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A Comprehensive Train Model for Driving Optimization and Energy Saving

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Abstract

A comprehensive train model for energy-efficient driving has been developed that takes into account user-defined driving styles, trajectory planners, and other constraints like adhesion limitations and comfort acceleration. The model comprises the electrical traction components and a steady-state HVAC model. It can also simulate coasting and dynamic braking based on requirements. There is also a generic battery model to simulate the battery powered train. It also has a track infrastructure raw data pre-processor to define the track information required for simulations. This model is a useful tool to conduct parametric studies about energy-efficient train operations, spatio-temporal power demands, battery-powered operations, and timetable requirements. More features, like hybrid-powered source trains and meta-heuristic optimization algorithms, will enhance the capabilities of this model.

Keywords: rail vehicle energy, battery powered train, train auxiliary power, efficient train driving, trajectory planner, train electrical components.

1 Introduction

Modelling and simulations are central to problem solving in all the engineering domains. In railways, the running time of a single train when it is traversing a route, is of interest to the traffic and planning departments. Evaluating running time for multiple trains is even more important for deciding an amicable, balanced, and time-contrast or interference-free time table. It also helps in optimal line capacity utilization and deciding the departures that can meet the forecasted passenger travel demands.

Simulating virtual train runs is an effective way to plan and prepare for improving transport capacity and efficient energy usage along with meeting time constrain.

Meeting a desired timetable with multiple running trains can also be used to calculate the spatio-temporal power demands. These power demands for each train are different. Even the same train running at a different time of the year can have different power requirements depending on passenger and cargo load, available rail-wheel surface adhesion determining the tractive effort, driving style and outdoor temperature deciding HVAC and auxiliary electrical components cooling load.

Different universities, research centres, and companies have developed their own single-train simulation models that can calculate running time, spatio-temporal power demands, and ultimately, the gross and net energy consumption. One such tool was developed a decade ago at the KTH Royal Institute of Technology, Stockholm, called STEC (Simulated Train Energy Consumption). It was modelled in MS Excel, utilizing Macros and Visual Basic for Applications. After defining track data, vehicle data, and parameters like traction and braking curves, adhesion limitations, etc., this program calculates various time variant variables, such as speed, acceleration, power, energy consumption, etc., for a given scenario.

However, there are several features that are missing in STEC when compared to other advanced train simulation models like OpenTrack [1], OPEUS [2], RailSim [3], etc., like a travel journey planner to meet a time table, power flow across AC or DC traction chain components, power source models like diesel, batteries, and fuel cells, HVAC and auxiliary power models, etc.

To simulate more realistic scenarios with variable driving styles, energy-efficient operations or battery powered catenary free operations, there is a need for a more advanced modelling tool if compared with STEC. This led to a detailed model's development, of a new version of STEC, i.e., STEC 2.0, or KTH Rail Vehicle Energy Calculator. This model is introduced in this work that has been developed in Matlab with inputs and outputs executed using MS Excel files. This model can be useful to conduct parametric studies to identify opportunities for energy efficient operations of trains, to identify the power demand of spatio-temporal power demands, compare real train data vs simulations and to decide the battery sizes requirement for battery powered trains. Some features and parameters that are modelled, developed and included in this model are listed below.

- Train data
    - Vehicle data
    - Traction and braking curves
    - Other traction chain components
    - Rated dimensions of components
    - Efficiency maps
    - HVAC and Auxiliary power
    - Battery propulsion

- Track data
    - Altitude
    - Horizontal curve radius
    - Section speed limit

- Constraints
    - Time table
    - Maximum acceleration/deceleration
    - Traction/Brake adhesion utilization

- Driving style
    - Traction percent
    - Mechanical brake percent
    - Electrical brake percent
    - Coasting for speed reduction
    - Partial coasting and auto-switch to braking

2 Methods

A train's state of motion is always one of these states, i.e., acceleration, deceleration, cruising, or coasting, that is achieved by controlling longitudinal forces by adjusting traction or braking forces at the wheel. Different driving styles such as the rate of acceleration and deceleration, the number and duration of cycles and acceleration, deceleration, cruising and coasting contribute to the variations in power consumption even on meeting a particular timetable.

The motion of a train can be modelled using Newton's second law of motion, where a train is considered as a point object with its mass (m_e), after accounting for the rotational inertia of the rotating mass coupled to the wheels. The sum of all longitudinal forces results in acceleration (a_x) along the track. The equations are solved numerically by considering a fixed distance step as a discretized length element. The equations have been solved using the First-order forward Euler method. The variables like time, speed, acceleration, and power at the wheel, power at motor etc are subsequently calculated.

$$m_e a_x = \sum_{i=0}^{n} F_i = F_T + F_G + F_C + F_R \tag{1}$$

The losses due to resistances such as the aerodynamic drag, rolling resistance, and surface friction are accounted in the running resistance term (F_R). Rolling resistance is the energy loss during the wheel-rail contact due to plastic deformation and friction in bearings and dampers, which depends on the type of running gear and the friction coefficient between the wheel and rail. Aerodynamic drag due to train shape, cross-section area, and protruding parts leads to pressure drag force. Impulse resistance is due to ventilation, air intake, and brake cooling. Surface friction resistance is caused by the skin friction of moving air. The Davis equation (2) is used to define running resistance (F_R) which depends on the vehicle speed (v), and combines rolling and aerodynamic resistance. A-coefficient is due to rolling resistance; B-coefficient is due to track standard and train length but not to axle load; and C-coefficient is due to aerodynamic resistance. A resistance field test of a train is performed to find out these coefficients for the train. [4]

$$F_R = A + Bv + Cv^2 \tag{2}$$

Gradient resistance (F_G) is due to the component of gravity in the longitudinal direction when a train or some mass (m_t) of it is on a gradient (G) which is defined per-mil. The model uses the equation (3). [4]

$$F_G = m_t \cdot g \cdot \sin\frac{G}{1000} \tag{3}$$

Röckl’s equation (4) defines the curve resistance (F_C) when negotiating a curve of radius (R) as wheels are not perfectly aligned with rails. Different values of a and b coefficients are there for different types of bogies and running on different types of tracks. Modified Röckl’s equations based on multibody dynamics simulations for radial steered bogies can also be used or other empirical relations. [4]

$$F_C = \frac{a}{R-b} m_t \ \forall R \geq 300\, m \tag{4}$$

Adhesion is a part of the wheel-rail friction that is utilized for the tractive forces (F_D) i.e. is the total longitudinal wheel-rail force on a vehicle which is transmitted by the wheel rail contact. (m_α) is adhesion mass or braked mass i.e. the total mass on all powered axles or braked axles respectively, which limits the transmitted force. Adhesion utilization is calculated using the equation (5) and maximum values as a limitation are defined in the inputs. [4]

Adhesion utilization ≤ Available adhesion < wheel-rail friction

$$\alpha = \frac{F_\alpha}{m_\alpha \cdot g} = \frac{m_e}{m_\alpha} \cdot \frac{a_x}{g} + \frac{F_D}{m_\alpha \cdot g} \tag{5}$$

A simple way to model traction force (F_T) is to use the traction curve i.e., the force-vs-speed diagram which is provided by the train manufacturer as shown in Figure 1. In the horizontal region of the curve, the traction effort is limited due to the maximum torque, limiting the jerk, or the adhesion utilization limit, or the maximum acceleration limit for the passenger comfort. Next is the maximum power region in which force is proportional to $\frac{1}{v}$ and in final section force is proportionally to $\frac{1}{v^2}$. Similarly, mechanical and electrical brake forces are defined in a force-vs-speed diagram as shown in Figure 2.

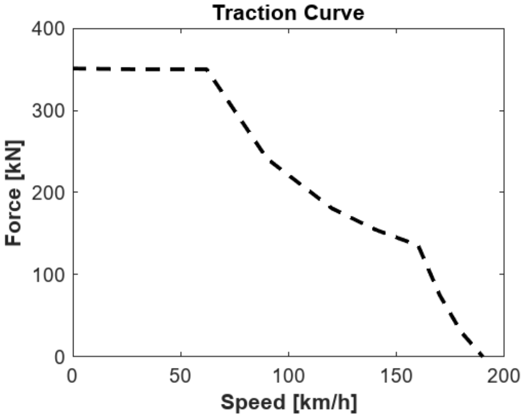

Figure 1: Traction Curve

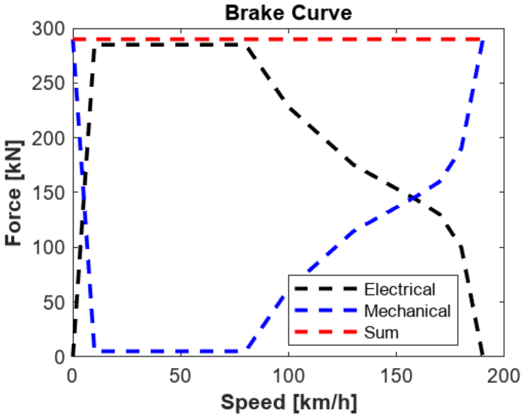

Figure 2: Brake Curve

A given scenario is computed by solving the equations and calculating all the variables of interest. Then, the power flow calculation is performed as described in Figure 3 if information about the components is available (Table 1). If not, then overall efficiency can also be used instead to find net and gross power, which can be integrated over time to find traction and regenerated energy.

Parameter	Gearbox	Motor	Motor Inverter	Line Converter	Transformer	Auxiliary Inverter
Efficiency map	Constant	f(ω,P)	f(ω,P)	f(P)	f(P)	f(P)
Cooling power	-	f(P)	f(P)	f(P)	f(P)	f(P)
No-load power	-	Constant	Constant	Constant	Constant	Constant

Table 1: Parameters associated with electrical components

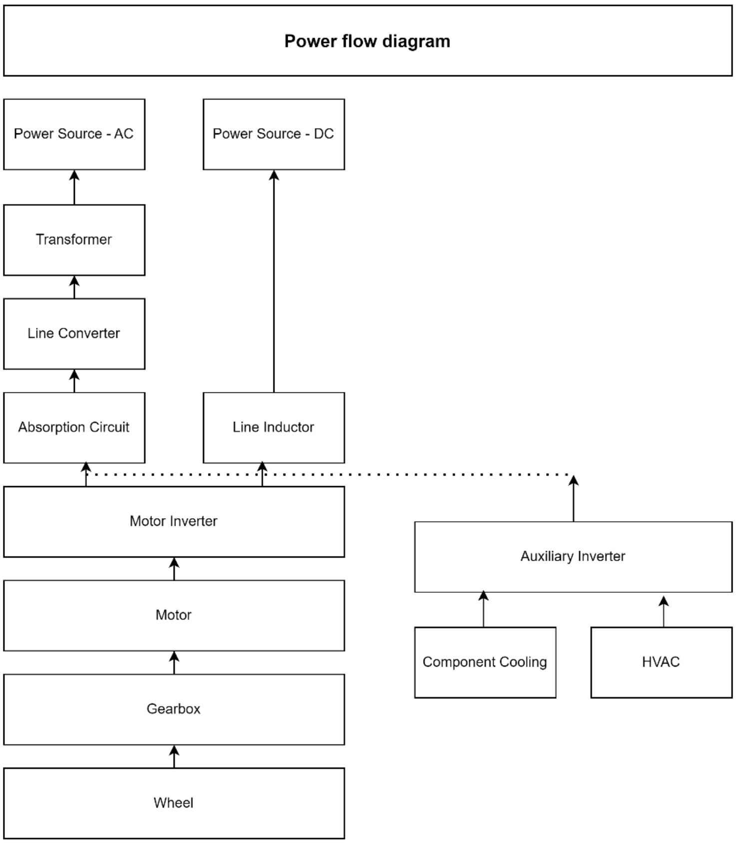

Figure 3: Power flow calculation diagram

Figures 4 and 5 represent the efficiency maps that are used in the model and are based on the normalized values of power and/or speed. This data is either available from the component manufacturers or can be generated by using statistical distributions, range-wise segmentations, or assumed to be some realistic constant value throughout.

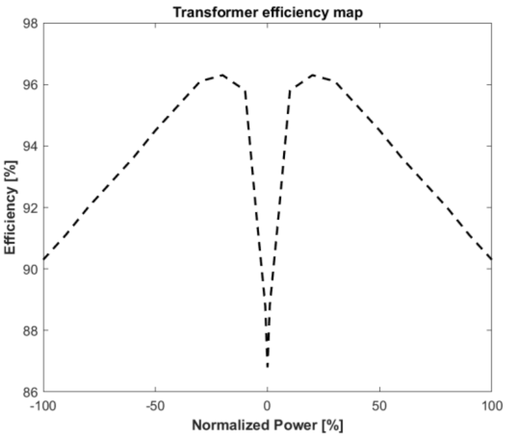

Figure 4 : Transformer efficiency map

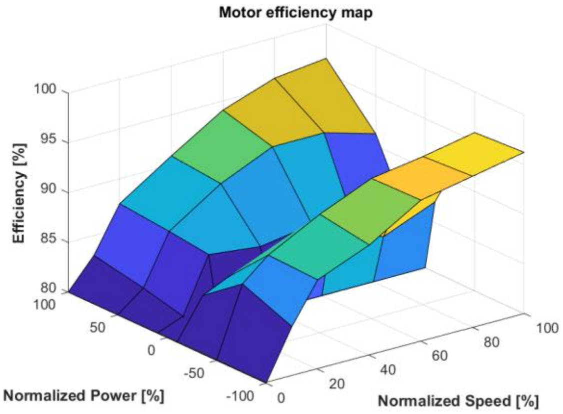

Figure 5 : Motor efficiency map

After traction chain components, next is heating, ventilation, and air conditioning (HVAC), which add to the auxiliary power requirements of a train. In comparison to the traction power, it constitutes a small fraction of it, but still, it is big enough to be ignored. HVAC power is mainly dependent on outdoor and indoor set point temperatures but also depends on the number of passengers, heat gain and loss, shell conduction, etc. A steady-state heat transfer model for the HVAC of a train is modelled using the equations from [5], and one such equation (6) that represent the heat balance in the train is shown.

$$Q_{HVAC} = Q_{shell} + Q_{ventilation} + Q_{Sun} + Q_{Window} + Q_{Passenger} + Q_{Auxiliary} \qquad (6)$$

Q_{shell}	$Q_{ventilation}$	Q_{Sun}	Q_{Window}	$Q_{Passenger}$	$Q_{Auxiliary}$
Heat exchange through the outer shell	Sensible & latent heat exchange due to ventilation	Sun radiation absorbed by the shell	Sun radiation transmitted through the window	Sensible and latent heat from passengers	Sensible heat from other auxiliary equipment

Table 2 : Heat gain and loss in a train

Catenary free operations can also be simulated using this program. For that, a battery is modelled using the generic battery cell model, which defines a cell as a dependent voltage source [6]. This approach models a single battery as an array of cells in series and parallel, as shown in the Figure 6. A single battery can be defined using the number of cells in series to meet a voltage requirement and the number of branches in parallel to meet energy capacity requirements.

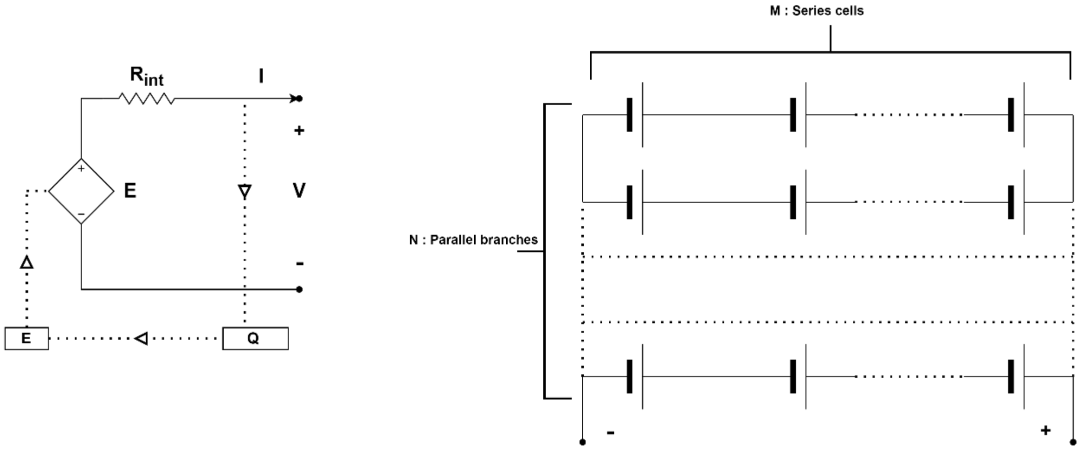

Figure 6 : Generic battery cell model and a configuration of cells array [6]

The model of a battery cell is defined using the equations (7), (8), and (9), which are modelled numerically as a Matlab function. The parameters of the equation, as shown in Table 3, depend on the type of battery cell and can be found in the data sheets or their standard discharge curves. It is assumed that all cells charge and discharge at the same rate. The aging effect can also be taken into account by changing the rated capacity and internal resistance values before a run that mimics an aged cell. [6]

Battery state of charge (SOC) and battery voltage (V) are calculated, and they are constrained such that they should not fall below a certain level. Also, the maximum charge or discharge power for the battery is constrained using look-up tables that are based on SOC or temperature values, if required, or else can be modelled as a constant number irrespective of any parameter.

$$Q = \int_0^t -I dt \tag{7}$$

$$E = E_0 - K \frac{Q_0}{Q_0 - Q} + A \cdot e^{-B \cdot Q} \tag{8}$$

$$V = E - I \cdot R_{int} \tag{9}$$

Battery Parameters	**Nickel-Cadmium**	**Lithium - Ion**	**Nickel-Metal-Hydrid**
Rated Nominal voltage [V]	1.2	3.6	1.2
Q_0 [Ah] : Nominal capacity	1.3	1	6.5
E_0 [V] : Battery constant voltage	1.2505	3.7348	1.2848
R_{int} [Ω] : Internal resistance	0.023	0.09	0.0046
K [V] : Polarisation voltage	0.00852	0.00876	0.01875
A [V] : Exponential zone amplitude	0.144	0.468	0.144
B [$(Ah)^{-1}$] : Exponential zone time constant inverse	5.7692	3.5294	2.3077

Table 3: Battery parameters for modelling [6]

Finally, Simulating a train’s run requires track information like its altitude, speed limits, as shown in Figure 7 and location of stations, and horizontal curve radius.
A Matlab pre-processing function has been modelled to take care of track height, section speed and horizontal curve radius data. This pre-function generates breakpoints at an interval of one kilometer with effective gradient and curve radius in that section.
For vertical gradient, a moving mean based on train’s length is computed after interpolating the track height and then the average value of moving mean is computed within a section. Similarly, effective curve radii is calculated based on the effective

curving force due to length and radii of all the circular curves within that sections. The post-processed track data is shown in the Figure 8.

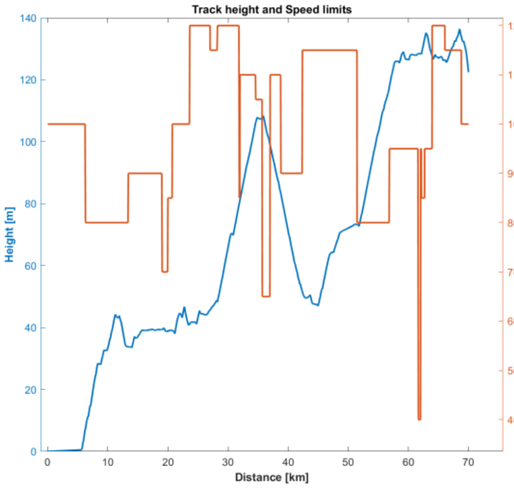

Figure 7: Track height and speed limit

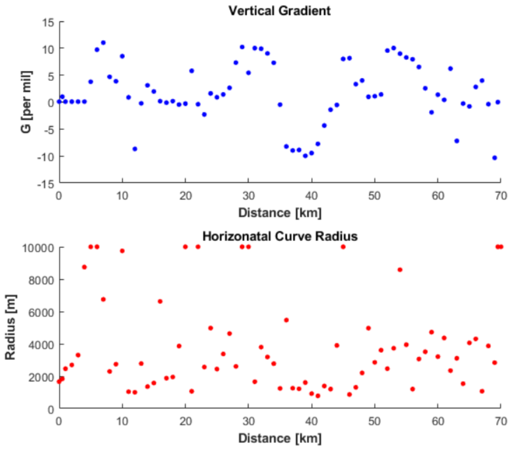

Figure 8: Post-processed track data

After input of track data, station information and time table and section wise driving style simulations can be performed either for time constrained or without time constraints.

Figure 9 shows the methodology deployed for meeting the time constraints, and Table 4 mentions different types of algorithms that can be selected. Algorithm five generates more uniform speed profiles. Figure 10 describes the partial coasting and transitioning from coasting to braking in the sections before a station.

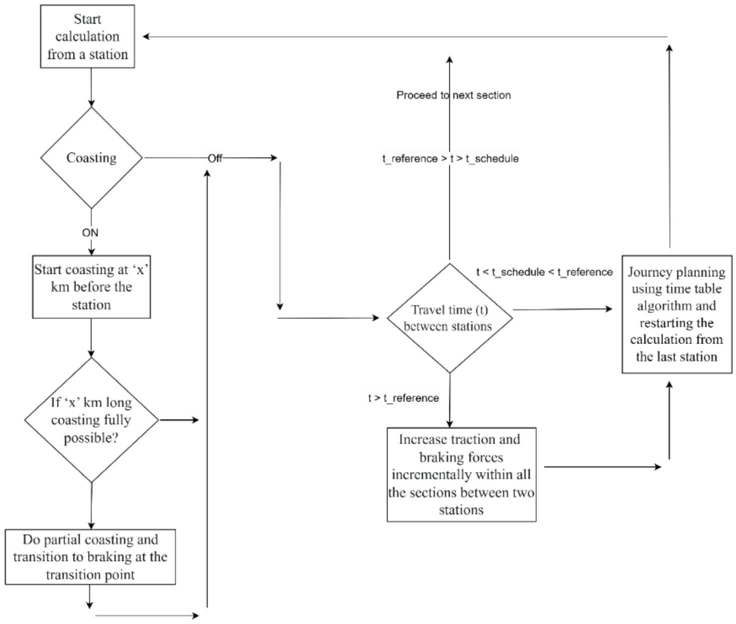

Figure 9: Journey Planner

S.No	Criterion	Describing Pseudo Algorithm
1	Targeting a section with biggest impact on time table	max(product(section speeds, section distances))
2	Targeting higher velocities in smaller section distances	max(V(sort(section distances))
3	Targeting maximum section speed	max(section speeds)
4	Scaling down whole section speed profile	product(section speeds, scale factor)
5	Targeting an almost uniform speed profile	max(instantaneous speed)

Table 4: Strategies for meeting time table

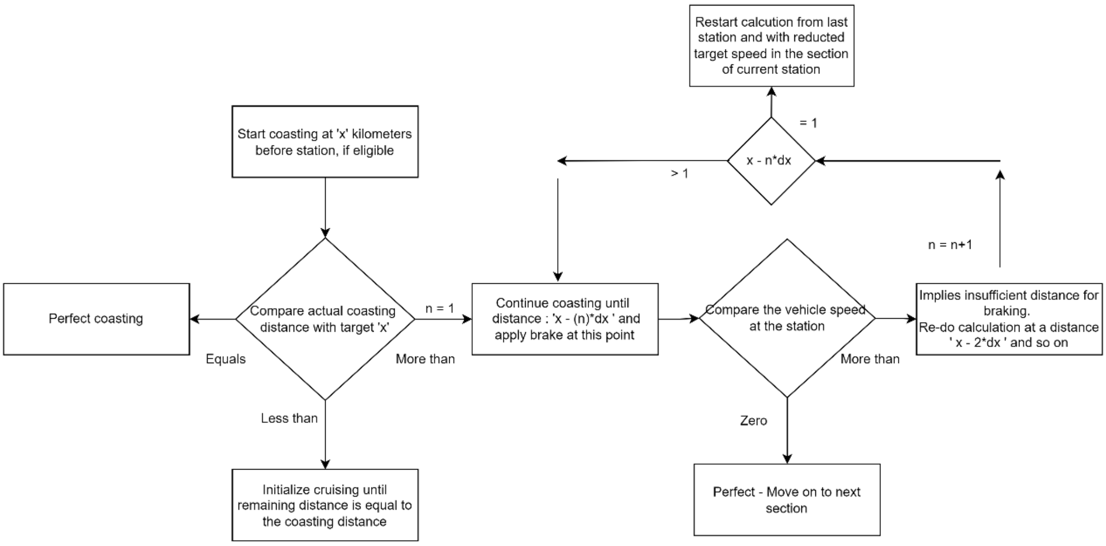

Figure 10: Logic: Partial Coasting - transition from coasting to braking

3 Results

This model is currently being used in KTH, Stockholm by various students. Case studies on Stockholm commuter train were also conducted using this model that can be found in [6].

Some sample results for a hypothetical metro train’s scenario has been shown below just to demonstrate the different types of simulations that can be performed by suing this model, e.g. all out mode vs time table mode, or by altering the driving style by changing the section wise traction and braking percentages, or using a battery propulsion in a section of train.

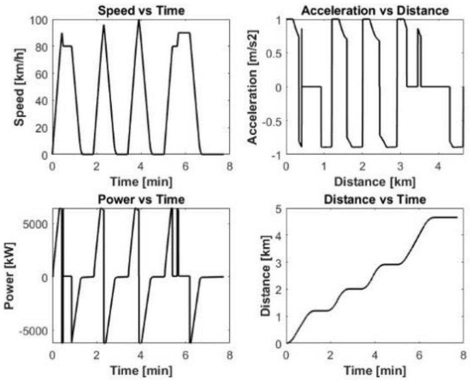

Figure 11: All out mode

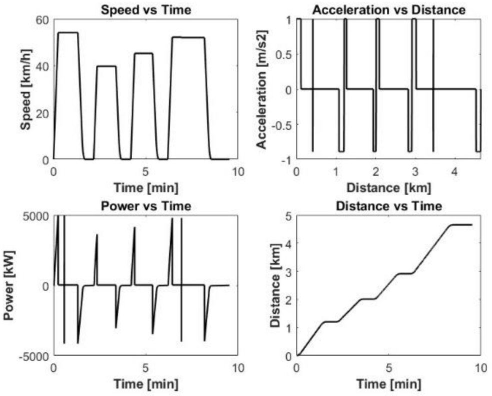

Figure 12: Trajectory planning

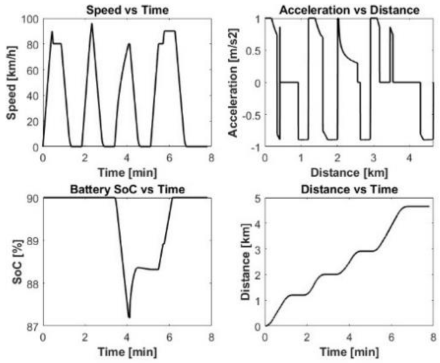

Figure 13: Battery in a section & all out

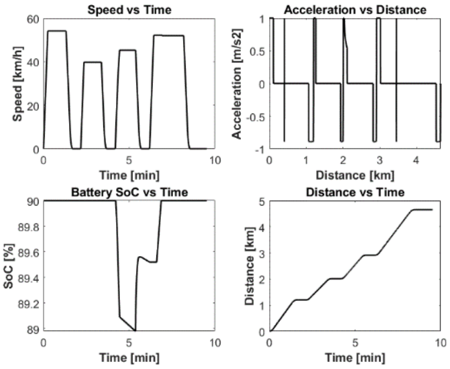

Figure 14: Battery in a section & trajectory planning

Parameter	**All out**	**Time Table**	**Battery + all out**	**Battery + time table**
Travel Time [s]	313.73	421.74	318.18	421.57
Stop time [s]	150	150	150	150
Distance [km]	4.655	4.655	4.655	4.655
Traction Energy at Motor [kWh]	126.81	33.95	114.1	33.98
Regenerative Energy at Motor [kWh]	-118.48	-31.8	-106.54	-31.82
Total braking energy [kWh]	118.48	31.8	106.54	31.82
Traction Energy at Catenary [kWh]	157.63	50.78	144	50.93
Regenerative Energy at Catenary [kWh]	-93	-21.91	-82.92	-21.91
Net Energy at Catenary [kWh]	64.63	28.87	61.08	29.02

Table 5 : Comparison of scenarios

Many more results, graphs and summaries are generated by the program and are calculated values at each discretized step are available in the Results excel file. Summary of above runs have been complied and presented below.

Similarly, other cases can be simulated with different driving styles by changing section-wise braking percentages, i.e., in the below case, it is 80% mechanical and 60% electrical.

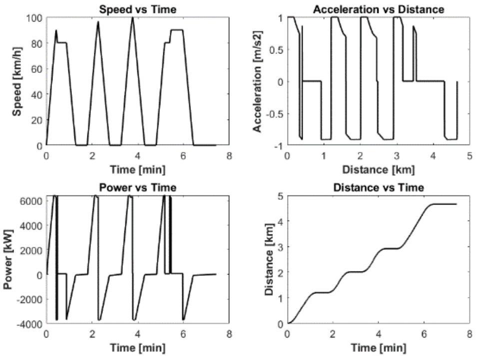

Figure 15: All out

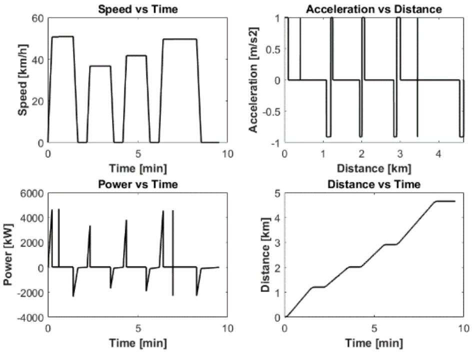

Figure 16: Time table

Parameter	All out	Time table
Travel Time [s]	295.6	421.56
Stop time [s]	150	150
Distance [km]	4.655	4.655
Traction Energy at Motor [kWh]	127.48	29.82
Regenerative Energy at Motor [kWh]	-69.11	-16.23
Braking energy for mechanical brake [kWh]	51.8	12.28
Total braking energy [kWh]	120.91	28.51
Traction Energy at Catenary [kWh]	158.36	45.94
Regenerative Energy at Catenary [kWh]	-52.22	-10.53
Net Energy at Catenary [kWh]	106.14	35.41

Table 6 : Scenario comparison with for a particular brake percentage

4 Conclusions and Contributions

This work briefly describes the development methodology and modelling strategies adopted in building the model, along with the different features and capabilities that can be used to simulate single train journeys by considering different factors, like user-defined driving styles, power flow calculations from wheel to power source across electrical components, sizes of components and battery etc.

The presented model can be used for future research on efficient train driving, battery powered trains, and journey planning. More features, like hybrid powered sources trains and meta-heuristic optimization algorithms, shall be implemented to increase the capabilities of this model.

The author of this work has created and coded the whole model in Matlab after discussions with all the co-authors. The model has been constantly updated after taking feedback from all the users whenever abnormalities have been highlighted.

Acknowledgements

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