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Multi-Train Energy Optimization using Timetable Optimization via Dynamic Programming and Simulated Annealing with Regenerative Braking Considerations

System Modelling and Simulation Team

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Executive Summary

Metro railway sector consume significant energy due to its high frequency of service. Ensuring energy efficiency in this sector is crucial. Various energy efficiency measures cover a wide range of subsystems available. System-wide thinking is essential to provide a holistic approach to energy saving. However, this is easier said than done, given various subsystem designers often work in isolation. Using design inputs from various subsystems, the traction power system designer designs the traction power system without two-way discussion to ensure inputs received lead to energy-efficient traction design.

This research focuses on developing modelling and simulation software that enables power system designers to interact and provide feedback to other subsystem designers to achieve an overall energy-efficient design. A feature that is missing from most commercially available simulation software. The proposed software includes multi-train journey with integrated exact electrical model. Integrated optimization of driving strategy using dynamic programming and train timetable using simulated annealing method is used. Numerical and heuristic method yields optimum result with high convergence compared to analytical approach. This software can also determine the most optimum regenerative energy recuperation technology to be deployed. The software's output is to provide the project developer with an optimum timetable and driving strategy for consideration before full-fledged traction power system design is undertaken.

Optimally deployed energy saving greater than 20% is possible to achieve.

March,2025 Agenda

Strategic Overview

in elevating Railway Efficiency

Practical and Swift:

Seamlessly bridges traction power and signalling

Immediate Impact:

Unlocks energy savings and boosts operational performance.

Value-Added:

A grounded, results-focused approach tailored for **signalling OEMs**

1. Introduction and Industry Benefits
2. Problem Statement, Objectives and Significance
3. Methodology and Theory
4. Value Proposition
5. Validation and Collaboration Opportunity
6. What’s next ?

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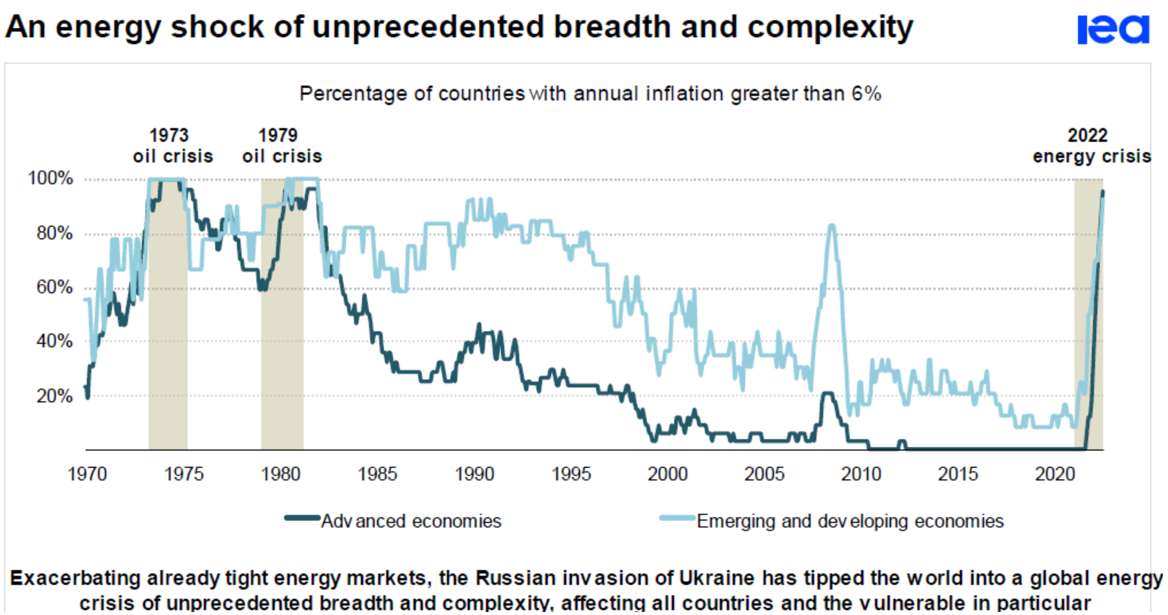
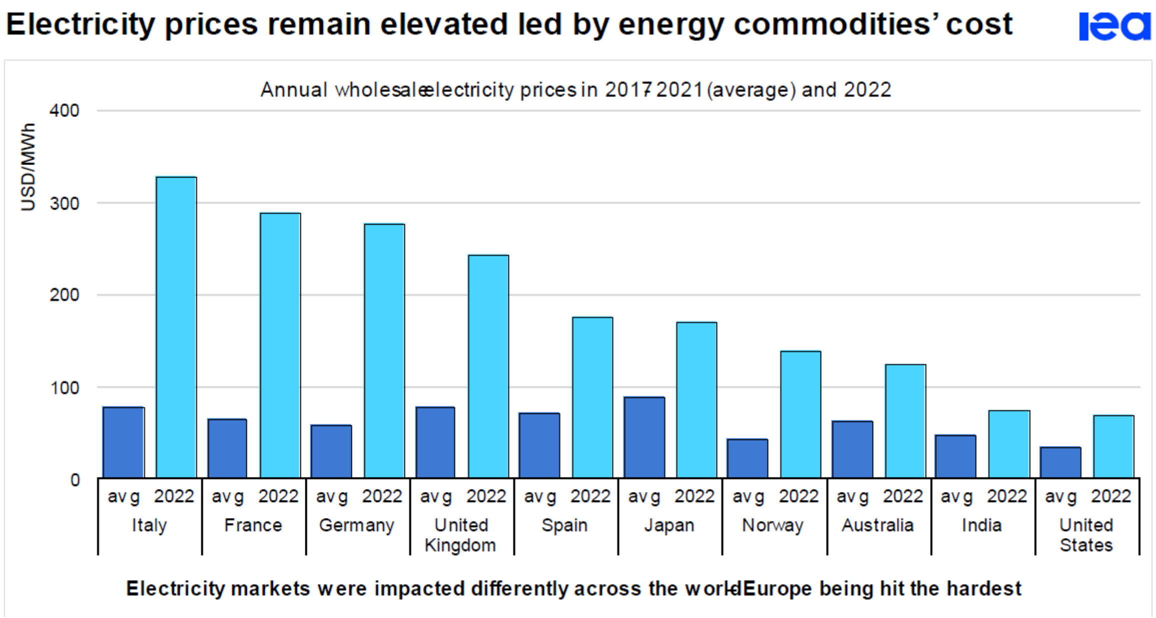
Energy Crisis becomes a pertinent issue

The World with much dependency on Electricity





Energy is becoming a LUXURY commodity

Inflation in emerged and emerging countries *(IEA – World Energy Outlook, 2022)*

The "pain" of electricity price

Average annual wholesale electricity prices (2017-2021) compared to 2022 (IEA – Electricity market report, 2023)

How relevant Energy Saving is to railway ?

Large rail operators are frequently one of the **largest end users of electricity** in their country due to the high level of electrification in many railway systems

(Source: Energy saving in Rail: Consumption assessment, efficiency improvement and saving strategies, overview report Version 14 March 2024)

UK Network Rail:

£ 300 million

Spending of annually prior to year 2015
(Source: *Case Study Network Rail: Driving the Energy Revolution*)

UK Network Rail:

£ 885 million

Year 2023/2024
(Source: ***https://www.financial-news.co.uk/network-rails-soaring-electricity-costs-unveiled/***)

China: Transportation

13.9%

of Total Final Energy Consumption, 2022
(Source: ***https://www.iea.org/countries/china/efficiency-demand***)

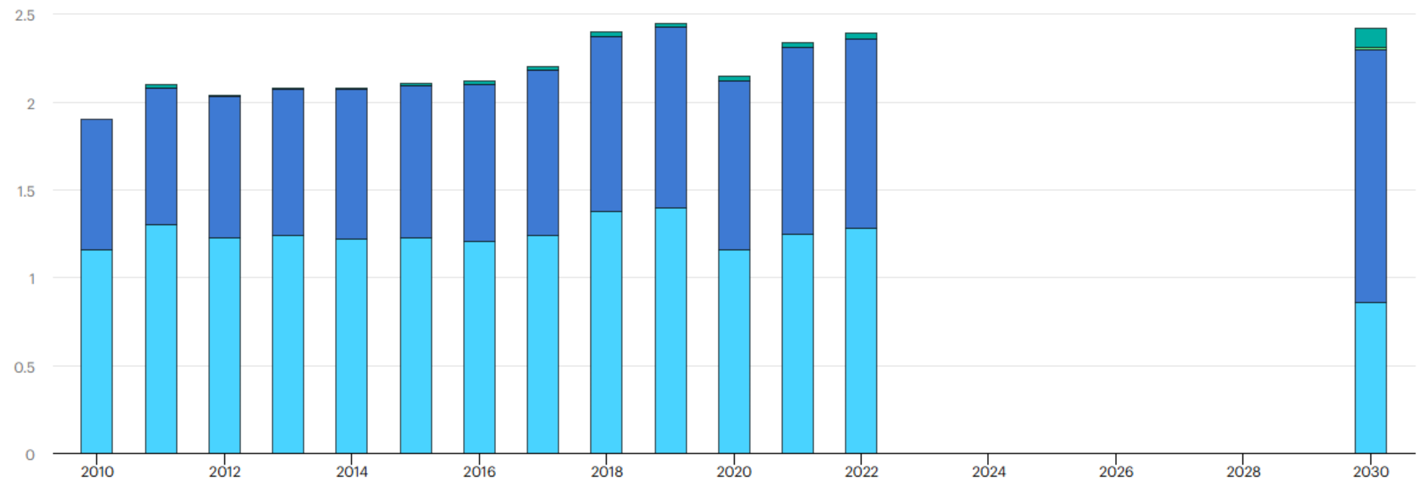
Malaysia: Transportation

35%

of country total energy usage
(Source: ***Ministry of Transport. (2019). National Transport Policy 2019—2030***.)

Energy consumption for rail in the Net Zero Scenario, 2010-2030

Source: *https://www.iea.org/data-and-statistics/charts/energy-consumption-for-rail-by-fuel-in-the-net-zero-scenario-2010-2030*



- **Legend**
  - **Green - Hydrogen**
  - **Dark Blue - Electricity**
  - **Light Blue - Diesel**

What about the dream of hydrogen powered vehicle?

Industry Benefits

SDG 9 - Industry, Innovation and Infrastructure

Achieve Target 9.4 by upgrading infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies

Public Private Partnership (PPP)

With PPP Model, private investor is looking for more energy efficiency railway business model because the profit is directly proportional to the reduction of operational cost.

SDG 13 - Climate Action

Better energy efficiency can reduce carbon footprint.

Value Added Solution

Signalling and Traction Power providers enters into contract independently, synergy between them could bring more value-added energy saving opportunities.

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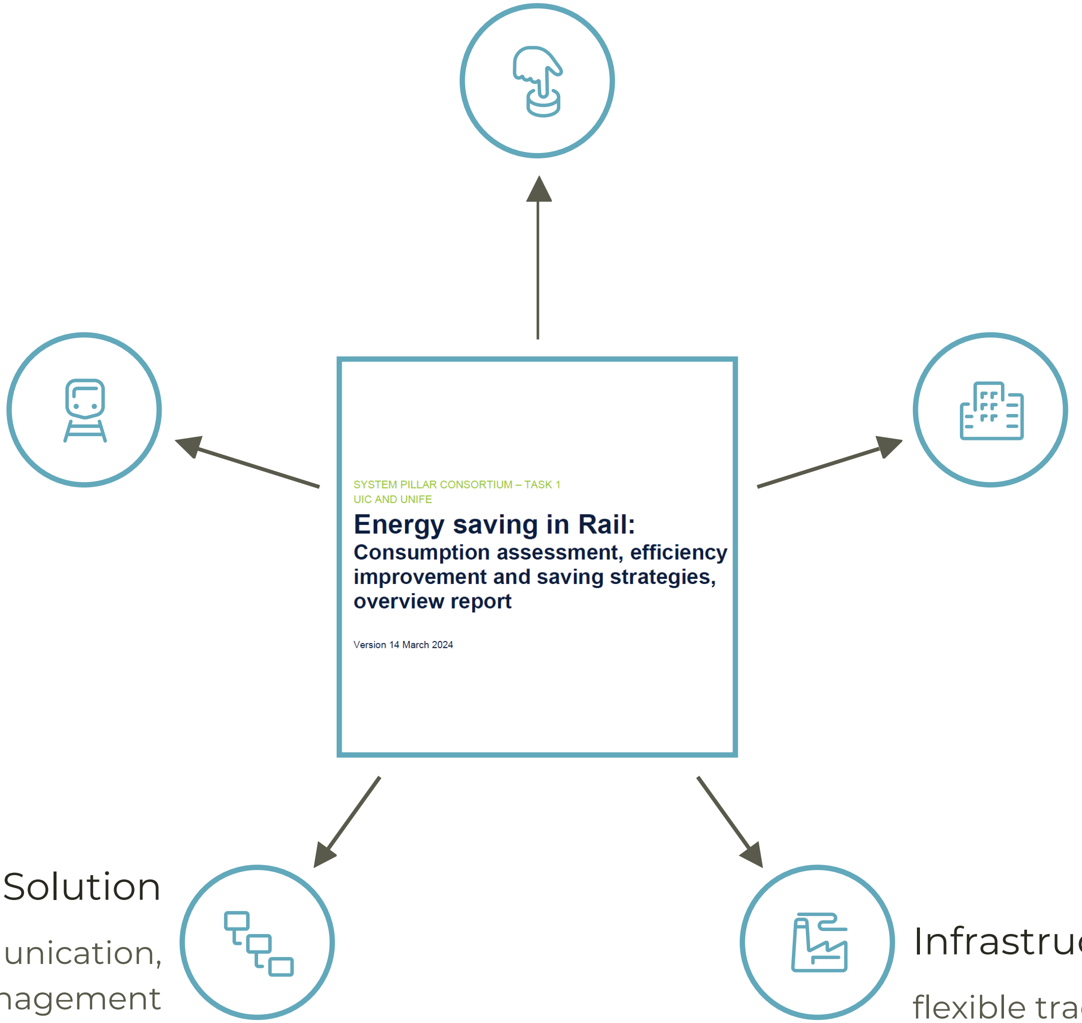
Chapter 2 - Problem Statement, Objectives and Significance

Energy Saving Measures in Railway

*(Source: **Energy saving in Rail: Consumption assessment, efficiency improvement and saving strategies, overview** report Version 14 March 2024)*

Operation Solution

Eco-driving, Driving Advisory Systems (DAS), fine tuning of train services etc



Rolling Stock Solutions

SiC semiconductors, IGBT traction converters, EMB, on-board energy storage, heat pumps for HVAC

Building Solution

Solar, Smart building, HVAC efficiency

Process Solution

Staff Communication, management

Infrastructure Solution

flexible traction energy supply system, energy recovery system, trackside energy storage

Operation Solution

4.3. Assessment and classification of operation solutions

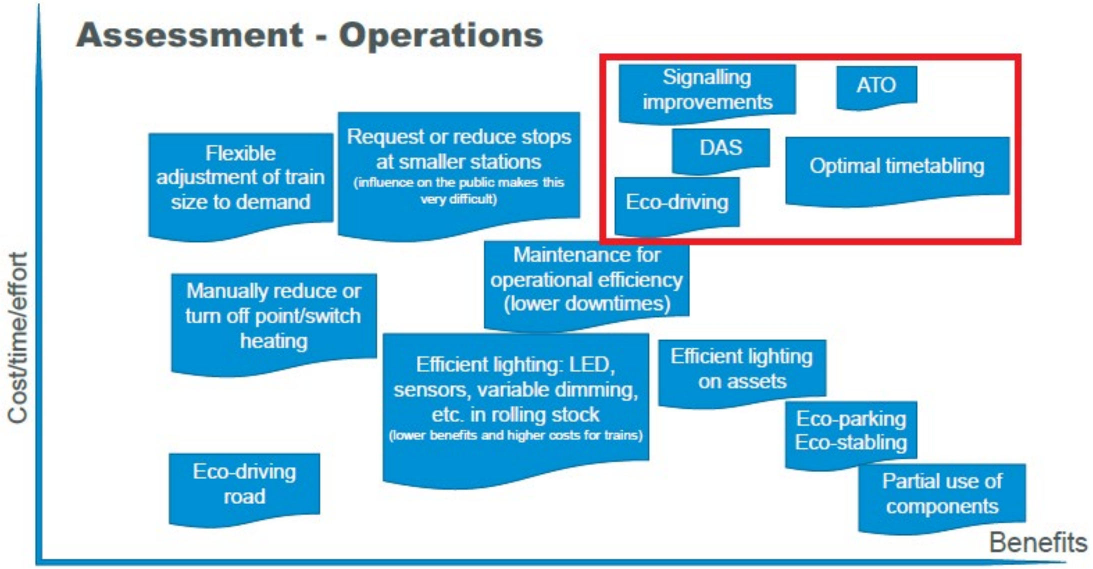


Figure 21: Main potential energy saving solutions for railway operations sorted by cost/benefit ratio assessment

Train Operation as one of the pertinent measures for energy saving.

(SOURCE: ENERGY SAVING IN RAIL: CONSUMPTION ASSESSMENT, EFFICIENCY IMPROVEMENT AND SAVING STRATEGIES, OVERVIEW REPORT VERSION 14 MARCH 2024)

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Our Proposal

Maximization of regeneration energy utilization

Research contribution

Train time table optimization

Driving strategy optimization

Most Energy efficient

Largest energy usage

70% used in traction

EE in traction is vital

Electrification rate
75% - passenger train
50% - freight train

Utility Grid (Not fully decarbonized yet

Reduction of
a) Operational cost
b) Emission

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Thus, research on EE of railway is relevant & pertinent

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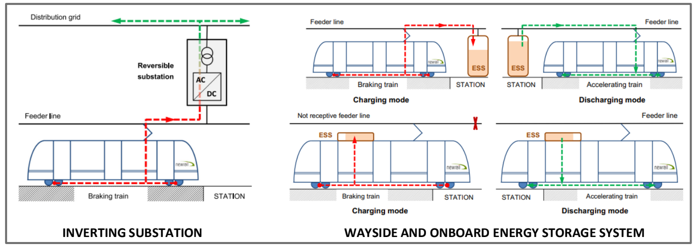
Problem statement and research objectives

PROBLEM STATEMENT

Using fixed speed profile and timetable traction system is designed → Leaves very little or no flexibility for traction power system energy optimization → Technology selection for regen recuperation done without rigorous modelling

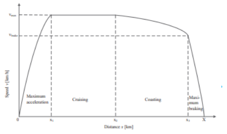
AARU	Cheapest
TERS	
TESS	Most expensive

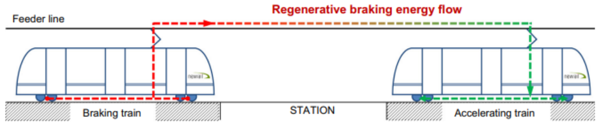


Prove of hypothesis

Commercially available design software uses fixed speed profile & train timetable → **Impediment to achieve energy optimization and new software need to be developed.** → Analysis of ref. site shows a non optimum train scheduling and driving strategy thus not efficient*

*
1). Non ideal pair of accelerating and braking train.
2) No coasting operation





OBJECTIVE

Development of simplified modelling software to search for optimized EE solution → Search for Optimized driving strategy (Eco Driving) → Search for Optimized train time table (Journey time, headway and dwell time)

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SIGNIFICANCE

(1) Allows owner / operator to decide on EE design proposal
(2) All stakeholder to work together to build EE railway system

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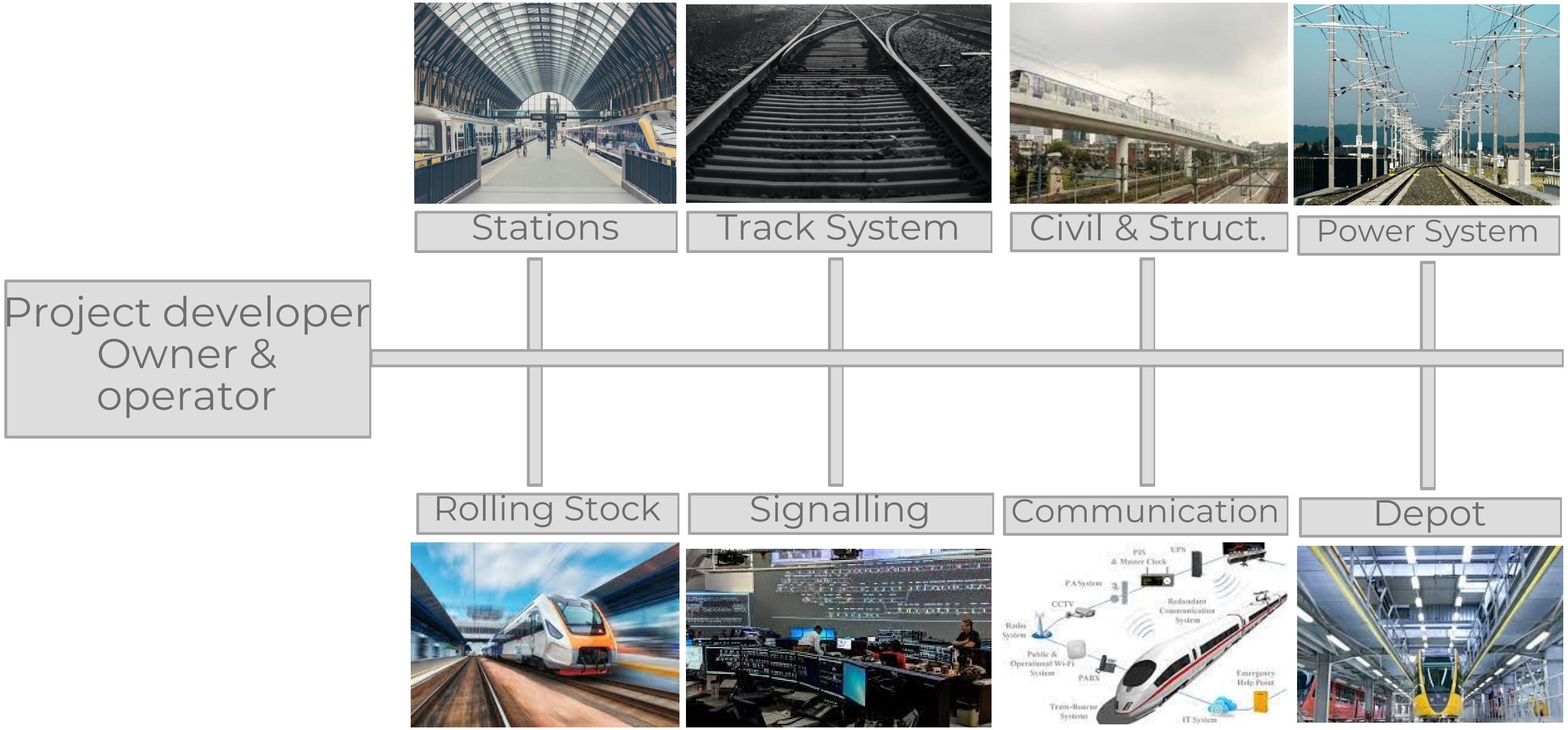
Significance of Research

Various Stakeholders in railway project



- Railway system is an integration of various sub-system and a true system wide thinking is necessary to design the most energy efficient system.
- Various Stakeholder working together to reduce overall energy consumption and improve EE.

Significance of Research

Bridging the Current Research Gap

Current Research: Energy Efficiency Optimization using simplified modelling

Current research for rail energy efficiency assumed simplified modelling of single train mechanical motion to populate to multi-train operation.

Current Research: Lack of integration of Eco-driving and multi-train interaction

Most current research focus on either aspect of eco-driving of single train OR regenerative energy without holistic integration.

Current Research: Ignoring the effect of Voltage dependency

Voltage is an important element, affecting the tractive capability. Ignoring this will render the energy efficiency optimization to be inaccurate.

Methodology

An overview

Simulation Inputs consolidation	Module 1 - Single Train Modelling	Module 1 - Multi-Train Modelling	Module 2 - Driving Strategy Optimization ECO driving	Module 3 - Timetable Optimization	Output
Track Alignment Data, Rolling Stock Data etc	Single Train Motion to create a pocket system operational limit	Analytical method for multiple train with consideration of electrical network.	Apply dynamic programming to find optimal driving strategy	Pairing acceleration and deceleration with Simulated Annealing	Optimum Driving and timetable

Module 2 and 3 may iterate if necessary

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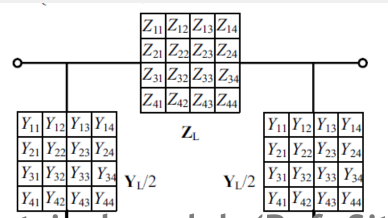
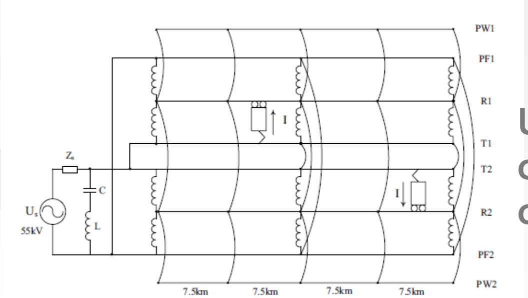
Methodology



Electrical model (Ref. Site)



Uniform multi-conductor chain circuit topology

INPUT (Ref. Site)

ALIGNMENT & PROFILE
- Speed Profile
- Chainage (Station & Substation)
- Curvature Radius
- Gradient
- Tunnel / Open Area

ROLLING STOCK DATA
- Traction Force vs Speed
- Traction & braking chain efficiency
- Braking force vs speed
- Conf., weight, capacity
- Resistance vs Speed

Module 1
Multi Train Journey Model
(Incorporating Electrical Model)
(Analytical Method)

Module 2
Driving Strategy Optimization - ECO Driving
(Dynamic Programming)

Iterate for optimum solution

Module 3
Train timetable Optimization - Pairing acceleration / braking
(Simulated Annealing)

Output
(1) Optimum Energy, Journey Time, Headway
(2) Selection of regenerative recuperation technology AARU, TERS or TESS

Start of design process
(Energy Efficient Design)

Significance of research

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Theory – Module 1

- Equation of motion
  - Kinematic
    - Velocity profile
      - Maximum acceleration
      - Cursing
      - Coasting
      - Maximum Deceleration
    - Acceleration, deceleration
    - **Safe braking distance**
  - Dynamic
    - Traction / braking force
    - Mechanical and electrical power
    - Energy

$$P_m = F_T \times v \quad -(9)$$

$$\eta_{TE} = \frac{P_m}{P_e} \times 100 \quad -(10)$$

Traction energy consuption

$$= \int_0^{TC} power \times time\ dt \quad -(11)$$

$$F_T = F_{rr} + F_a \pm F_g + F_{cr} \quad and\ (-F_T = F_B) \quad -(1)$$

Route	F_a	F_{rr}	F_g	F_{cr}
Straight and even	X	X		
Uphill	X	X	X (+ve)	
Downhill	X	X	X (-ve)	
Curve Route	X	X		X

Adhesion (for rolling without slipping)

$$F_{ad} = \mu_a \times R_a \quad (max F_t < F_{ad})$$

Acceleration Resistance, Fa

$$F_a = ma \quad -(2)$$

$$m = m_{tare} \times (1 + \lambda_{rot}) + m_{pass}$$

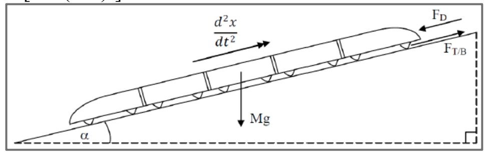
a = Acceleration [m/s2]
m = Resulting train mass [kg]
m_{tare} = Mass of empty train [kg]
m_{pass} = Mass of passenger [kg]
λ_{rot} = Rotational mass factor (>1)

Rolling Resistance, Frr

$$F_{rr} = a + bv + cv^2 \quad -(3)$$

a = Rolling resistance coefficient [kN]
b = Mechanical resistance coefficient [kN/(m/s)]
c = Aerodynamic coefficient [kN/(m/s)^2]

Gradient Resistance, Fg



$$F_g = m_{total} g \sin\alpha \quad -(4)$$

$$m_{total} = m_{tare} + m_{pass}$$

$$\alpha = \tan^{-1}\left(\frac{G}{100}\right)$$

m total = Total mass of train [tonne]
g = Gravitational acceleration [m/s2]
α = Slope angle [rad]
G = Gradient [%]

Curvature Resistance, Fcr

$$F_{cr} = \left(\frac{9.8}{1000}\right) \times \left[\frac{(153 \times S) + 289.6}{R}\right] \times m_{total} \quad -(5)$$

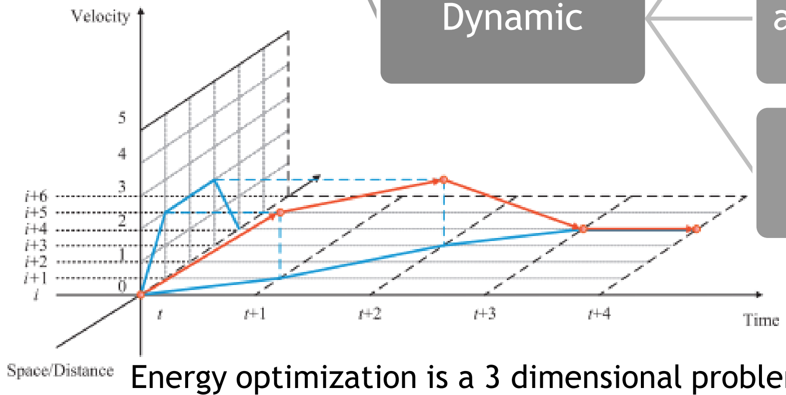
S = Wheel diameter [m]
R = Curve radius [m]

$$a = \frac{Estimated\ F_T - (F_{rr} \pm F_g + F_{cr})}{m} \quad -(6)$$

$$dv = a \times dt$$

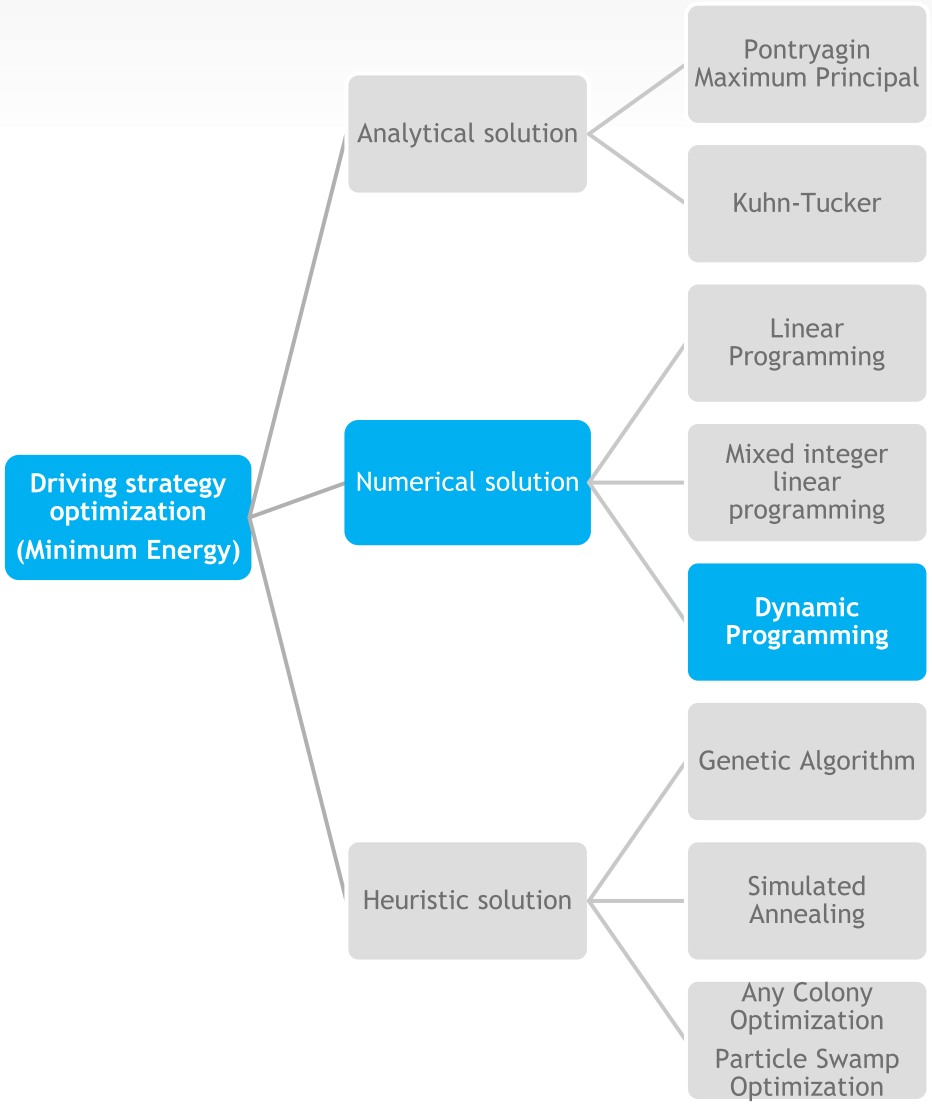
$$v = v_{t-1} + dv \quad -(7)$$

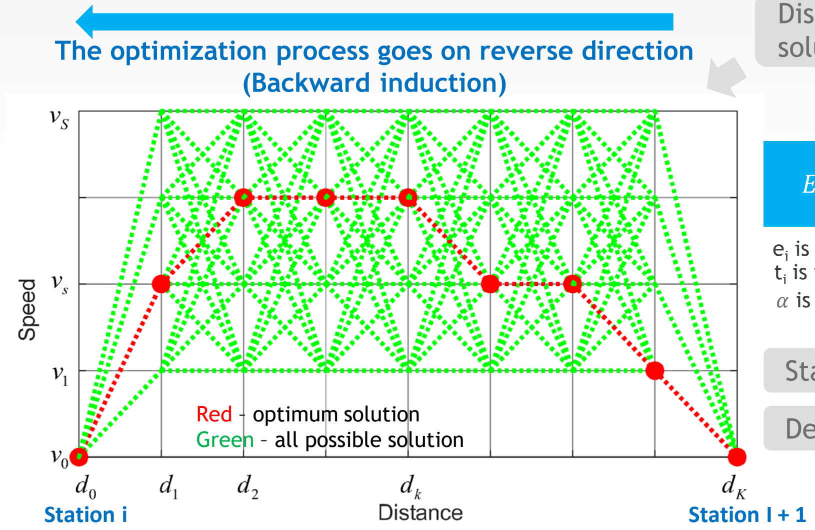
$$ds = v_{t-1} dt + \frac{1}{2} a_{t-1} dt^2 \quad -(8)$$



Energy optimization is a 3 dimensional problem in time, space(distance) and velocity profile (driving strategy)

Theory – Module 2





Weighted Multi Objective Function

$$E_{i_{min}} = \frac{e_i}{E_{Tmax} - E_{Tmin}}\alpha + \frac{T_i}{T_{max} - T_{min}}(1-\alpha)$$

e_i is energy to transition from one stage to another
t_i is time to transition from one stage to another
α is the selected (optimum) weight

State Variable - velocity

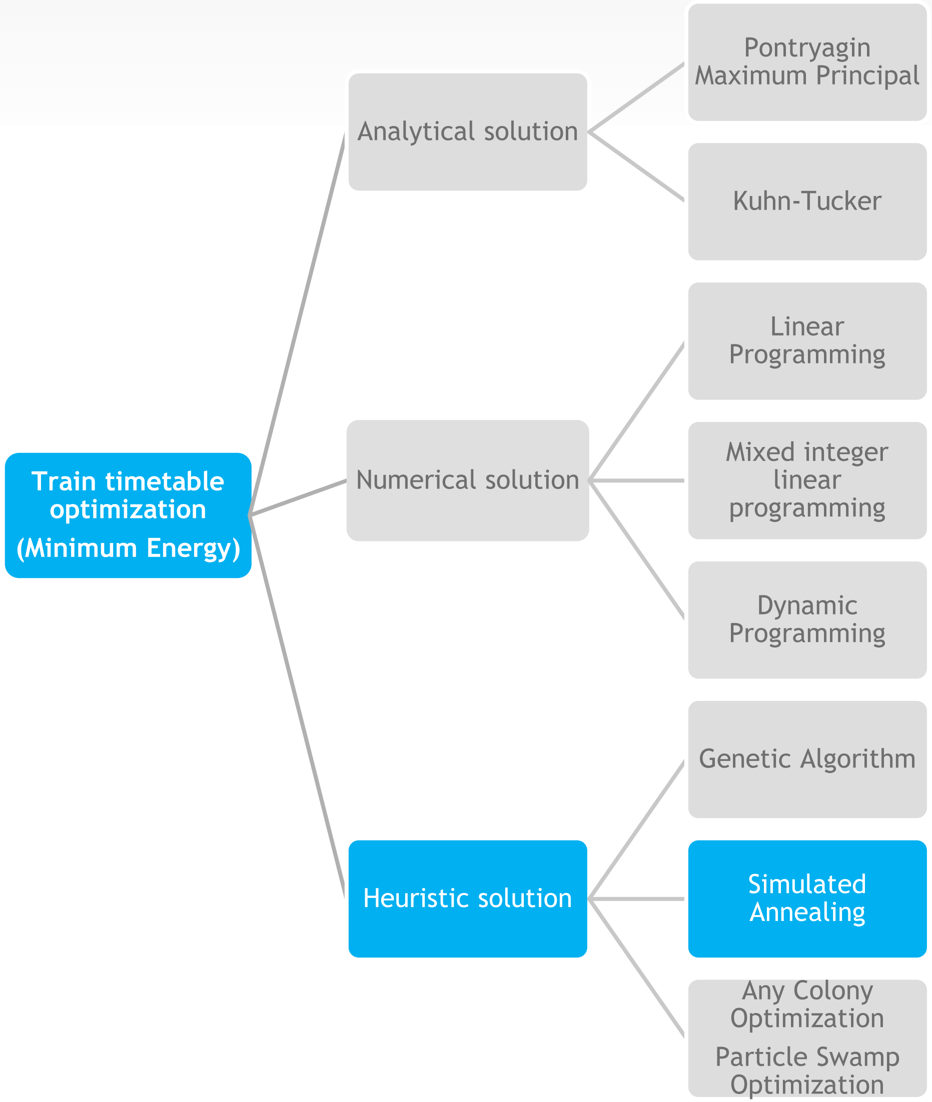
Decision Variable - MA, CR,CO,MB

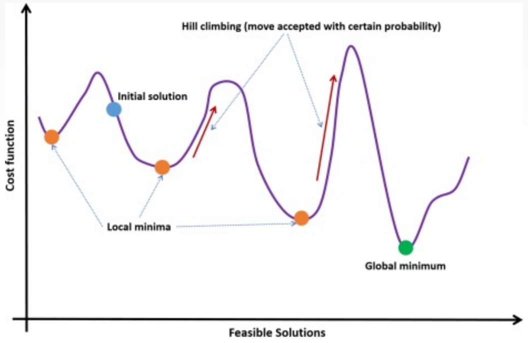
- Dynamic programming is an optimization approach that transforms a complex problem such as optimum driving strategy (eco-driving) into a sequence of simpler problems.
- Its essential characteristic is the **multistage nature of the optimization procedure. Decision** is made at **every stage** and the **overall decision** is the **sum of all decisions** at each stage.
- The objective is to minimum both energy and travel time simultaneously. These are contradictory objective so weights are applied for energy and time.

Bellman Principle of optimality

Any optimal policy has the property that, whatever the current state and decision, the remaining decisions must constitute an optimal policy with regard to the state resulting from the current decision.

Theory – Module 3

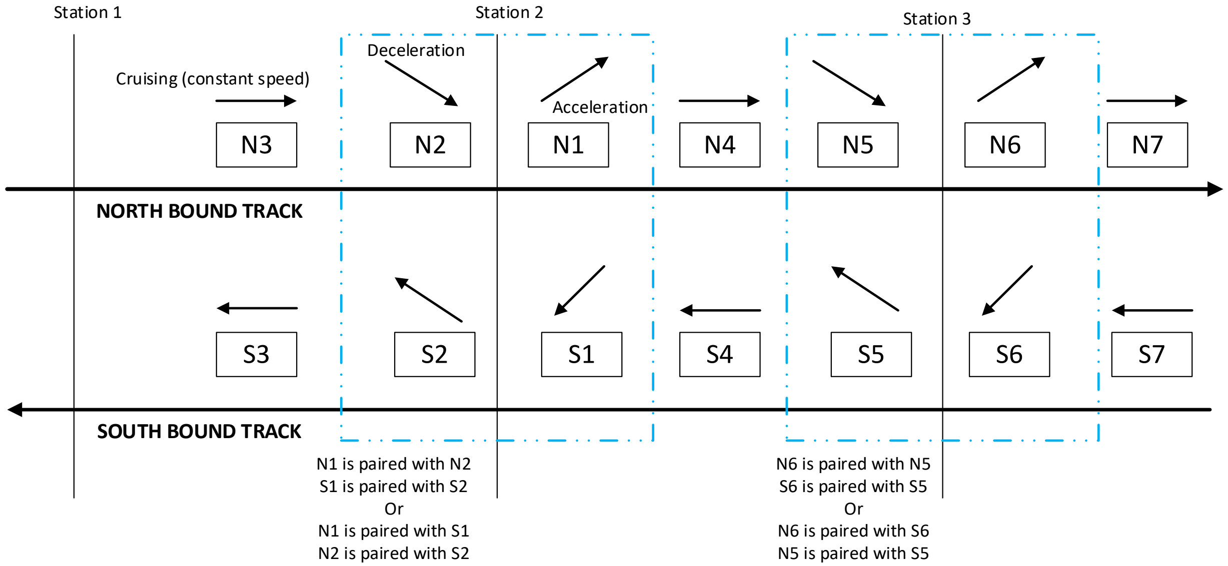




Based on the current initial solution, a new solution X is generated in the solution space by stochastically increasing or decreasing the:-

- trip times by 0.1 seconds or
- headway by 1 second
- Dwell time by 1 second

The goal is to increase pairing between accelerating and braking train to exchange regen energy



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The framework

Infrastructure input:-

- Train Traction Parameter
- Route Data
- Power Supply Data

t=0

SINGLE TRAIN MOTION SIMULATOR

Dynamic Input:
Driving strategies
$f(v_{cruising\ max}, v_{coasting\ min})$

Dynamic Programming

Equation of motion
Kinematic and dynamic

Output:

- Train Speed Profile
- Train Power Requirement
- Traction Energy Consumption

Dynamic Input:
Time Table (Interstation journey time, dwell time and headway)

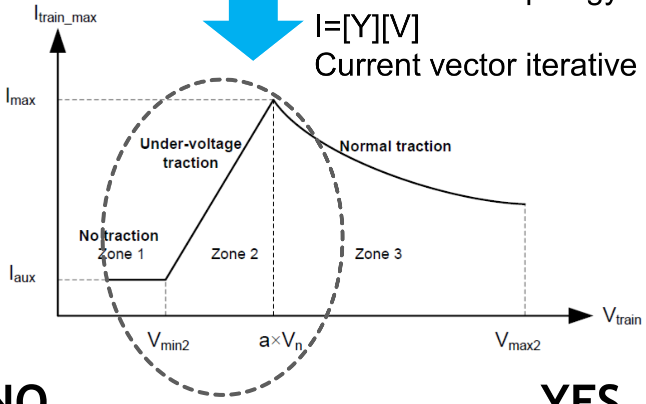
Simulated annealing

MULTI TRAIN MOTION SIMULATOR
POWER NETWORK
DC LOAD FLOW
AC LOAD FLOW

Output:

- Total system energy & system Energy Flow & losses
- All electrical parameters
- Voltage profile

Chain circuit topology
I=[Y][V]
Current vector iterative



Test System

1) MRT1
2) MRT2
3) EN50461
4) Ref. Site 1
5) Ref. Site 2

Regenerate dynamic inputs for driving strategy and timetable

Recalculate velocity profile using lower Pm / Ft

t=t + 1

NO

YES

STOP

Minimum energy consumption achieved?

NO

If voltage in this region (under voltage traction)

YES

1) Power network calculation to be verified by MATHLAB Simulink or other circuit analysis software.

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Beginning with the end goal in mind

- CAPEX and OPEX reduction

  Reduce CAPEX by minimizing investment in traction power infrastructure.

  Reduce OPEX where energy saving of up to 25% is achievable

- ESG reporting and SDG

  Efforts in supporting SDGs are essential for ESG reporting and will have many benefits in future business opportunities.

22%

Reduce OPEX where energy saving of up to 25% is achievable

- Value added benefit as complete solution

  The solution will bring benefit for both traction power and signalling packages where it will be an important differentiation strategy during project bidding.

- Embrace Public Private Partnership framework

  CAPEX and OPEX reduction are essential element for developer considerations as partners in PPP framework

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Validation Approaches

Validation against EN50641:2020

To prove the analytical calculation modules correctness

Comparison against an industrial proven software*

With the optimized timetable, validate the energy savings calculated using an industrial proven software

- *Note*

a. Comparison against the industrial proven software depends on the availability and budget approved for such activity.

b. Alternatively, validation can also be done in an actual simple track if there is an opportunity to reprogram on the signalling system,

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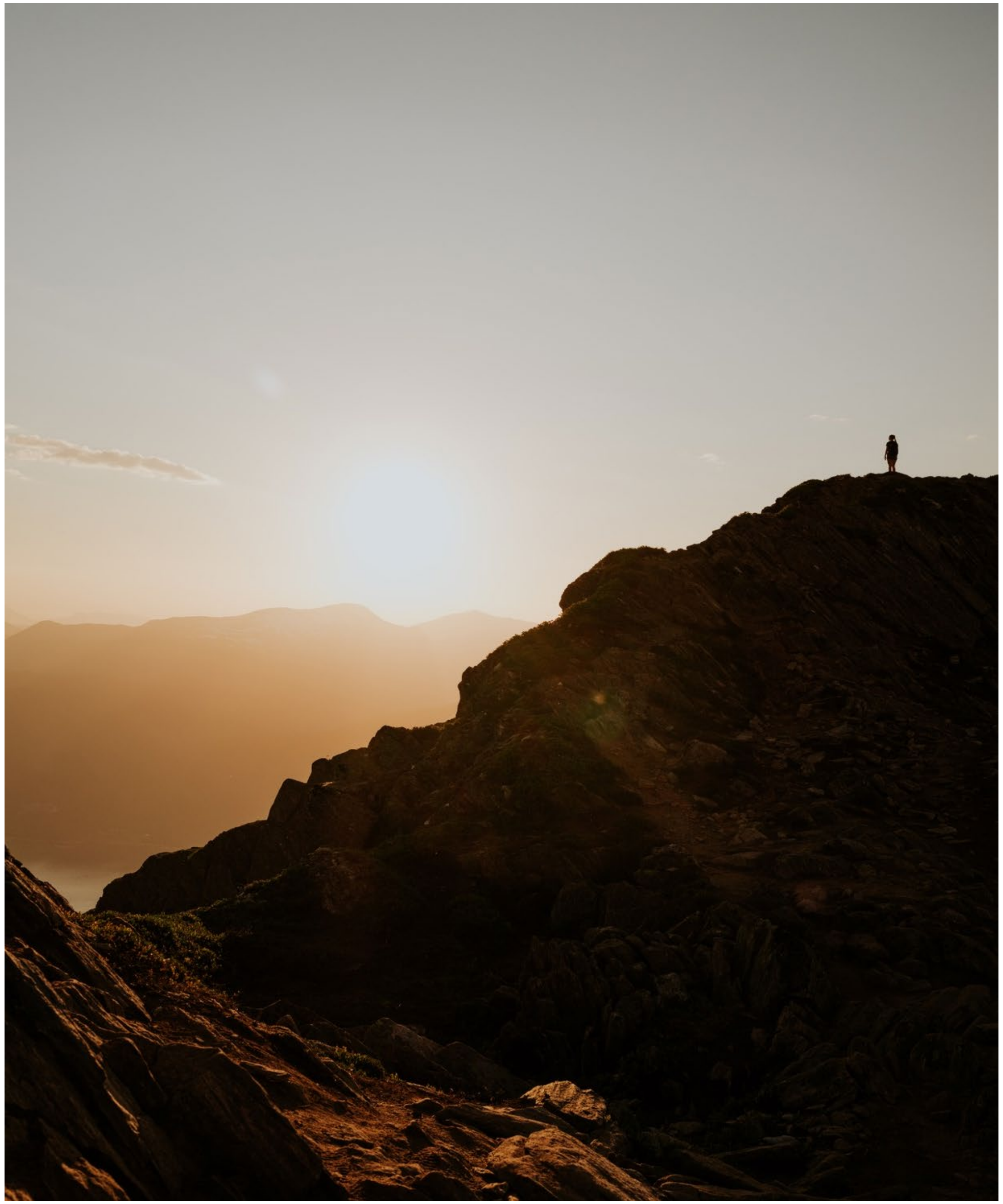
Chapter 6 - What's Next ?

Do we stop here ?



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Chapter 6 - What's Next ?

Moving into realtime

Online Optimization Module requires **real-time** interaction and adaptation. It is **FAST**, **AGILE** with **SAFETY** in mind.

All encompassing self adaptive solutions taking into **consideration** of **disturbance** to the system, **train delay** on own network and train delays from other networks at **interchange** station. Ultimate **passenger comfort** is assured.

Stage 1: **Offline Implementation**

Our current offering

Stage 2: **Online DAS System**

Future further collaboration

If the product calculation for stage 1 is satisfied, we could explore for Stage 2 enhancement implementation.

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Offline and Online Implementation

Implementation does not compromise the safety and signaling system !!

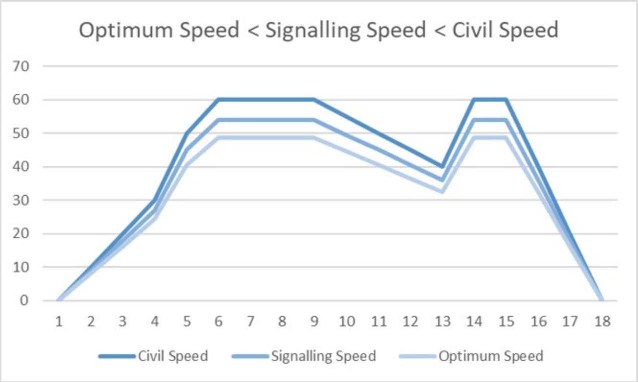
FRMCS - Future Railway Mobile Communication System

Offline Implementation

- Non time critical.
- Analytic / Heuristic

Speed Profile Program

1. Ref to Baseline timetable and driving strategy
2. Comparison between optimum profile / timetable and reference profile / timetable
3. Fast but not reactive



Online Implementation

- Real Time
- AI adoption

Speed Profile Program

1. Real Time DAS (Driver Assistance System)
2. Requires migration from GSM-R to FRMCS*
3. Consideration of system disturbance, train delay (own and adjacent network), interchange and passenger comfort.

Chapter 6 - What's Next ?

Online System

"If Online System is the future, why not we start with that ?"

A practical start and market acceptance

We are focusing a grounded, applicable system. Current market sentiment is still on the train arrival punctuality. Offline time-table optimization shall be a beginning step to optimize energy

Technology readiness

Safety is at the core of signaling system, and hence real time system requires vehicle safety in terms of FRMCS adoption.

Offline timetable as fall back and Adoption of real-time based on offline

Real-time system is computational intensive. Hence, the algorithm shall be implemented based on the backbone of the offline timetable and focus shall be given on "correcting" the travel according to the offline timetable.

Chapter 6 - What's Next ?

The future

Can FULL receptivity of regenerative energy be possible ?

The real "green energy" is energy that is saved !!

Design at heart	Suitability	The system	Signalling in re-invention	Implementation
Suitable for AC or DC traction power system (Better savings for DC traction)	Ideal for METRO (Rapid Transits) with short headways	Can be implemented for systems with any type of regenerative recuperation technology (AARU, TERS, TESS way side, TESS on board)	Suitable for signaling systems with ERTMS or CBTC	Can be implemented offline or real time

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THANK YOU

Let's do great things together.

Modelling and Simulation Team

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is a seasoned electrical engineer who graduated from the University of Malaya in 1994 and earned a master's from the University of Bath in grid system stability. He spent 20 years at ABB in various international roles—from design and commissioning to senior management—ultimately serving as Vice President of ABB Malaysia for Power Systems and Products. In 2014, he became CEO of PESTECH International, leading rail electrification and power generation until retirement in February 2025. He is also an active member of IEEE, IEM, and BEM, serves on the Industrial Advisory Panel at the University of Malaya, and is a founding member of the Malaysian Rail Industry Consortium.

BanJuan, OOI

earned a First-Class degree in Electrical and Electronics Engineering from the University of Malaya in 2012 and later an MBA from KEDGE. He began his career at ABB as an instrumentation, control, and automation engineer for various power plants, then joined PESTECH Technology Sdn Bhd, where he advanced from Lead Engineer to Principal Engineer and built a renowned team in power system modelling, simulation, and traction design—leading multiple complex projects until his retirement in March 2025. He holds several professional memberships (PEng, PTech, MIEM, CPEng, A.C.P.E., CEng) and serves as the alternate on the Industrial Advisory Panel for the University of Malaya's Electrical & Electronics Engineering Department.