Sustainable Transportation with electric train

Tahan Lumban Tobing, Universitas Kristen Indonesia

Abstract – The shared desire to maintain the world to be inhabited by the next generation has been carried out in the agreement of nations, the last of which is the Paris agreement. This agreement also regulates better transportation issues. Some of the influences on transportation issues occur in transportation in a densely populated area or city. The most efficient use of rail-based mass transportation vehicles has been stated by many studies. This encourages the following studies. So the progress of optimizing the use of energy in mass transportation vehicles is important and is reported in this paper.

Keywords: *electric railway, optimization, sustainable transport, SDG, rail based*

The movement of people and goods requires transport, which is essential in society. Transport has many economic, social and environmental benefits. However, transport also requires 64% of global oil consumption or 27% of all energy use and produces 23% of the world's energy-related carbon dioxide emissions. (sdg-un 2015a)

These weaknesses must be addressed according to the standards agreed upon by stakeholders in the Sustainable Development Goals (SDG) principles. The things that are improved in transport are found in SDG 3, which reduces pollution, increases human physical activity and reduces greenhouse gas emissions, then in SDG 13, which meets the value of greenhouse gas emissions per passenger-kilometre, the percentage of electric vehicles in the fleet and the share of renewable energy in energy use, in SDG 7, meeting vehicle energy efficiency and public access to electric vehicle charging infrastructure, on SDG 11, the percentage of the population using public transport, more convenient pedestrian and cycling facilities and reduced congestion, on SDG 9, investment in smart transport systems and development of sustainable transport technologies, and SDG 17, stakeholders cooperation on this initiative. (sdg-un 2015a) The conclusion of this initiative can be seen in Figure 1.

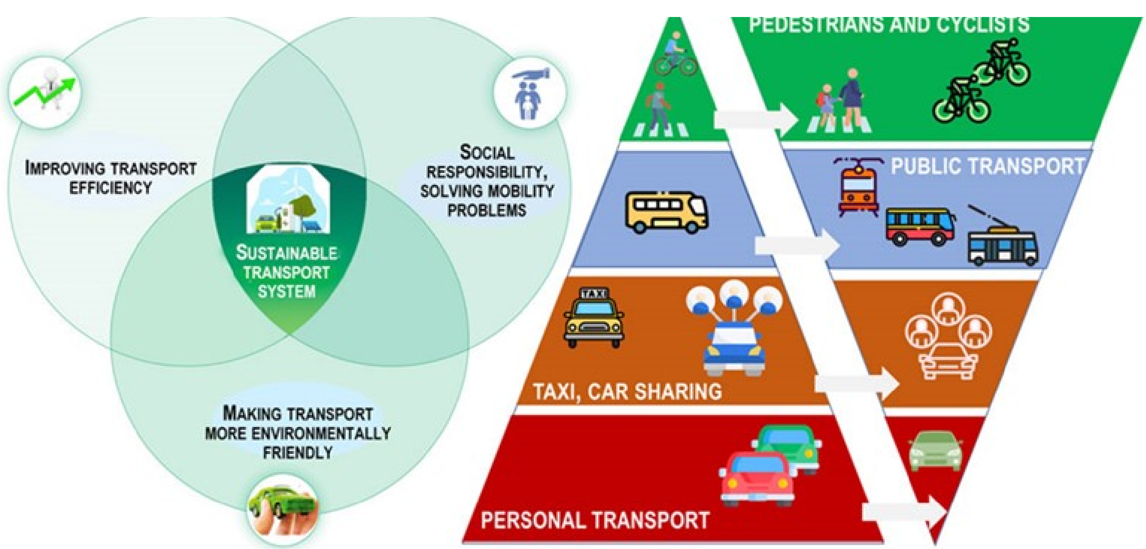

Figure 1. Sustainable Transport System and Shifting ways of transport (itdp 2015)

In Figure 1 on the left, we can see three important sectors that support a sustainable transport system according to the SDGs discussed in the previous paragraph, namely improving transport efficiency, making transport more environmentally and socially responsible, and solving movement problems. This has resulted in a shift in the way people transport, as shown in Figure 1 on the right. (sdg-un 2015ba)

In the framework above, which can be seen in Figure 1, the role of government and stakeholders is very important in providing good public transport. Where good public transport will encourage a shift in the way people transport. Transport systems for passengers travelling in groups based on time on specific routes and possibly for a fee are called public transport (mass transit). Public transport usually consists of buses, trains (land), ferries (sea) and airplanes (air). Inter-city public transport is dominated by airlines, buses, and intercity trains. High-speed trains have also been used in various parts of the world. It seems to depend on the dimension, but the current focus is more on urban transport and its surroundings, i.e. buses or trackless vehicles, and trains or rail-based vehicles. (sdg-un 2015a)

Public transport (sdg-un 2015b)

Public transport is a mass transportation system available for people to travel in groups. These vehicles include buses, trains, ships, ferries, airplanes and other modes of transportation that operate on set routes and schedules.

Public transportation between cities is dominated by airlines, ferries, buses, and intercity trains. And increasingly high-speed rail networks are being deployed in some parts of the world.

Public transportation within the city develops according to its needs. Most cities do not yet have rail-based mass transportation or are still in the planning stage to be developed. More use mass transportation buses. But it is necessary to think further about using a rail-based mass transportation system, due to the advantages and disadvantages of comparing buses and rail-based transportation (see Tabel 1).

Tabel 1. Advantages and disadvantages

No.	Criteria	Bus	Rail based
1	Capacity/unit	Low	High
2	Capacity line	Low	High
3	Ease of operations	Flexible	Depending on Infra-structure (rail)
4	Controlling	Easy	Difficult
5	Commercial Speed	Low	High
6	Air Pollution	Yes	No
7	Cost infra-structure dan Vehicle	Low	High
8	Cost operational/ passenger	High	Low
9	Vehicle life	short (10 years)	long (30 years)

(Yanursyah 2016)

There are many long-term benefits that can be obtained if a rail-based mass transportation system is chosen as a transportation system in a city. The criteria for cities that require a class of rail-based mass transportation system can be seen in table 2. Public transport and City Population (Yanursyah 2016)

Light Rail Transit (LRT) or Light Rail Vehicle (LRV) for relatively small cities with a maximum population of around 500,000 - 1 million people. (Yanursyah 2016)

Mass Rapid Transit (MRT) is more suitable for big cities such as Jakarta, Surabaya, Medan, Bandung, Makassar and Palembang. An Example of MRT System is Jakarta MRT System, see Figure 2.

Table 2. Public transport and City Population (Yanursyah 2016)

No	CRITERIA	URBAN	
		(LRT)*	(METRO/ *SUBWAY*/MRT)
1	Capacity of *train set*	190/1100	420/1260
2	Line Capacity	< 44000	max: 50000
3	Investment	middle	high

*From the LRT system can be upgraded to Metro system.

Figure 2. Jakarta MRT System (Courtesy PT MRTJ)

Literature Review in electric train

The energy usage in the network can be significantly reduced through implementing an optimal speed trajectory. (Tian 2019)

The minimization of total operating cost of electrified railway system consisting of cost of power generation from the external power system, cost of uncertain power obtained from renewable energy resources such as wind and solar PV sources, cost of power from storage systems such as battery storage and supercapacitors, and the income obtained by selling excess power back to the main electrical grid. (Salkuti 2021)

The optimization problem to find the optimal capacity and location of the PV farm, wind farm and energy storage system to achieve the lowest global daily costs was solved by the Brute Force Algorithm. Results revealed that the global cost and carbon emissions are reduced considerably with both ESS and RESs installed. (Kano 2023)

The charge/discharge command and speed profile of the vehicle must be optimised, with a mathematical model based on sequential quadratic programming optimisation techniques, assuming an electric double layer capacitor (EDLC) as the energy storage device. (Miyatake 2009)

To store train braking energy in hybrid storage system (composed of batteries and super-capacitors cells) and to restate it judiciously at different moments of the day (during peak or low energy consumption hours) to various kind of station loads. (Galaï-Dol 2016)

A power flow analysis model for a electrified railway traction system considering two types of static var compensator (SVC) connections: line-to-ground and line-to-line connections. By minimising the losses of the electrified railway traction system with particle swarm optimisation by utilising the power flow calculation method. An electrified railway traction system can be operated economically. (Lee 2020)

A model has been created integrating a database-driven rail network model with a dc power supply network. The model is combined with a genetic algorithm to optimise system parameters (storage size, charge/discharge power limits, timetable, train driving style/trajectory) and also enables identification of cases in which poorly specified storage technology would have little impact on peak power and energy consumption. (Fletcher 2020)

Optimisation of subway movement schedules with Genetic algorithm in order to utilise regenerative energy from train braking at stations. The effect of headway and reserve time on the amount of energy consumption was found. (Nasri 2010)

With a detailed train model and operating on a partly electrified tracks, battery control is optimised along with train control, using a direct method problem solver to find the minimum energy trajectory. It is shown that the speed profile and control adapt in a way to minimise battery usage. (Schenker 2021)

To obtain a train speed trajectory that optimises energy consumption and travel time simultaneously taking into account passenger comfort, analytical optimisation methods and analytical metaheuristics are used. (Bigharaz 2014)

The installations when the budget is split into different time periods, which a multi-stage formulation of two nature-inspired optimization algorithms (Genetic and Fireworks) to address the installation of ESSs in a realistic railway line. Results demonstrate the excellent behavior of the proposed multi-stage optimization. (Roch-Dupré 2021a)

The main objectives are the installation cost, the environmental impact, the cost of major electrical components such as catenary, traction substation, neutral zone, and the difficulty to connect the substation to the public power grid. On the other hand are exploitation costs, such as maintenance costs and energy losses depending on the dimensional design. So the multi-objective genetic algorithm (NSGA-II) is used. Electrical analysis and simplification due to the search for the highest power peak required by the train during simulation help minimize the number of studies. (Soler 2015)

A semianalytic solution that leads to discretisation and the application of the Langrage multiplier method to solve speed n-tuple optimisation. With this solution, it is possible to include all details about train operation, such as timetable restrictions or braking types, considering restrictions like traveling time or speed limits. (Rodrigo 2013)

Optimal operation of railway electric energy systems and their economics considering the uncertainty of renewable energy sources (PV panels and wind turbines), regenerative braking capabilities, and the behaviour of hybrid electric energy storage systems (ultracapacitors and batteries). This problem is a large-scale nonlinear optimization problem. (Aguado 2016)

The installation (location and sizing) of a wayside Energy Storage System (ESS) in a DC electrified railway system is one of the main measures to improve its energy efficiency. A nature-inspired optimisation algorithm is applied in combination with a highly realistic railway simulator. (Roch-Dupré 2021b)

Through optimising the Train Speed Curve for Energy Saving. It is found that with the addition of coasting mode into the proposed model, the operational energy consumption is reduced by about 58%. (Zhao 2018)

The optimal train speed profile by minimising the total energy consumption is discussed. Three methods to solve the formulation, namely dynamic programming (DP), gradient method, and sequential quadratic programming (QP), are introduced. The latter two methods can also control the state of charge (SOC) of energy storage devices. The importance of solving not only the optimal speed profile but also the optimal SOC profile of energy storage is emphasised. (Miyatake 2010)

DC railway powerflow algorithm considering storages is developed to analyze the railway system with storages and to calculate the optimal power and storage capacity of them. (Lee 2011)

The integration of hybrid energy storage system (HESS) in alternating current (AC) electric railway system is simulated with a new two-level model of railway traction substation energy management system (RTSEM) developed. The slave level is formulated as a mixed integer linear programming (MILP) model by coordinating HESS, traction load, regenerative braking energy and renewable energy. As for the master level model, a comprehensive cost study in the project period is conducted, considering the battery degradation and replacement costs. The obtained results shows significant potential economic savings with the integration of HESS and renewable energy. (Liu 2018)

Detailed modeling of system load flow and energy storage devices for a given traffic scenario in a typical DC railway system has been performed, resulting in a MINLP optimization model that minimizes the total energy consumption. The optimization result simplified to MIP optimization is the reasonable location and number of ESS in the system. (López-López 2012)

The AC optimal power flow (AC-OPF) problem is formulated by optimizing the total operating cost of a railway electrical system. The railway electrical system consists of uncertain renewable energy resources (wind and solar photovoltaic systems), regenerative braking capability, and a hybrid energy storage system (storage batteries and supercapacitors). The problem is solved using the differential evolution algorithm (DEA). (Park 2019)

An innovative combined modeling approach suitable for the energetic (braking phase) optimization analysis of railway systems considering the use of energy storage devices, and based on the use of the new object-oriented language Matlab-Simscape™. (Frilli 2016)

China's high-speed railway is developing steadily towards the "carbon peaking and carbon neutrality". the energy storage system can effectively reduce energy consumption and improve system stability (the existing power quality), a comprehensive review on energy storage system of electrified railway is performed. On this basis, key issues that remain unsolved in electrified railway energy storage system are summarized. (Yuan 2024)

Optimal sizing and positioning of energy storage systems (ESS) on railway lines, based on supercapacitor technology and calculation of economic benefits. This problem is solved by a bi-objective nonlinear mathematical model involving only discrete variables. The placement of ESS is limited to the wayside, which imposes constraints on placement in accordance with the main electrical substations. Thus the problem has a small dimension. Feasible solutions have been analyzed from an economic point of view, considering the least share of energy to be taken from the primary network, based on the energy purchase price. (Lamedica 2022)

A two-level model that optimizes the timetables to achieve energy-efficient railway system control. The upper level of the model ensures the relative stability of the timetable while maintaining the safety constraints of the trains, which makes the train operation more comfortable for the railway sector and passengers, while the lower level of the model optimizes the arrival and departure times between intermediate stations to minimize the energy consumption of each train. Then, a unified iterative optimization algorithm incorporating particle swarms is developed to solve the model, and thus a timetable that ensures the optimization of energy consumption is obtained. (Zhang 2019)

In order to provide optimal energy management and determine the locations of rectifier substations (RS), as well as calculate the power supply capacity (PSC) of traction units, the optimal design and simulation of DC railway traction power supply system (RTPSS) in urban areas are proposed. The cost-based convergence characteristic curves for the Dogleg optimization method are compared with the particle swarm optimization (PSO) approach. (Hu 2021)

an AC optimal power flow (AC-OPF) problem by utilizing mixed integer linear programming (MILP) to optimize the operating cost of a railway station's electrical system. Renewable energy resources (RER), energy storage systems (ESS), and regenerative braking energy (RBE) are considered, as well as the power grid. by considering uncertainties of RER, ESS, and RBE, using real-time data, significant cost reductions in the daily operation of the smart railway station are achieved. (Davoodi, 2025)

Onboard energy storage devices (OESDs) are used to assist traction and recover regenerative energy. OESDs are used to minimize catenary energy consumption in practical train operation by using a mixed integer linear programming

(MILP) model based on energy flow and energy conservation, three types of OESDs are widely used—supercapacitors, Li-ion batteries, and flywheels. (Wu 2020)

The reduction of power absorption is based on the interpretation of the traction diagram, along with the absorption curve. The measurement data are all electromechanical quantities from the train track and are transmitted to the remote control station via a network connection. An optimized protocol for train operation is generated. (Landi 2008)

To improve the techno-economic performance of Flexible traction substation (FTSSs) , proposed a sizing method to jointly size PV, railway power flow controllers (RPFC), and battery-ultracapacitor hybrid energy storage systems (HESS). Firstly, a flexible operation model of FTSS is established. Next, a linearized approach is developed for estimating battery aging. Then, a joint sizing optimization model of PV, HESS, and RPFC is established to minimize the total annualized investment and operation cost of an FTSS. (Huang 2024)

An optimisation framework based on genetic algorithms is developed to optimise a DC electric rail network in terms of a comprehensive set of decision variables including storage size, charge/discharge power limits, timetable and train driving style/trajectory to maximise benefits of energy storage in reducing railway peak power and energy consumption. (Nallaperuma 2021)

The train regulation problem is stated as a dynamic multi-objective optimization model to take advantage in real time of accurate results provided by detailed train simulation. The aim of the optimization model is to find the Pareto front of the possible speed profiles and update it during the train travel. The dynamic multi-objective optimization algorithms DNSGA-II and DMOPSO combined with a detailed simulation model are applied to solve this problem. The results show that dynamic algorithms are faster tracking the Pareto front changes than their static versions. (Fernández-Rodríguez 2018)

To improve the electric multiple unit (EMU) operation strategy, a multi-objective optimization model of EMU operation is developed on the basis of dynamic analysis and speed restriction mutation. Using a modified particle swarm optimization algorithm, a Pareto optimal solution set is obtained by the online optimization of the EMU′s operation strategy. (Yang 2015)

The automatic train operation (ATO) system of urban rail trains includes a two-layer control structure: For upper-layer control, the multi-objective model of urban rail train operation is built with energy consumption, comfort, stopping accuracy, and punctuality as optimization indexes, and the entropy weight method is adopted to solve the weight coefficient of each index. Then, genetic algorithm (GA) is used to optimize the model to obtain an optimal target speed curve. For the lower-layer control, the predictive speed controller is designed according to the predictive control principle to track the target speed curve accurately. The softness factor in the predictive model needs to be adjusted online to improve the control accuracy of the speed. (Liu 2019)

Evolutionary multi-objective optimization (EMO) to find the solution. By using two optimization steps: firstly, finding the Pareto optimal solutions with NSGA-ii method, and secondly, selecting from the Pareto optimal solutions by using higher-level information to obtain the best solution. (Tobing 2023)

Example one of research in electric train system (Tobing 2023).

Background and Problems

The electrical power supply system for mass rapid transit (MRT) trains must be designed to meet the requirements of sustainable development, environmentally friendly, and energy saving (Tobing 2023).

Has the MRT Electricity Supply System met the efficiency and effectiveness of electrical energy by using the EMO optimization method?

Problems:
1. the position of the connection points of the traction substations (Gt) to the overhead power system
2. power capacity of each traction substation (Gt)

Research and Novelty

This research improves the results of previous research that uses single objective function optimization. a single objective function, into a multi-objective function optimization problem.

Constraint:

Equal peak power load sharing to all traction substations
Equal energy usage to all traction substations
Minimum distance between traction substations for maintenance purposes

Methodology

Build a direct current power supply system model of the MRT train system on a single train system
Examine the Evolutionary Multi-objective (EMO) optimization method to find the position and nominal power of direct current power traction substations with multiple train operations
Apply the simulation of optimization method (EMO) to find the position of traction substation and power capacity uniformity of direct current power traction substation with multiple train operation

Two step optimisasi pada EMO: (Tobing 2023).
Formulation of the multi-objective function used in the first step of EMO (NSGA-ii: Non-dominate Sorting Genetic Algorithm)

Peak Power Demand (Tobing 2023).

$$P_{max}(i) = \sup\{P(i)|P(0) \leq P(i) \leq P(t_p)\}[kW]$$

Energy Needs

$$E = \sum_{j=1}^{m} \widehat{P}_j.\Delta t[kWh]$$

EMO searches for the objective values of the objective functions by shifting the positions of each substation and calculating the objective functions. positions of each substation and calculates the objective functions and Selects the values that minimize it

Formulation of higher-level information function for EMO second step (Tobing 2023).

$$f_{obj} = \alpha_1 \sum_{i}^{n_{ss}} |x_i - x_{i+1}| + \alpha_2 \sum_{i}^{n_{ss}} c_i^2$$

$$f(x) = \omega_1 f_1(\bar{x}) + \omega_2 f_2(\bar{P})$$

Conclusion (Tobing 2023).
Load sharing between Traction Substations from simulation results with EMO optimization is relatively more evenly distributed compared to MRT data.
The use of regenerative braking energy can reduce the relative nominal power of the Traction Substation.
The simulation results of optimization with multi-objective function are relatively better than optimization with single-objective function, where the nominal power obtained is better with multi-objective optimization.

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