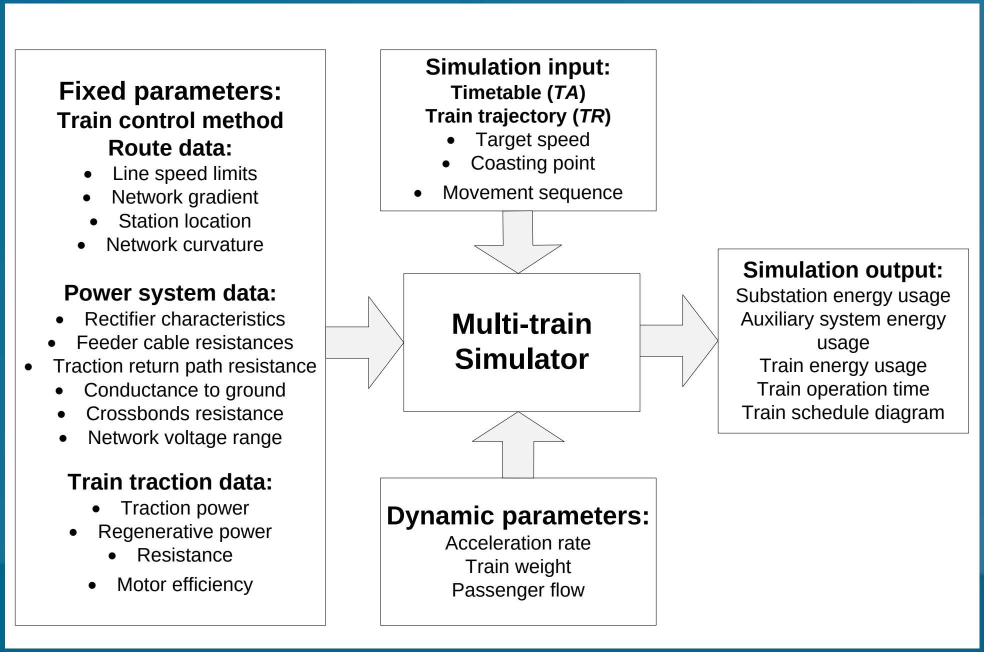
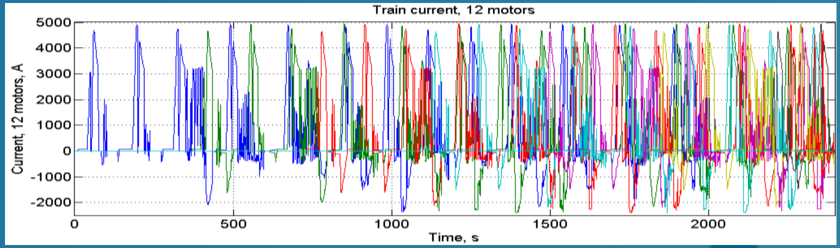
Objective 4: Multiple train operation optimisation

- Based on the results from the previous simulations and optimisations;
- A genetic algorithm will be implemented to optimise the full-day timetable to take the full advantage of regenerative braking.





Traction current simulation

Simulation flow chart

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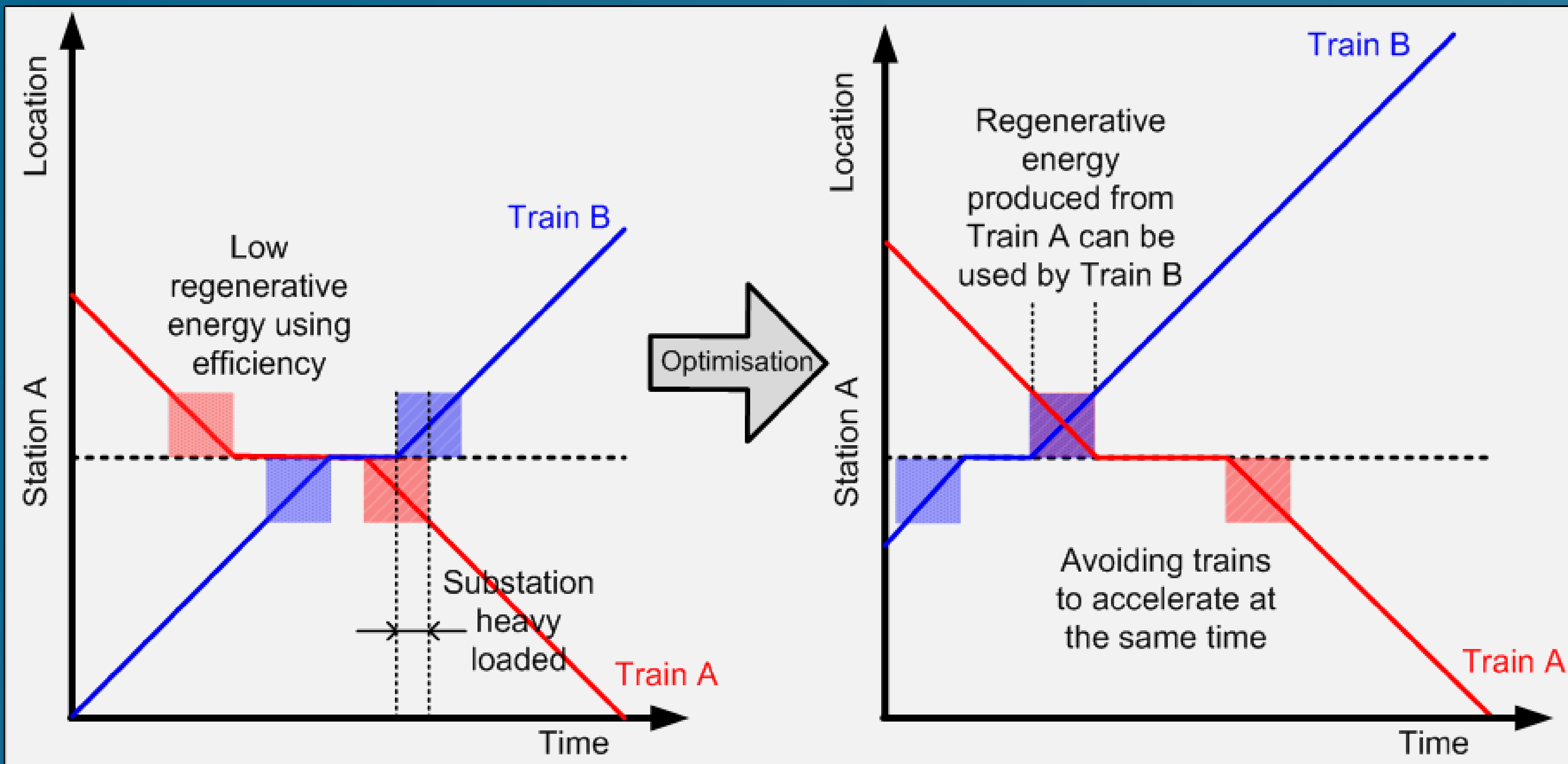
Timetable Optimisation



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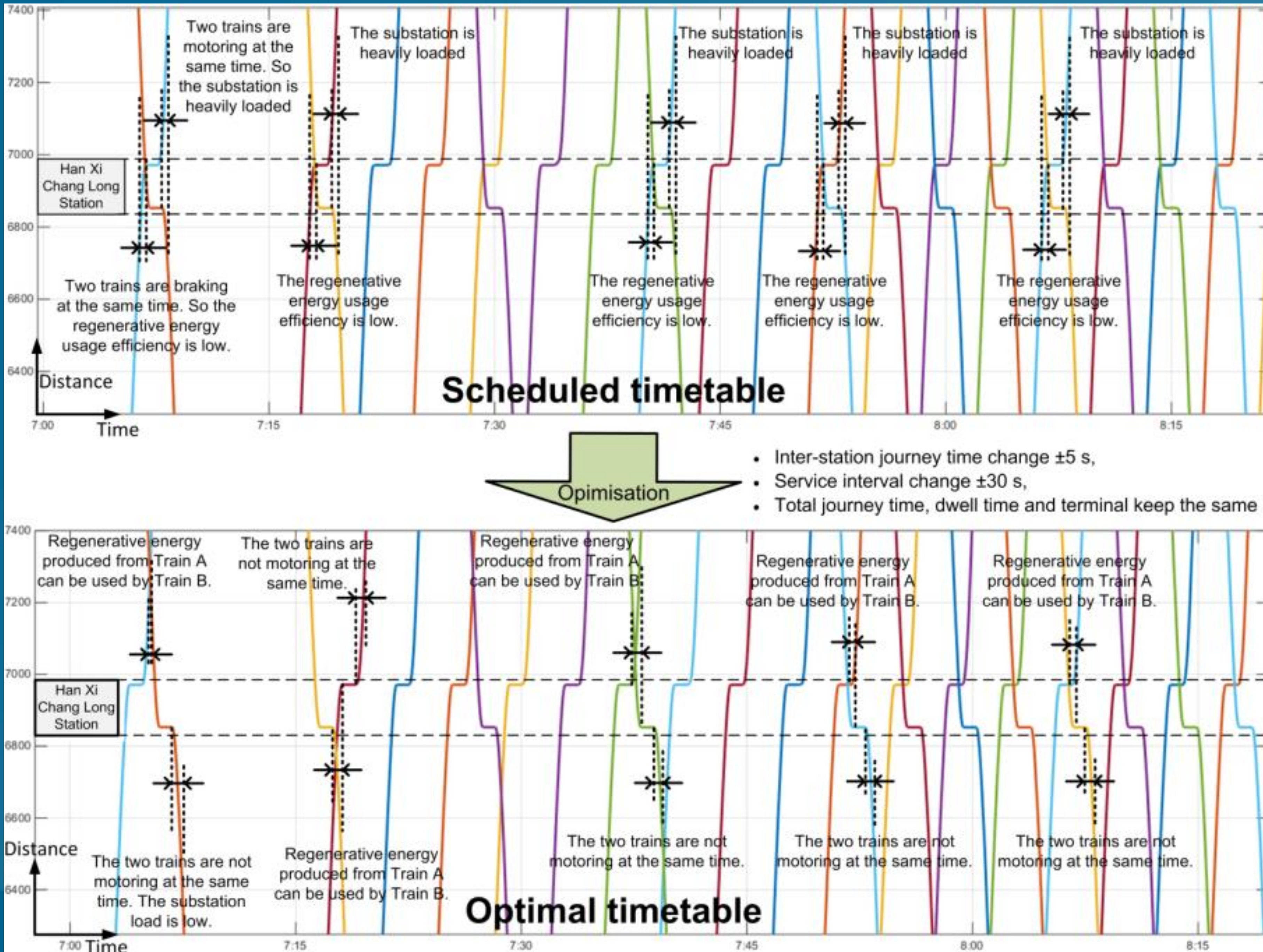
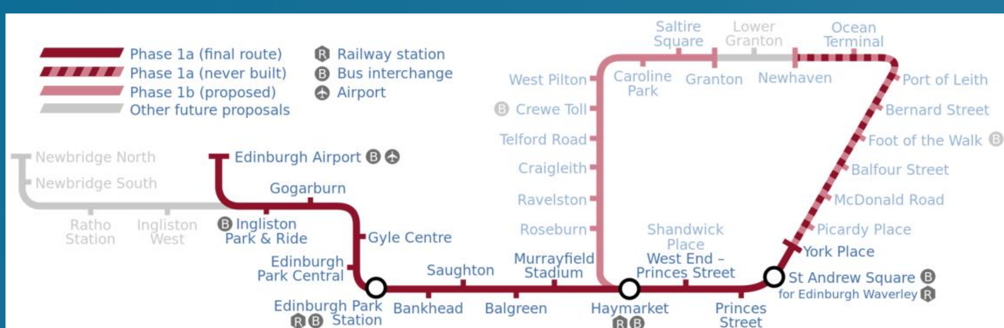


Two trains are motoring at the same time. So the substation is heavily loaded
The substation is heavily loaded
The substation is heavily loaded
The substation is heavily loaded
The substation is heavily loaded
Han Xi Chang Long Station
Two trains are braking at the same time. So the regenerative energy usage efficiency is low.
The regenerative energy usage efficiency is low.
The regenerative energy usage efficiency is low.
The regenerative energy usage efficiency is low.
The regenerative energy usage efficiency is low.
Distance
Time
Scheduled timetable
7:00
7:15
7:30
7:45
8:00
8:15
Opimisation
Inter-station journey time change ±5 s,
Service interval change ±30 s,
Total journey time, dwell time and terminal keep the same
Regenerative energy produced from Train A can be used by Train B.
The two trains are not motoring at the same time.
Regenerative energy produced from Train A can be used by Train B.
Regenerative energy produced from Train A can be used by Train B.
Regenerative energy produced from Train A can be used by Train B.
Han Xi Chang Long Station
The two trains are not motoring at the same time. The substation load is low.
Regenerative energy produced from Train A can be used by Train B.
The two trains are not motoring at the same time.
The two trains are not motoring at the same time.
The two trains are not motoring at the same time.
Distance
Time
Optimal timetable

Case Study 1: Edinburgh Trams

- **Edinburgh trams is an suburb tramway in Edinburgh, operated by Transport for Edinburgh;**
- **Connecting between York Place in the city and Edinburgh Airport with 15 stops, total length 14km, 750V overhead line power supply system.**
- **Edinburgh trams is now applying the optimal train trajectory in their daily services to all the drivers.**



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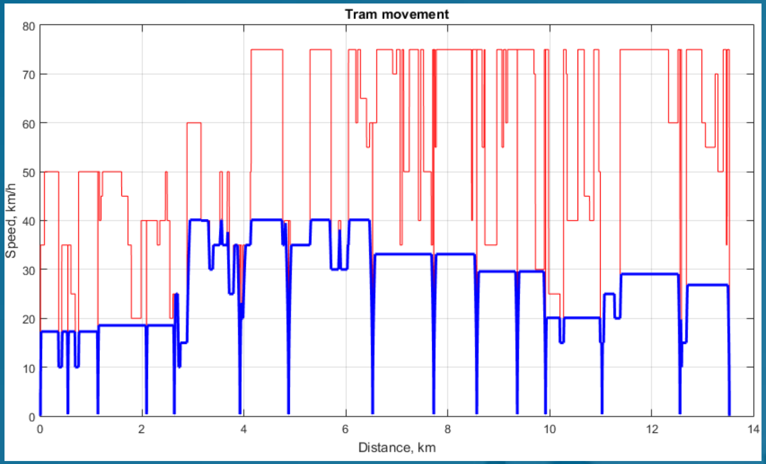
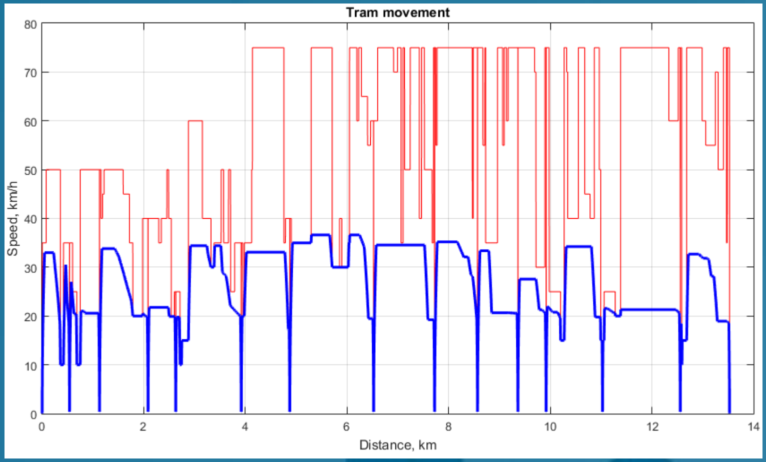
Single Tram Trajectory Optimisation-

	Normal operation (kWh/day)	Optimised operation (kWh/day)
Wheel energy usage	39.19	30.95
Motor energy usage	46.11	36.41
Train energy usage	54.24	42.84 **(-21%)**

Normal operation



Optimised operation



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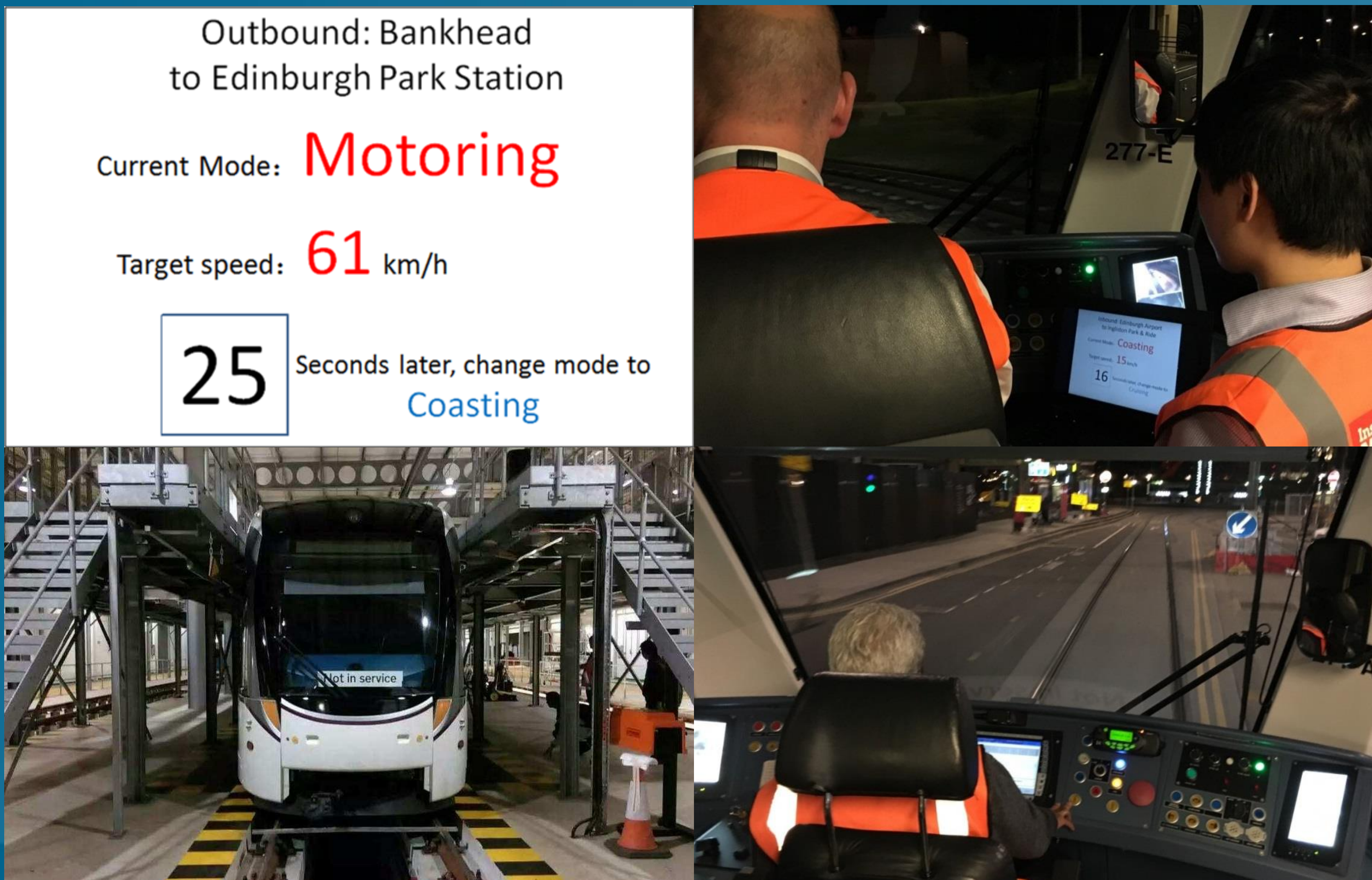
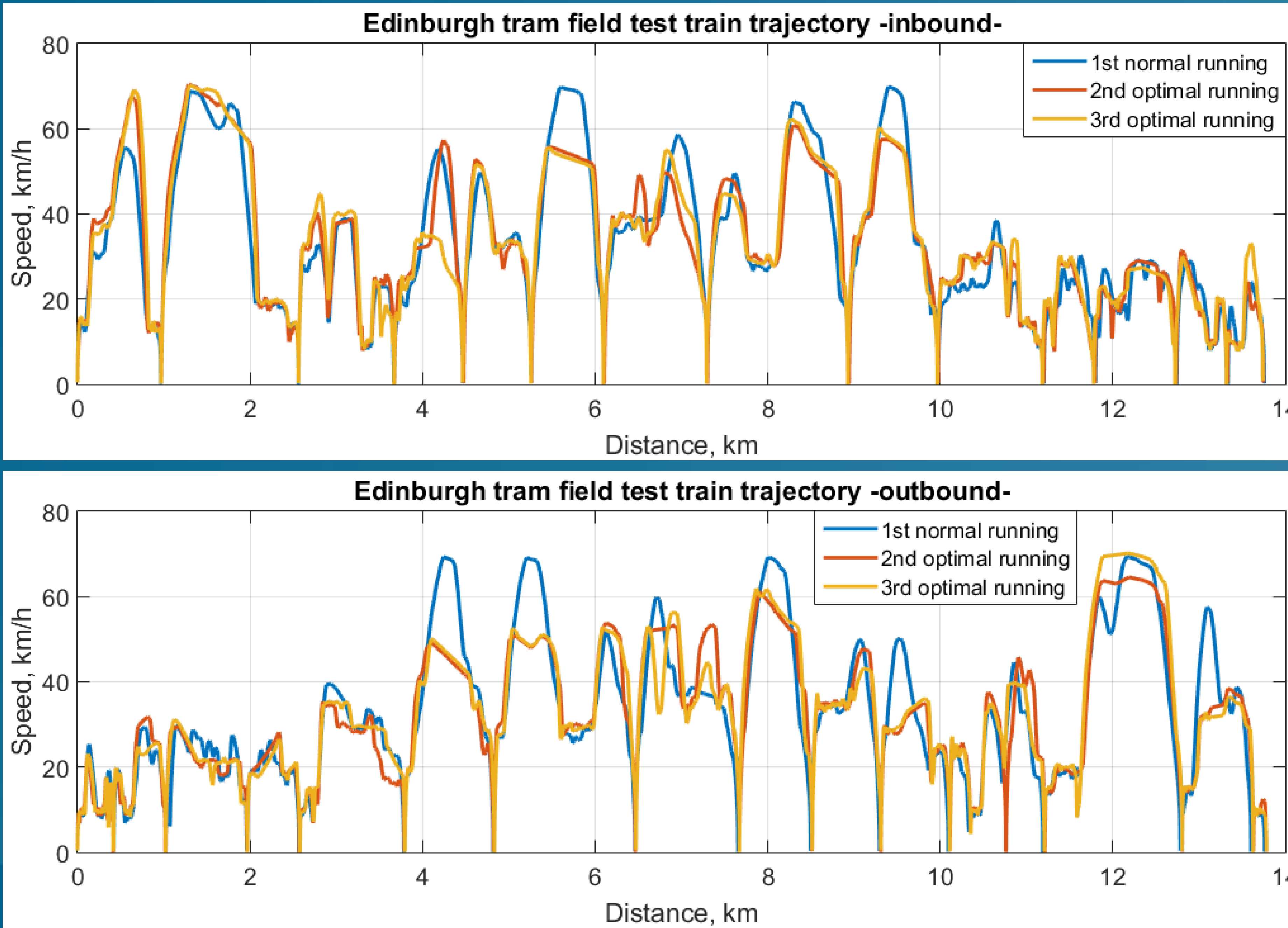
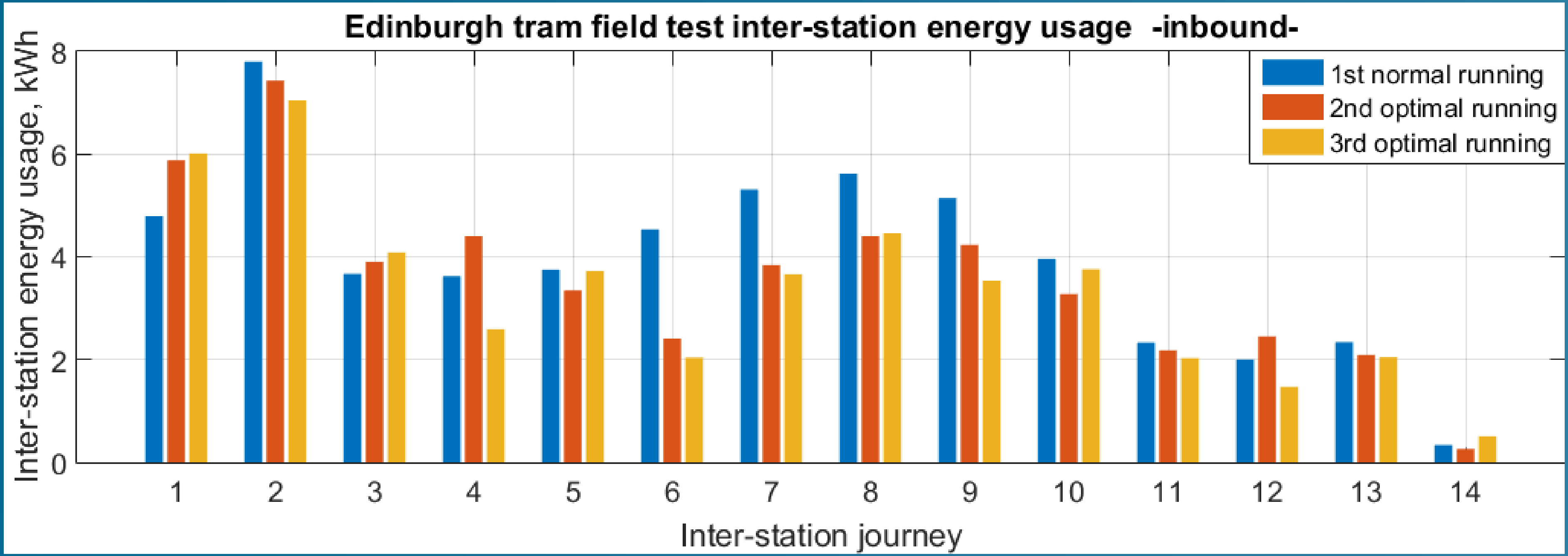
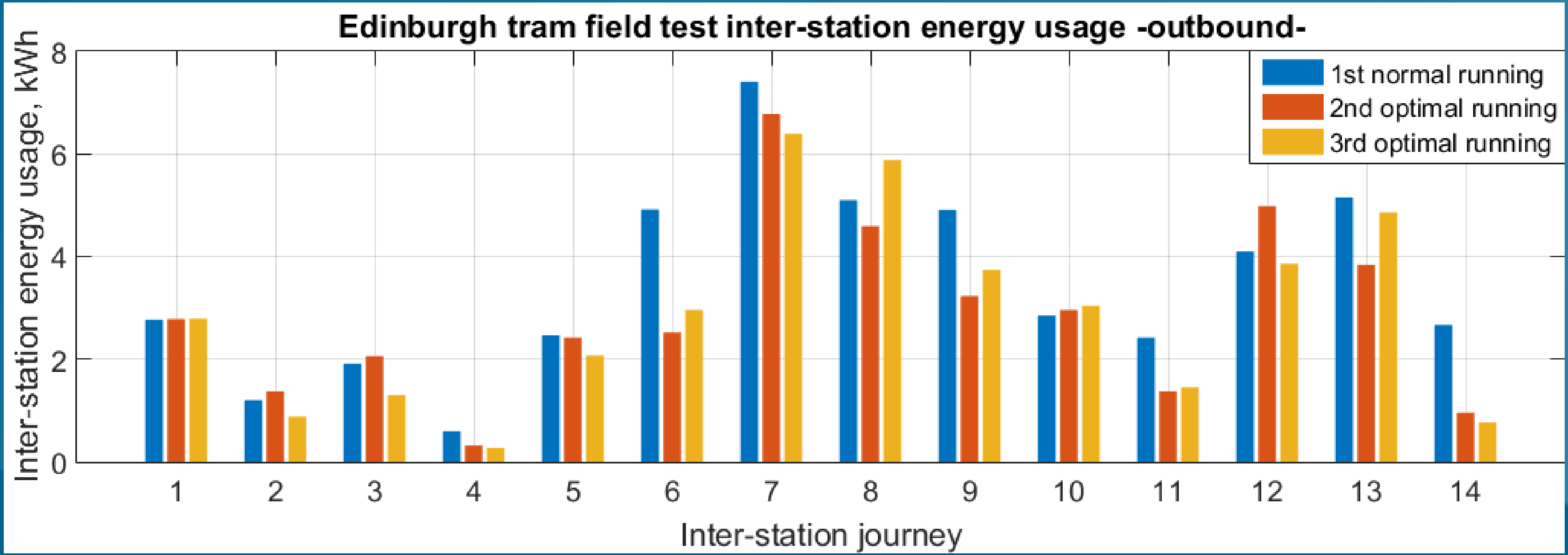
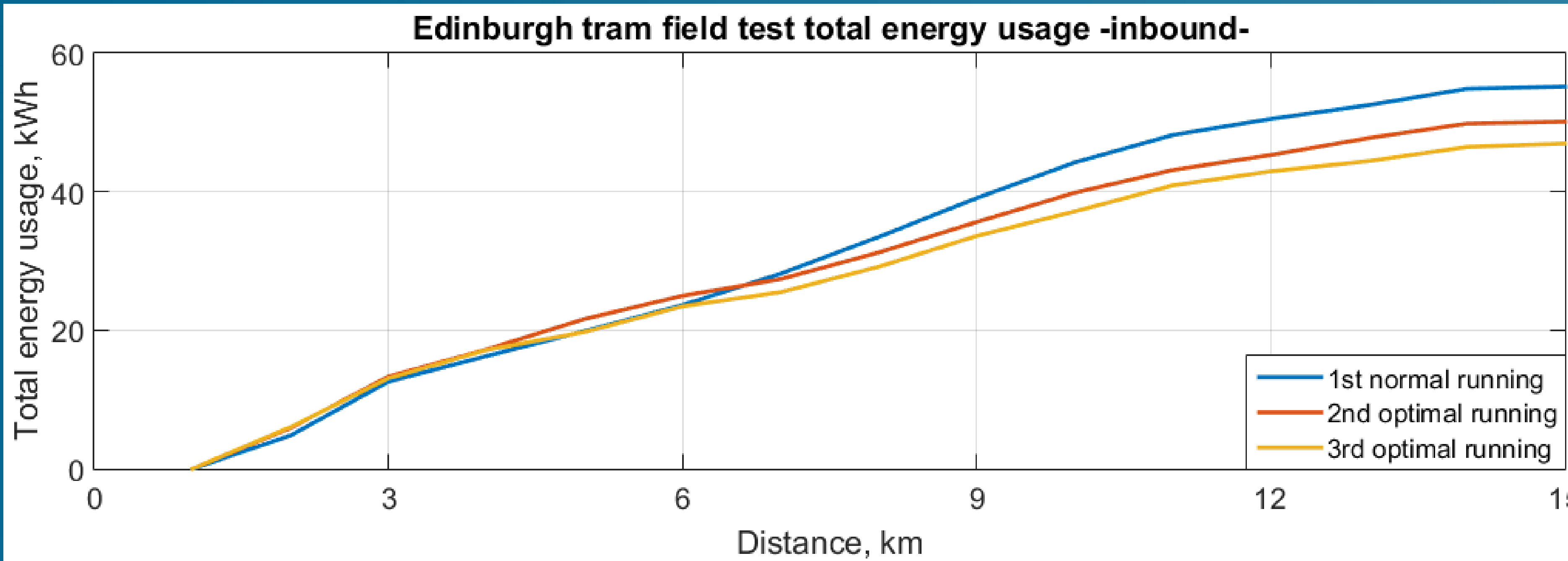
Trajectory Optimisation Field Test

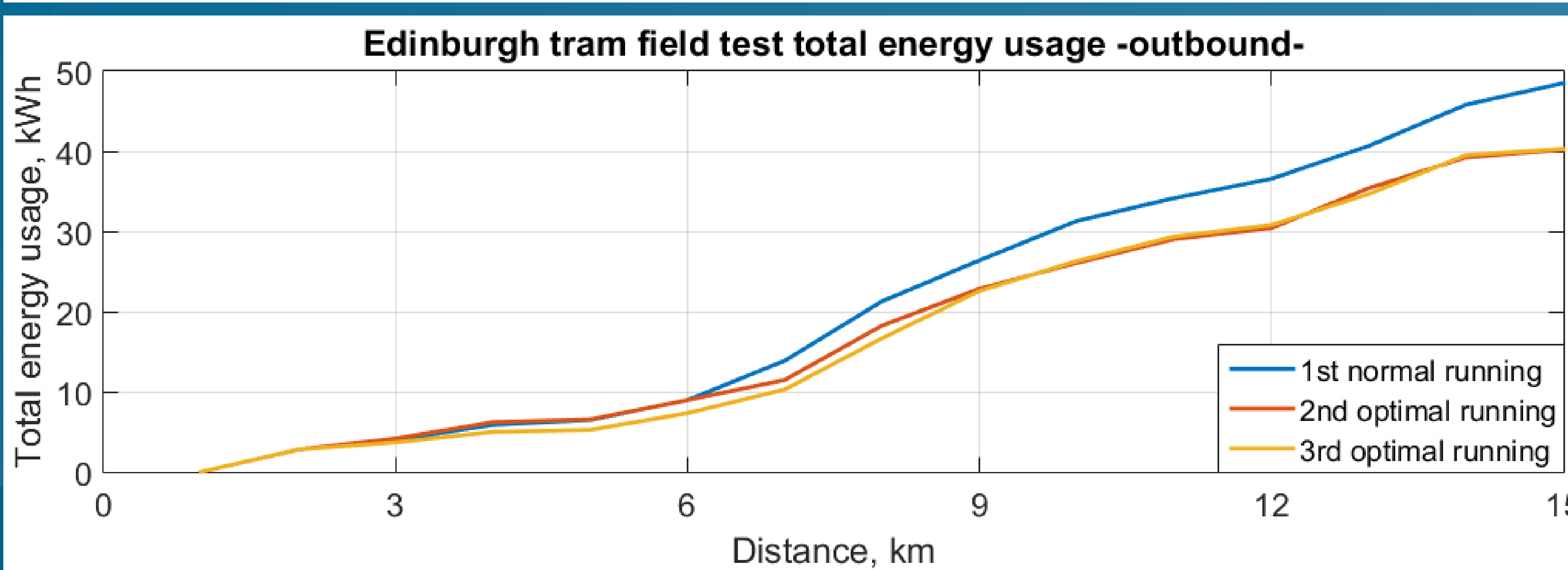



Edinburgh tram field test train trajectory -inbound-
Speed, km/h
Distance, km
1st normal running
2nd optimal running
3rd optimal running
Edinburgh tram field test train trajectory -outbound-
Speed, km/h
Distance, km
1st normal running
2nd optimal running
3rd optimal running


Edinburgh tram field test inter-station energy usage -inbound-
1st normal running
2nd optimal running
3rd optimal running
Inter-station energy usage, kWh
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Inter-station journey


Edinburgh tram field test inter-station energy usage -outbound-
1st normal running
2nd optimal running
3rd optimal running
Inter-station energy usage, kWh
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Inter-station journey


Edinburgh tram field test total energy usage -inbound-
Total energy usage, kWh
0
20
40
60
0
3
6
9
12
15
Distance, km
1st normal running
2nd optimal running
3rd optimal running


Edinburgh tram field test total energy usage -outbound-
Total energy usage, kWh
0
10
20
30
40
50
0
3
6
9
12
15
Distance, km
1st normal running
2nd optimal running
3rd optimal running

Inbound	Normal operation		1st Optimised operation		2nd Optimised operation	
	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)
	2062	55.19	1974	50.10 **(-9.2%)**	1997	46.97 **(-14.8%)**

Outbound	Normal operation		1st Optimised operation		2nd Optimised operation	
	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)
	2139	48.48	2071	40.18 **(-17.1%)**	2067	40.28 **(-16.9%)**

Optimal Tram Trajectory Implementation

- **Due to the excellent results obtained in the field tests, Edinburgh Tram has implemented the optimal train trajectory in practise;**
- **A driver training has been carried out to Edinburgh Tram drivers to help implement the energy saving features of the optimisation to the drivers.**
- **Edinburgh Tram is now implementing the optimal driving strategy in their daily services to all the drivers.**

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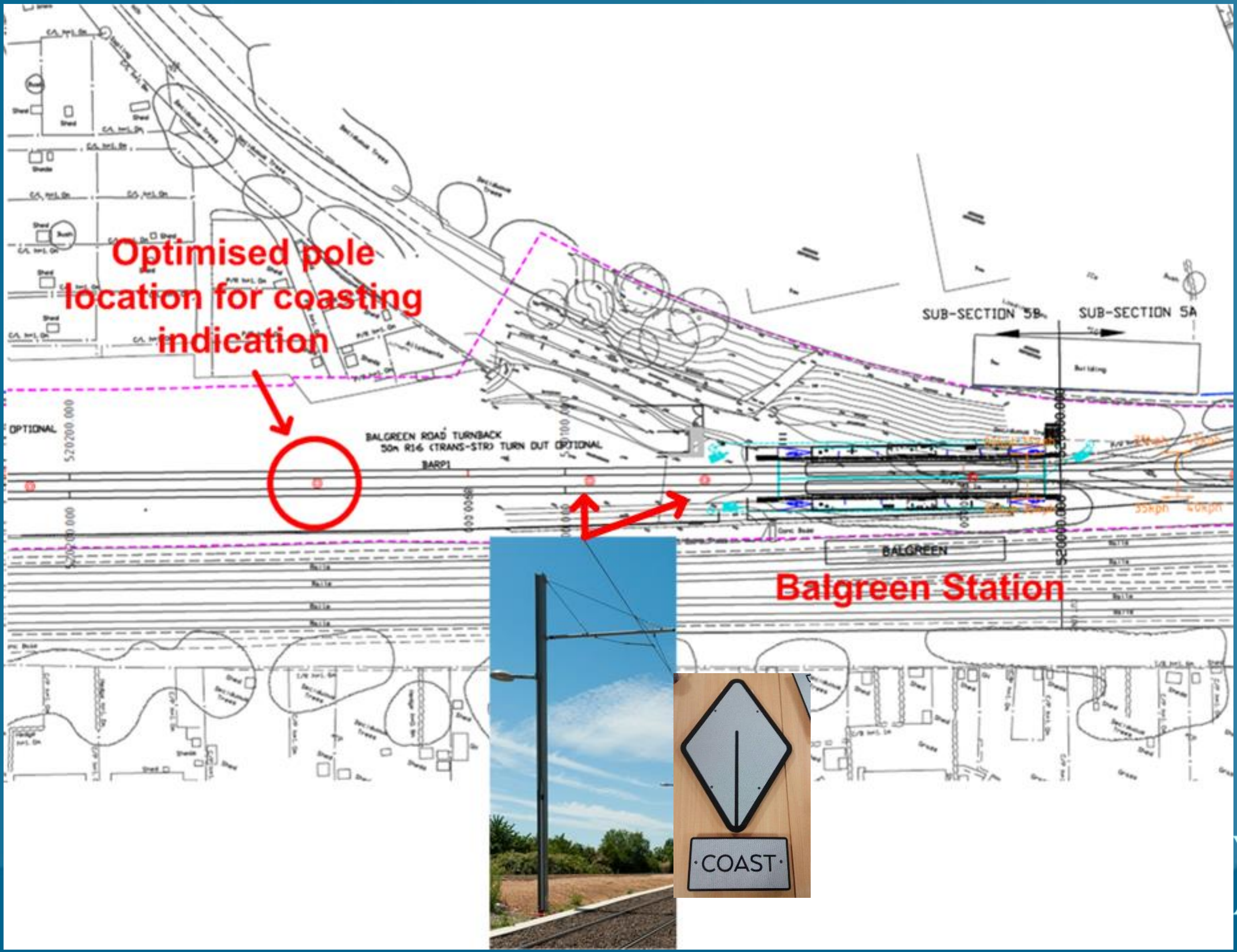
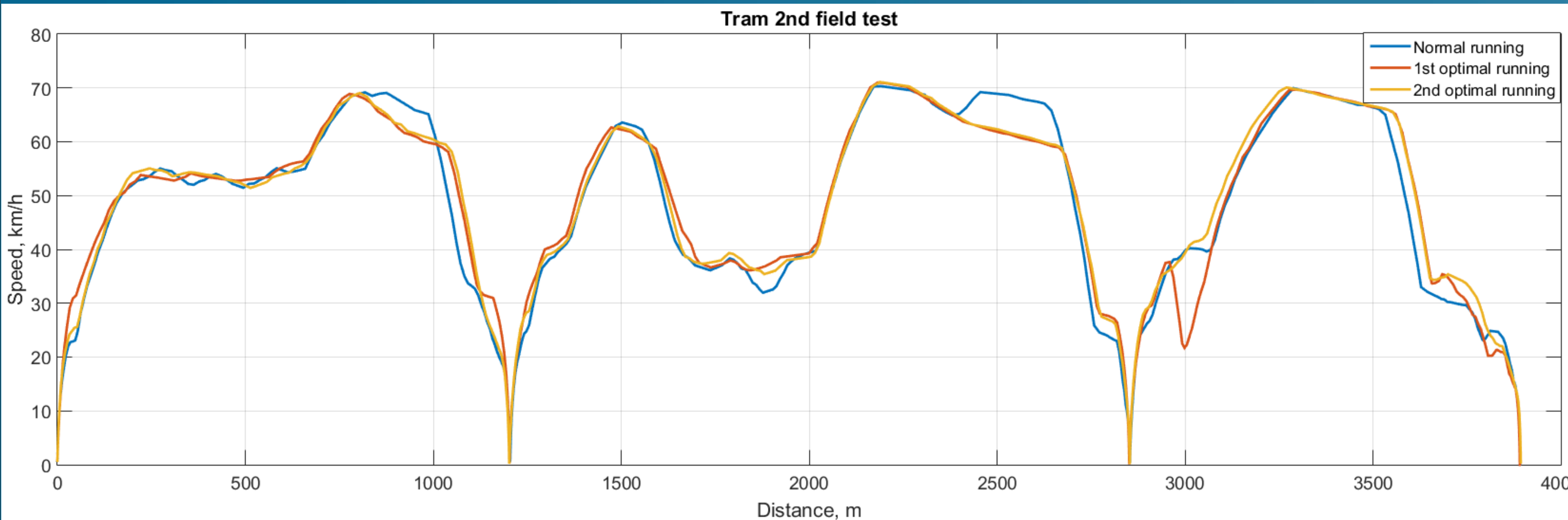
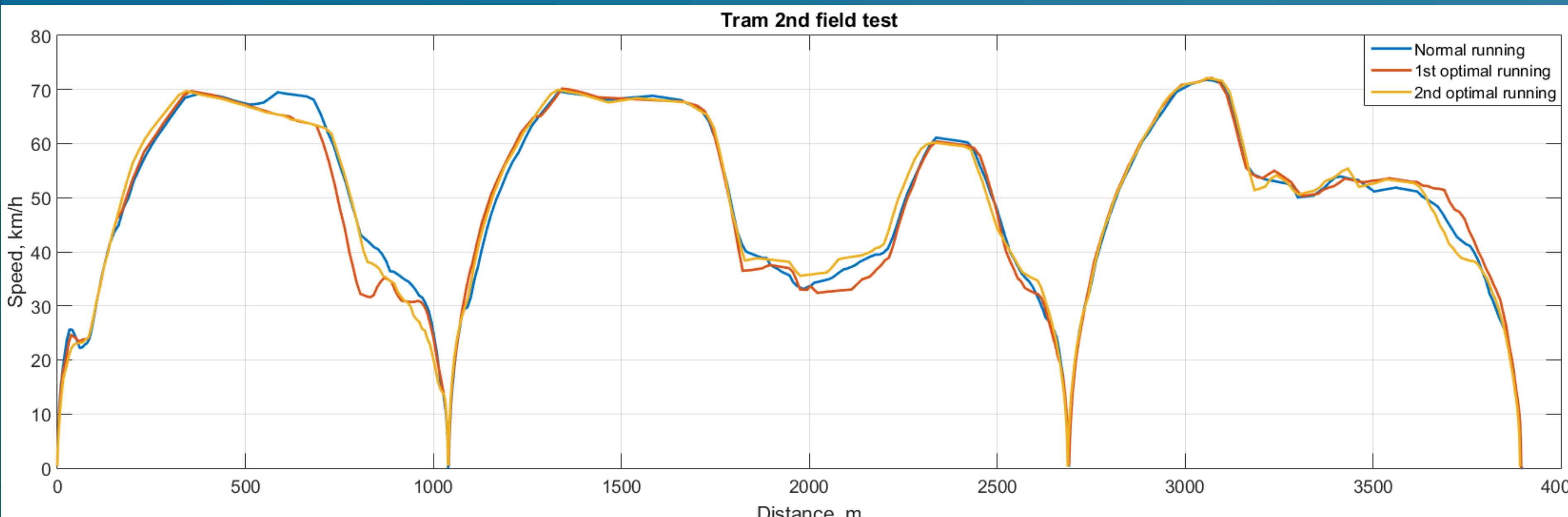
Coasting Board Design

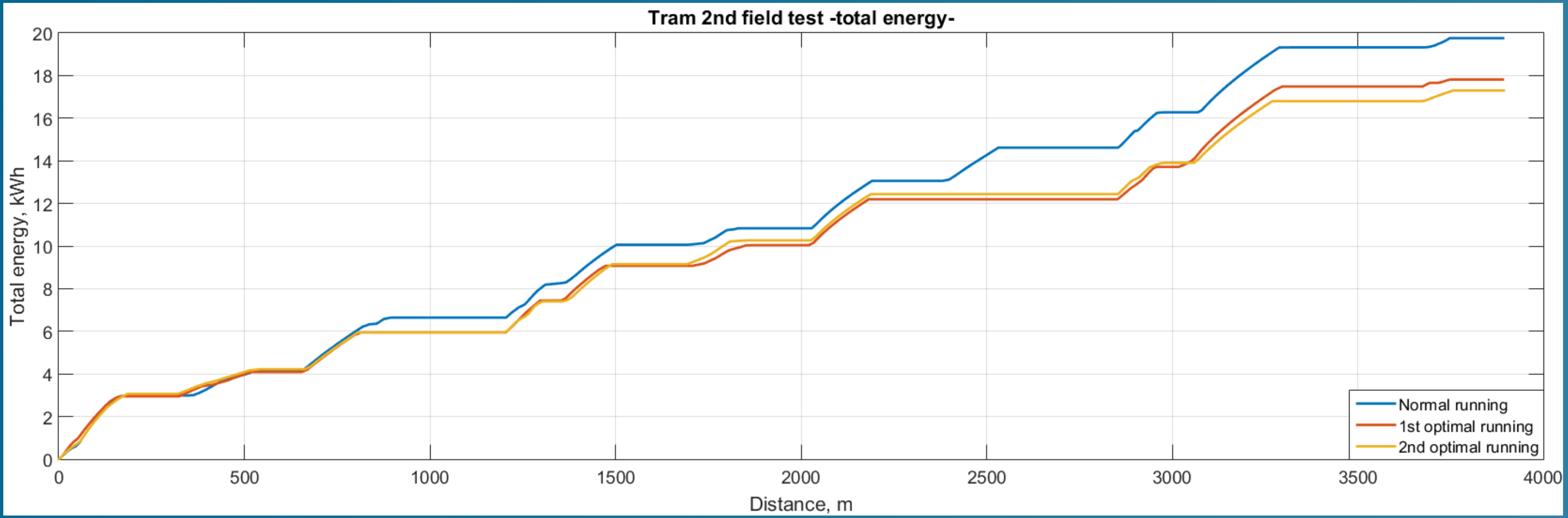




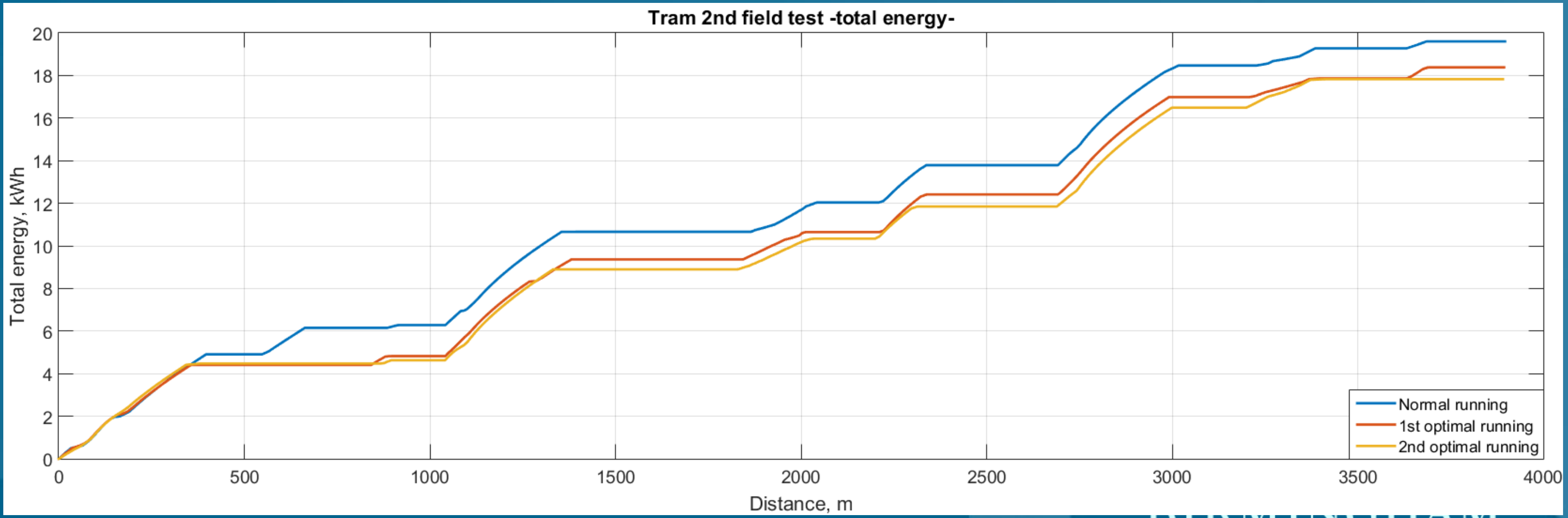
Edinburgh tram trajectory -city bound-



Edinburgh tram trajectory -airport bound-



Energy usage –city bound-



Energy usage –airport bound-

		1st (Normal)	2nd (Optimal)	3rd (Optimal)	4th (Optimal)
City bound	Time (minutes)	7.4	7.5	7.7	6.9
	Energy (kWh)	24.3	21.2 (-12.8%)	22.2 (-8.6%)	21.1 (-13.2%)
Airport bound	Time (minutes)	7.3	7.4	7.4	7.0
	Energy (kWh)	27.5	23.2 (-15.6%)	24.4 (-11.3%)	23.4 (-14.9%)

Multiple Tram Operation Optimisation

	Existing timetable operation	Optimised timetable operation
Tram journey time, seconds	4825	4855
Substation energy, kWh	84.04	76.82 **(-8.6%)**
Substation loss, kWh	1.45	1.21
Transmission loss, kWh	2.68	2.63
Tram traction energy, kWh	95.09	90.12
Tram electrical braking energy, kWh	22.28	20.12
Tram regenerative braking energy, kWh	15.18	17.13
Tram regenerative braking efficiency	68.1%	85.1%

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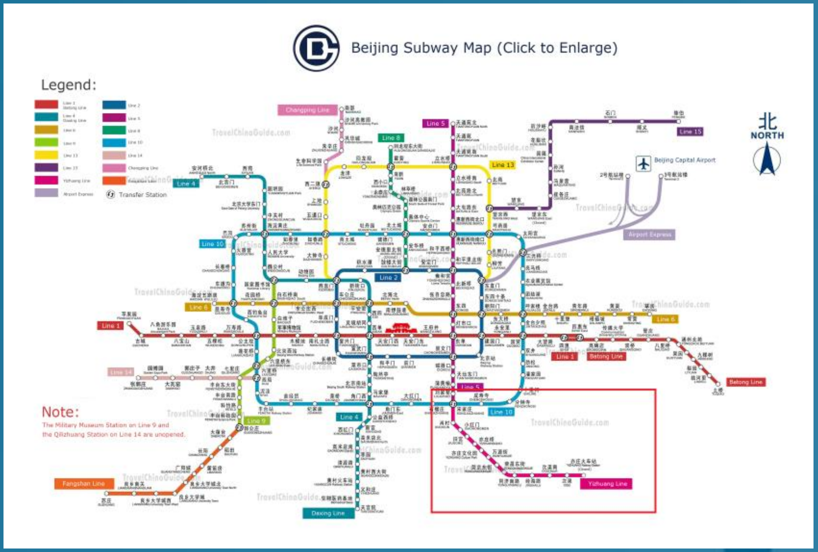
Case Study 2: Beijing Yizhuang Metro Line

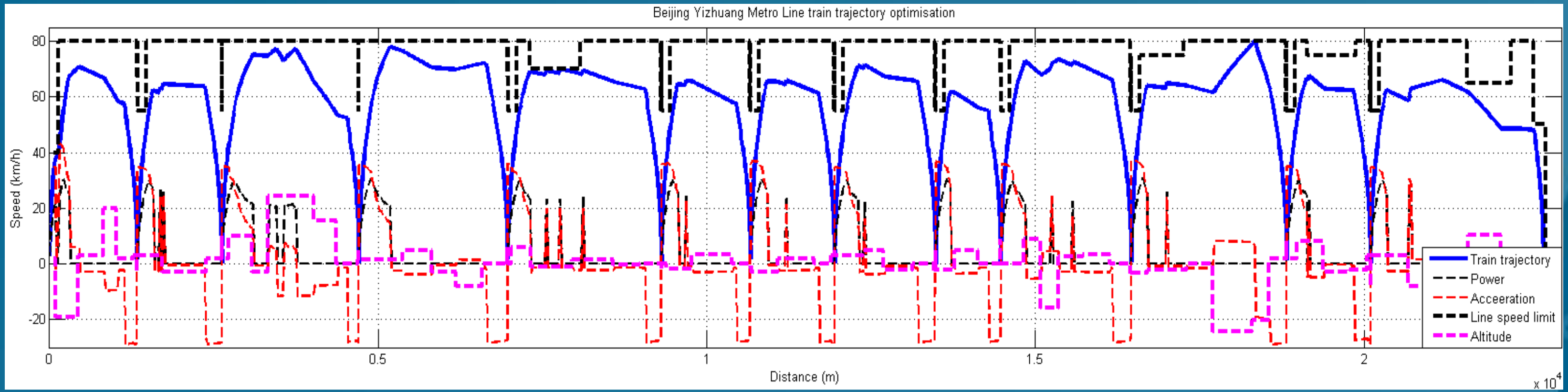
- **Beijing Yizhuang Metro is a suburb commuter railway line equipped with CBTC system;**
- **Energy consumption is becoming a critical concern for modern railway operation;**
- **There is an opportunity to improve the energy consumption of the system through analysis, simulation and optimisation of both static and dynamic design parameters.**



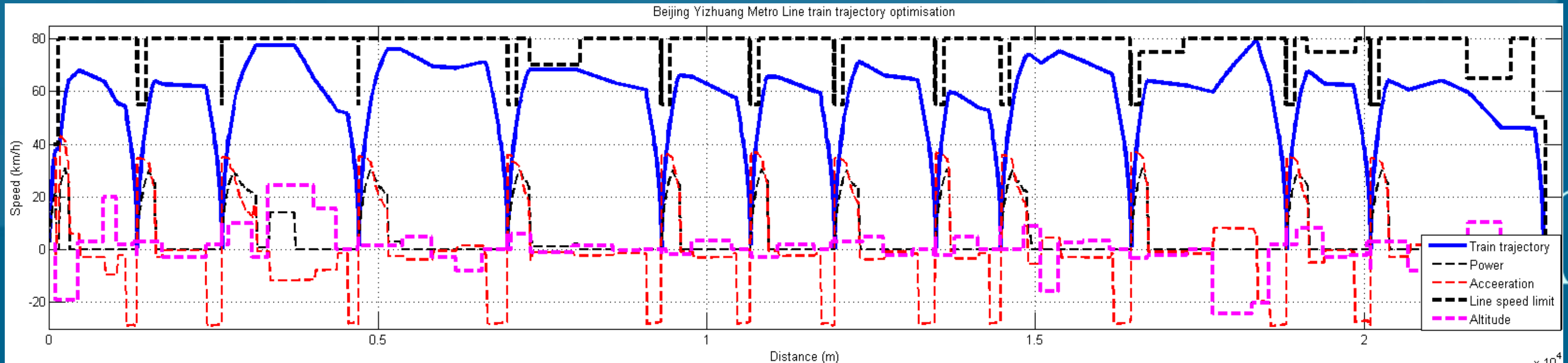
Beijing Yizhuang Metro Line -Single train trajectory optimisation-

Real train trajectory		Trajectory optimisation				Trajectory optimisation + Time disturbance optimisation			
ATO system		ATO system		Human driving		ATO system		Human driving	
Time (s)	Energy (kWh)	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)	Time (s)	Energy (kWh)
1630	380.6	1630	308.8 (-18.9%)	1630	310.8 (-18.3%)	1630	304.4 (-20%)	1630	304.4 (-20%)

Optimisation result for ATO systems



Optimisation result for Human driving systems



Train Trajectory Field Test

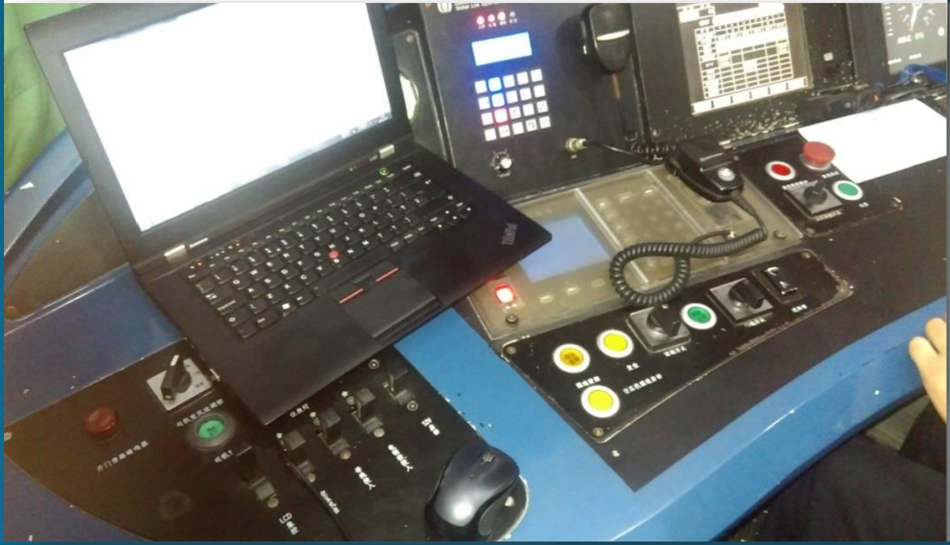
上行1：亦庄火车站至次渠1
Up direction: Yizhuang Railway Station to Ciqu

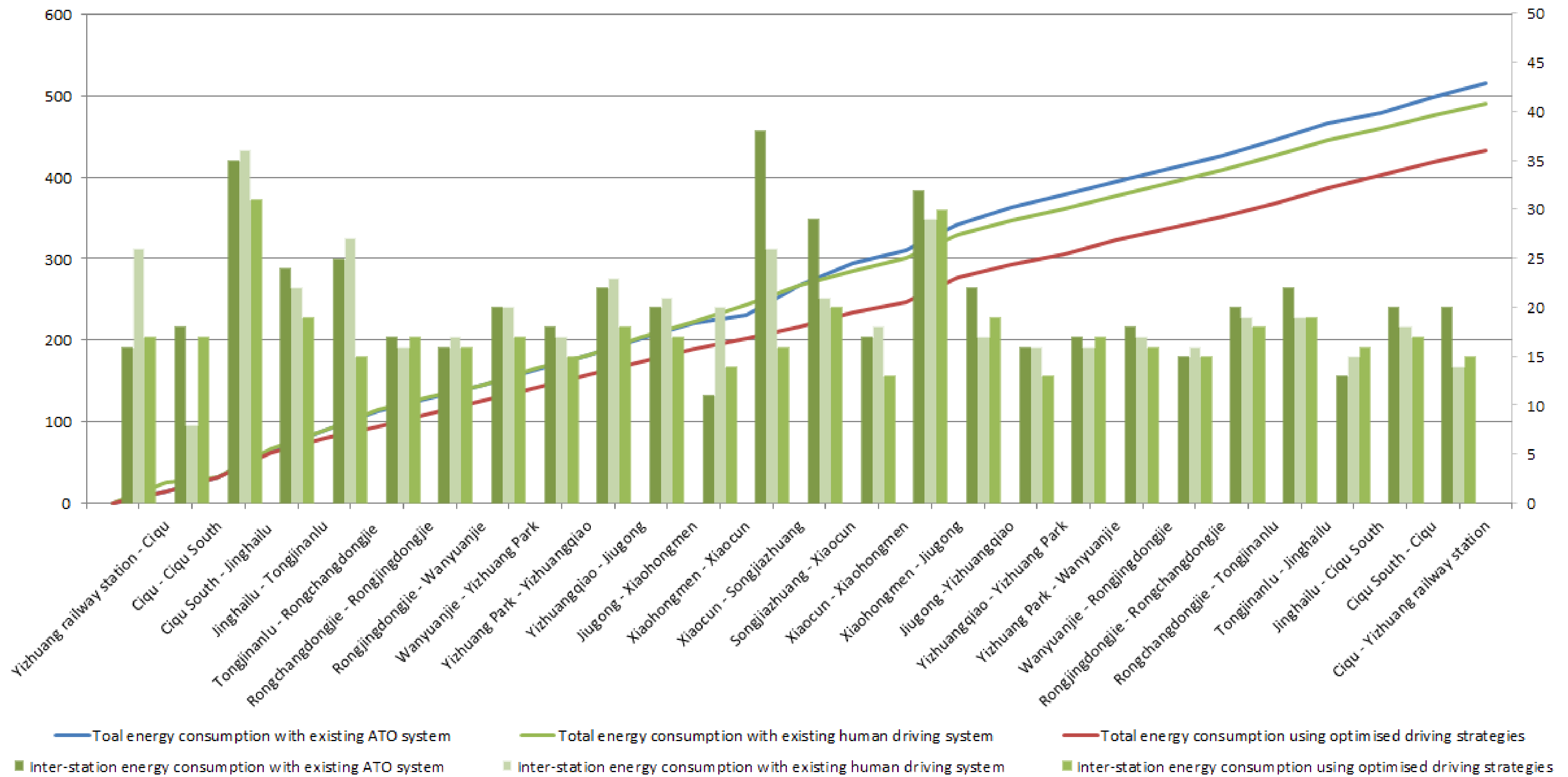
当前工况：牵引
Current movement mode: Motoring

目标速度：35 公里/小时
Target speed: 35 km/h

目标距离：79 米
Target location: 79 km/h

12 秒 后，转换工况为巡航
Seconds later, change to Cruising





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	Notice	Inter-station journey time, s	Traction system, kWh	Auxiliary energy, kWh	Total energy, kWh	Average energy, kWh
Existing ATO	1st Up direction	1609	268	11	279	268.75
	1st Down direction	1616	246	10	256	
	2nd Up direction	1689	268	12	280	
	2nd Down direction	1615	248	12	260	
Existing human driving	1st Up direction	1651	267	12	279	251.5 (-6%)
	1st Down direction	1646	223	10	233	
	2nd Up direction	1651	235	9	244	
	2nd Down direction	1660	239	11	250	
Optimised driving strategies	1st Up direction	1647	217	12	229	227 (-16%)
	1st Down direction	1610	215	11	226	
	2nd Up direction	1625	222	9	231	
	2nd Down direction	1685	213	9	222	

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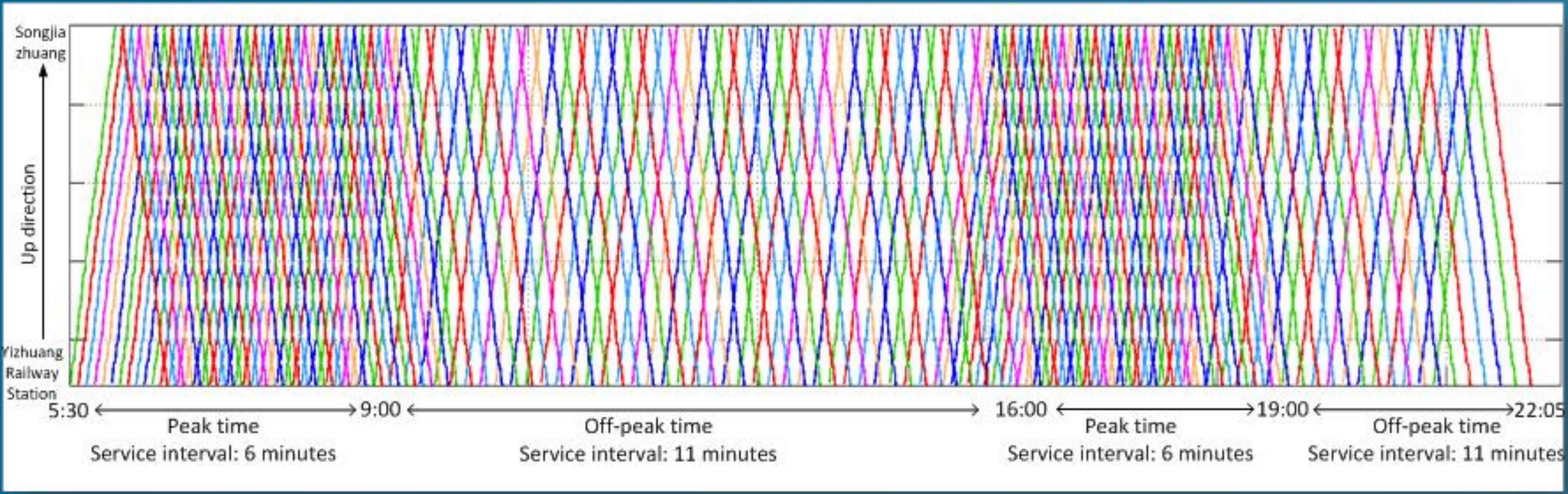
Existing Power Network Simulation



Subject		Results
Auxiliary energy consumption	Lighting, kWh	14
	Cab heating, kWh	21
	Passenger heating, kWh	117
	PIS，kWh	40
	Broadcast, kWh	30
	Air conditioner, kWh	578
	Air compressor, kWh	22
	Total, kWh	823

Subject	Results
Train total journey time, hours	17.7
Train energy usage, kWh	84594
Substation, kWh	88188
Transmission loss, kWh	3594
Substation efficiency	96.0%
Total passenger flow, million	1.13

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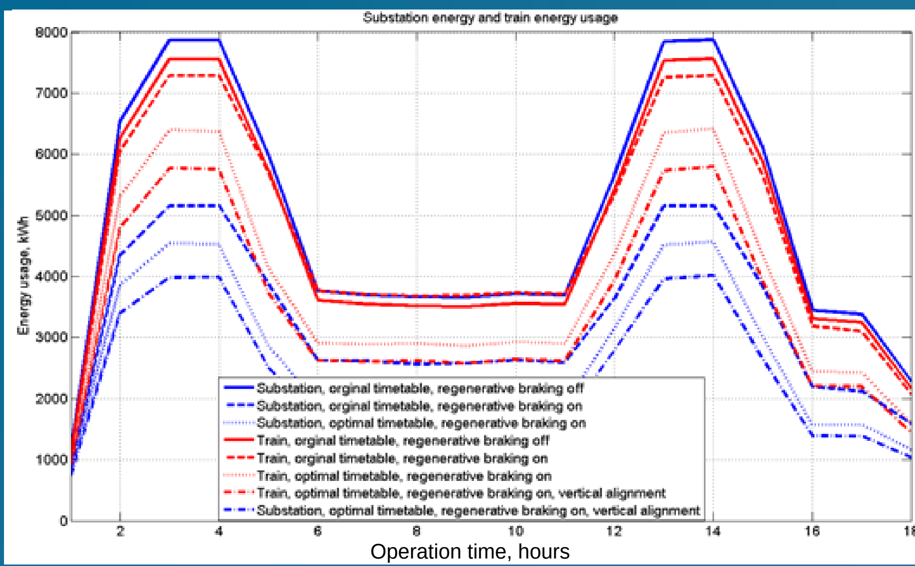
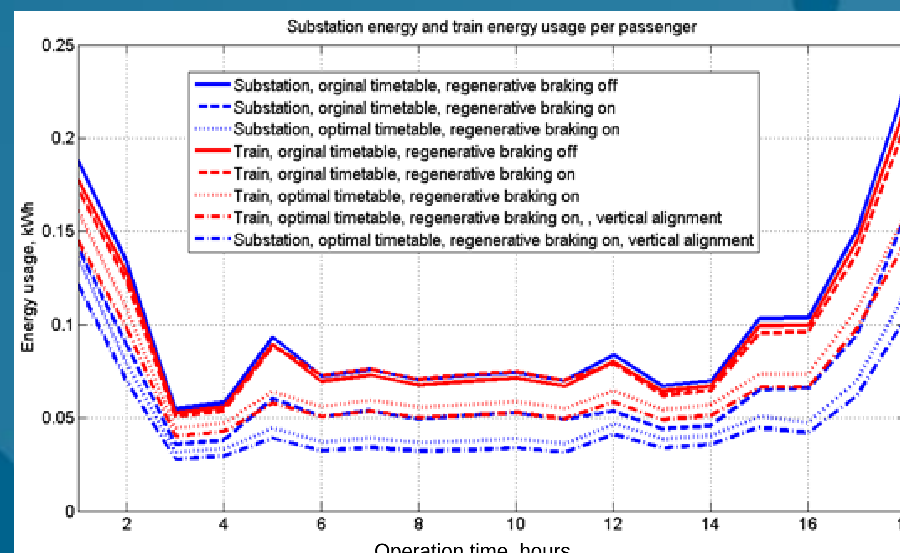
Multiple Train Operation Optimisation

Original timetable			Optimised timetable			Optimised timetable and vertical alignment optimisation		
Substation energy, kWh	Train energy, kWh	Regenerative energy, kWh	Substation energy, kWh	Train energy, kWh	Regenerative energy, kWh	Substation energy, kWh	Train energy, kWh	Regenerative energy, kWh
58696	83563	30333	47645 (-18.8%)	68509 (-18%)	25395 (-16%)	41878 (-29%)	61871 (-26%)	23649 (-22%)



Substation energy, train energy and transmission loss with different timetable and regenerative braking modes in a full-day operation, kWh



Substation energy, train energy and transmission loss with different timetable and regenerative braking modes in a full-day operation, kWh per passenger

Thank you very much.

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