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Assessment of Energy Requirement of a Proposed Electric Railway System in Southern Sri Lanka

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Abstract

The focus of this study was to calculate the energy requirements of an electric railway service parallel to the southern expressway of Sri Lanka. It assumed a new 127 km single-track railway corridor from Kottawa to Godagama- Matara with eleven new railway stations for interchanges along the expressway.

High-speed X-2000 trains with 6-cars, capable of reaching a top speed of 200 km/h were assumed. Each train will have 465 seats, of which 25% will be in the premium class and 75% in the economy class. The average train length will be about 165 m with a mass of around 366 tonne. The average demand will be 9-11 kW/t, and the starting acceleration will be 0.42 m/s^2, and the load factor was estimated to be 55%. The calculated total annual energy requirement for the service was 26 GWh.

A 25 kV 50 Hz single-phase ac overhead line supplies power from the grid to the train. The study assumed train speeds of up to 160 km/h.

This study presents an energy cost analysis of the traditional diesel trains and grid connected electric trains. If the trains operate from grid power, the energy cost will be Rs. 561 million per annum while traditional diesel fuel cost will be Rs. 384 million per annum.

Keywords: rolling resistance, load factor, regenerative braking.

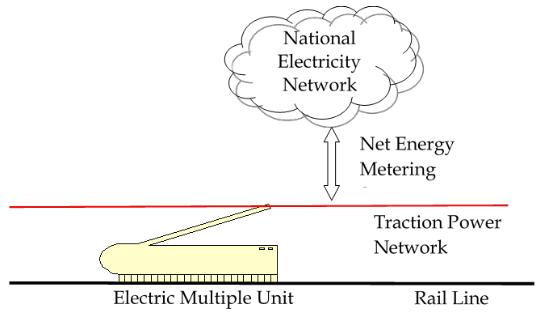
Introduction

The focus of this work was to calculate the energy use of an electric railway service in parallel with the southern expressway of Sri Lanka. If implemented, it will open a new 127 km railway corridor from Kottawa to Godagama - Matara. A single-track facility with eleven new railway stations was assumed.

Sri Lanka requires an electrified, more efficient and environment friendly railway network to attract more passengers. Reduction of energy consumption and travel time will be the main goal of such a service.

This paper analysed only the cost of energy. It used published parameters and data for electric multiple units and electrified railways. The proposed system, which is widely used in many countries, is illustrated in Figure 1.

Figure 1: Proposed Electrified Railway System



Theoretical Analyses

An electric train has features such as speed dependent tractive effort, regenerative braking, mechanical braking, auxiliary power, comfort power, electrical and mechanical system efficiency.

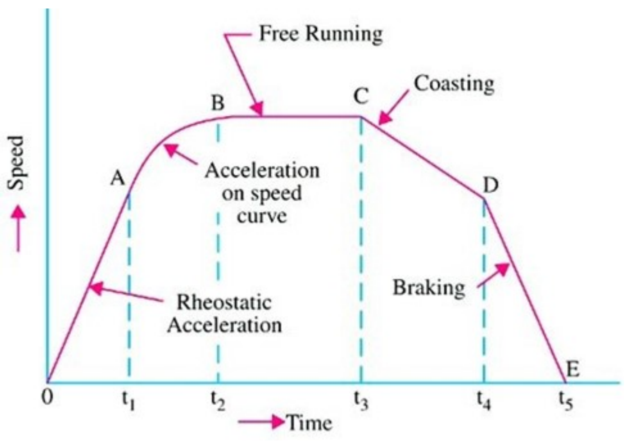
Generally, running resistance F_R of a train on level straight track is given by,

$$F_R = A + B\,v + C\,v^2 \qquad \text{Eq. 1}$$

Where, F_R: running resistance in N, v: train speed in m/s, B: a coefficient representing the impulse resistance due to ventilation and cooling in Ns/m. At higher speeds (say over 100 km/h), the speed coefficient C expressed in Ns^2/m^2 will dominate. Independent coefficient A expresses the mechanical resistance, sometimes called rolling resistance, in N.

Figure 2 shows the typical speed Vs time curve of a train between two stops.

Figure 2: Typical Speed Vs Time of a Train



Evaluation of Specific Energy Requirement

Total energy delivered to driving axles, is divided by train mass in ton and route length in km, to calculate the specific energy requirement. Consider the trapezoidal speed/time curve given by Eq 2 [6],

E_{spo} = 0.01072 V_m^2 M_e + (27.22G + 0.2778r) M D^1 Wh/t-km; D^1 = Da +D_{fr} Eq. 2

Where, V_m = maximum train velocity km/h, D_{fr} = distance travelled during the free-running period in km, D^1 = distance of travel during acceleration plus free running period in km, D = distance between stops in km, Da = distance travelled during the acceleration period in km, M = dead mass of the train in ton, M_e = effective mass of the train in ton, G = ascending gradient in %, r = running resistance in N/t.

Specific Energy Consumption

The specific energy consumption is obtained by dividing the energy requirement of the driving wheels by the combined efficiency of transmission gears and motors [6].

E_{spc} = [0.01072 V_m^2 /ηD x M_e/M + 27.25G/η x D^1/D + 0.2778r/η x D^1/D] Wh/t-km Eq. 3

If there is no gradient, then specific energy consumption is given by,

E_{spc} = [0.01072 V_m^2 /ηD x M_e / M + 0.2778r/η x D^1/D] Wh/t-km Eq. 4

Where, η = overall efficiency of transmission gear and motor.
The specific energy consumption of a train is influenced by distance between stops, acceleration, retardation, maximum speed, type of train and equipment, and track configuration.

Energy Management

Load Factor

The load factor of the train refers to the ratio between occupied seat-km and offered seat-km. Energy consumption of a fast passenger train is essentially independent of the actual load factor. Therefore, the specific energy consumption (per passenger-km) is inversely proportional to the load factor. This makes the load factor a crucial parameter in the context of energy consumption per passenger-km. Comparing the values used in studies e.g. 2009, this study used a load factor of 55% for intermediate and long-distance operations [5].

Energy for Auxiliary Systems and Passenger Comfort

For providing comforts to passengers and crew, compartments will use energy for ventilation, air conditioning, lighting, food preparation, automated doors, automated toilets, car body tilt, etc. Maximum demand for auxiliary systems and passenger comfort was estimated to be 345 kW per train.

Energy Efficiency of Propulsion, Converter Stations and losses in Pantograph and Catenary

The efficiency of the propulsion system of X 2000 6-car train varies with power and speed. For train speeds higher than 100 km/h, energy efficiency has been estimated to be 82% [5].

The energy efficiency in converter stations was assumed to be 91.5%. For modern trains with current and voltage approximately in phase energy loss in the catenary is about 4%. In total, energy efficiency would be 0.915 x 0.96 ≈ 0.88. Losses in pantograph are about 14%.

Energy Efficiency of Network Equipment

There will be energy losses in the electricity cables, bus bars, switchgear, and transformers. These losses should be added to calculate the energy input. The losses in the supply system are dependent of demand, which varies over time. This study estimates and considers the standard average losses. The energy efficiency of the recent useful electricity network equipment was assumed to be 75 % [5].

Energy Efficiency of Regenerative Braking

X-2000 6-car trains are equipped with electrical brakes, generating electrical energy to the power supply system (through the catenary) during braking. Regenerated energy is mainly used by the train for auxiliary power or fed back to the grid. The maximum electrical braking force (at wheels) for X-2000 is 140 kN (below 100 km/h).

The maximum electrical braking power was assumed to be the same as the maximum traction power. The reference train X-2000 which consists of 6 cars has only 4 axles powered out of a total of 28 axles. Thus the achievable braking force from the electric regenerative brake is quite low related to the total mass of the train.

Calculation of Power and Energy Requirements for the Proposed Railway

Three cases of train operations were studied, for the selected 6-car high-speed train X-2000 [1], [2], [5].

Case 1 - For one round trip from Kottawa to Matara railway station.

The total distance will be 127 km. The speed vs time diagram from Kottawa to Matara is shown in Figure 3. It was estimated that the average specific energy consumption would be 22.83 Wh/t-km, total energy requirement for one trip would be 1.04 MWh, total regenerative energy for one trip would be 0.02 MWh and total net energy consumption for one trip would be 1.02 MWh. The average regenerative energy was estimated to be 1.95%. The total travel time for one trip was estimated to be 49 minutes and the maximum power demand would be 1.25 MW. Table 1 summarizes energy used in each segment.

Figure 3: Train Speed vs Time Diagram for Case 1: Kottawa to Matara

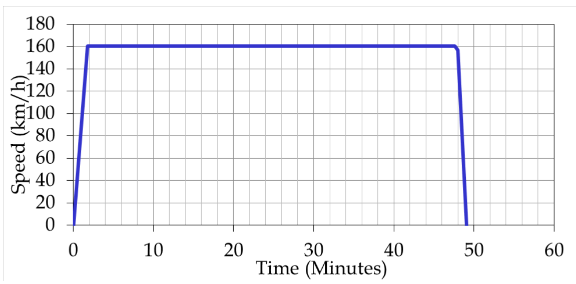


Table 1: Energy Requirements for Case 1

Operation	Total Energy (kWh)
Acceleration	19.72
Constant speed	1,023.16
Coasting	9.20
Braking	(11.15)

Case 2 – For one round trip from Kottawa to Galle railway station.

The speed vs time diagram from Kottawa to Galle is shown in Figure 4. This route will cover a total distance of 102 km. The estimated average specific energy consumption would be 23.4 Wh/t-km and the total required energy for one trip would be 0.85 MWh. The total regenerative energy for one trip is 0.02 MWh and the total net energy consumption for one trip would be 0.83 MWh. The estimated average regenerative energy would be 2.55%. The total traveling time for one trip will be 39 minutes with a maximum power requirement of 1.26 MW. Table 2 summarizes the energy used in each segment.

Figure 4: Train Speed vs Time Diagram for Case 2: Kottawa to Galle

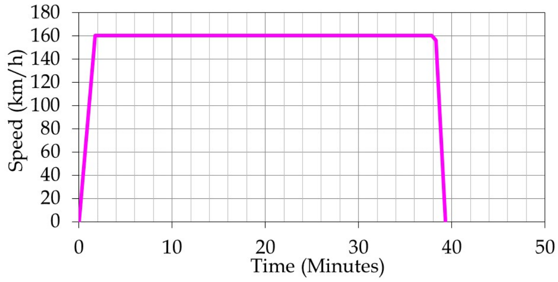


Table 2: Energy Requirements for Case 2

Time Period	Total Energy (kWh)
Acceleration	20.23
Constant speed	826.36
Coasting	10.19
Braking	(11.40)

Case 3 - One round trip with stops in each station from Kottawa to Matara.

This train is scheduled to stop at 11 stations from Kottawa to Matara. Train speed vs time diagram is shown in Figure 5. The total distance for one trip would be 127 km. The estimated average specific energy consumption is 59.7 Wh/t- km and total required energy for one trip would be 2.09 MWh. Total regenerative energy for one trip would be 0.48 MWh and total net energy consumption would be 1.61 MWh. The average regenerative energy would be 25.4%. It will lead to a total travel time of 1 hour. The maximum power requirement would be 1.54 MW. Table 3 summarizes the results.

Figure 5: Train Speed vs Time Diagram for Case 3: Kottawa to Matara

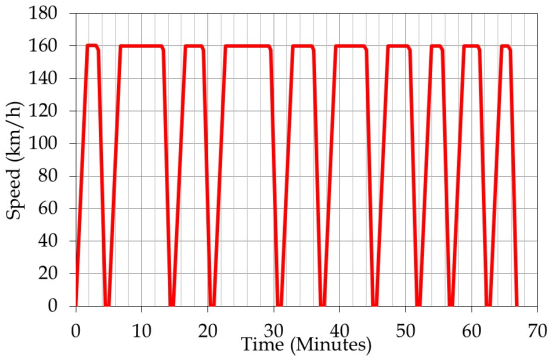


Table 3: Energy Requirements for Case 3

Time Period	Total Energy (kWh)
Acceleration	515.32
Constant speed	1,573.45
Coasting	188.85
Braking	(294.15)

Analysis of Bus & Train Operations

Existing Expressway Bus Operations

Information provided by the National Transport Commission was analysed. The seating capacity of a bus in the southern expressway is 50. The seating capacity of a train is 465 passengers. Table 4 and 5 summarise the bus operating services.

Table 4: Bus Operating Pattern Kottawa – Matara

Description	Tue, Wed & Thu/day	Fri & Sat/ day	Sun & Mon/ day
Morning Time - Operating Service			
Number of buses in one direction	30	35	33
Number of passengers	1,500	1,500	1,650
Number of trains required in one direction	3	4	4
Total number of trains required	6	8	8
Evening Time - Operating Service			
Number of buses in one direction	30	37	40
Number of passengers	1,500	1,850	2,000
Number of trains required in one direction	3	4	4
Total number of trains required	6	8	8

Table 5: Bus Operating Pattern Kottawa – Galle

Description	Galle to Kottawa/day	Kottawa to Galle/day
Morning Time - Operating Service		
Number of buses in one direction	24	21
Number of passengers	1,200	1,050
Number of trains required in one direction	3	3
Evening Time - Operating Service		
Number of buses in one direction	28	31
Number of passengers	1,400	1,550
Number of trains required in one direction	3	3

Proposed Electric Train Operations

Once all the energy parameters of the network have been defined, it is necessary to define the operating scenarios. In other words, it is necessary to consider all the operating stages in the network. e.g.: only one train accelerates, two trains accelerate at the same time, three trains accelerate, and one decelerates, etc. This task is tedious and could be summarised as performing a scrupulous study of the train schedule.

A total of three train movement patterns were identified. Each pattern has a distinctive demand profile that characterizes the timespan between terminal stations.

There could be multiple trains starting from both sides and required frequency of services as Case 1: Multiple trains starting on Tuesday, Wednesday & Thursday. Case 2: Multiple trains starting on Friday and Saturday. Case 3: Multiple trains starting on Sunday and Monday. A maximum of 20 trains would be allowable for safe travelling in single-track at a time. Table 6 and 7 summarise results of train operating services.

Table 6: Number of Train Required Stop at All Stations for Kottawa – Matara

Description	Matara to Kottawa/day	Kottawa to Matara/day
Morning Time - Operating Service		
Number of trains required	3	3
Evening Time - Operating Service		
Number of trains required	3	3

Table 7: Multiple Train Starting from Both Ends and Frequency of Operating Services

Case	Tue, Wed & Thu/day	Fri & Sat/day	Sun & Mon/day
Case 1: Matara to Kottawa & Kottawa to Matara	Morning: 6 Evening: 6 [12]	Morning: 8 Evening: 8 [16]	Morning: 8 Evening: 8 [16]
Case 2: Galle to Kottawa & Kottawa to Galle	Morning: 6 Evening: 6 [12]	Morning: 6 Evening: 6 [12]	Morning: 6 Evening: 6 [12]
Case 3: Calling at all stations in both directions	Morning: 6 Evening: 6 [12]	Morning: 6 Evening: 6 [12]	Morning: 6 Evening: 6 [12]

Energy Calculations for Train Operations

Energy used and regenerated was calculated, using the standard formula. [6]

$$E = \int_{t1}^{t2} p(t)dt \qquad \text{Eq. 5}$$

Where: E: energy in kWh, p(t): power Vs time function and dt: time differential.

"E_c" indicates energy consumption and "E_r" indicates energy regenerated by the train. Energy consumption previously calculated based on a single trip of a single train was:

Case 1: E_c = 1.32 MWh and E_r = (0.02) MWh
Case 2: E_c = 1.07 MWh and E_r = (0.02) MWh
Case 3: E_c = 2.45 MWh and E_r = (0.48) MWh

The annual energy requirement and regeneration were calculated considering the number of statutory holidays, weekends, and regular business days in 2018. The annual energy calculation for either E_c or E_r, expressed in MWh, could be given by:

$$E_{cr\,(year)} = \frac{144E_{cr\,(tue,wen,thu)} + 110E_{cr\,(fri,sat)} + 110E_{cr\,(sun,mon)}}{1000} \qquad \text{Eq. 6}$$

The estimated annual energy consumption for the proposed railway service is 22.3 GWh/year. The net energy requirement would be 20.01 GWh/year after deducting 2.29 GWh/year contributed by regeneration.

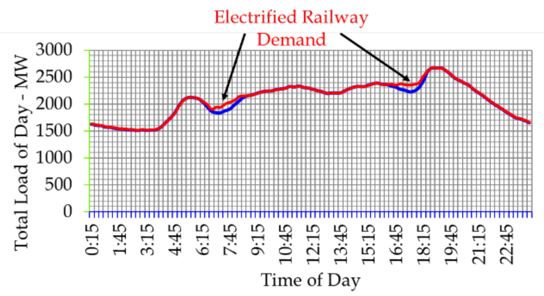
Total energy requirement for the train system would be 20 GWh per year. After considering the total effective efficiency of the supply-side to be 76%, total required energy input from the national grid will be 26.3 GWh per annum. Total maximum power requirement was estimated to be 50 MW.

Impacts on Sri Lanka Demand Profile

In the demand profile in Sri Lanka, there are two "valleys"; one in the morning from 6:30 am to 8:30 am and the other in the evening from 5:00 pm to 7:00 pm. See Figure 6.

The estimated maximum demand of 9 electric multiple units to provide the service will be 50 MW. This will be small compared with the total demand. Thus, the proposed railway service is unlikely to require additional generating capacity to be installed in the national grid. In contrast, the electrified railway service will use electricity during the off-peak periods and should thus enjoy a preferential tariff.

Figure 6: Daily Load Curve indicating the Electricity Demand of Trains



Energy Cost Analysis

This study did not consider the cost of construction, installation, commissioning, and maintenance of the proposed railway system. It also did not calculate the payback period and the cost-benefit ratio.

Cost of grid energy: According to the CEB LTGEP [6], from year 2015 to 2034, the baseload will be provided by coal power plants and the intermediate load will be provided by combined cycle or hydro power plants. The electricity demand for the train occurs during the off-peak time. During this time the cost of the energy mix will be LKR 21.32/kWh. The total cost of operating the proposed railway service would be LKR 561 million per year.

Cost of fuel: The total energy cost of a 5000 hp diesel train providing the proposed service in place of electric multiple units was estimated to be Rs. 384 million per year.

Conclusions

The proposed railway service will operate on grid power; the operating cost for electric energy was higher because it was calculated using the costs of intermediate energy mix in the long-term generation plan. More accurate costing of electricity and a corresponding tariff, considering that electric trains predominantly operate at off-peak hours, is likely to make electricity costs lower than what was calculated.

Electric trains have benefits compared with diesel trains. Energy saving with re-generative braking, absence greenhouse gas emissions at the point of use, lower maintenance costs, less noise, shorter traveling time and fuel cost saving with foreign currency savings (provided electricity is sourced from renewable sources). Furthermore, reduced travel time, comfortable speed and comfortable travel will be added benefits.

Other benefits are reduced travel time, improved safety, reduced traffic congestion on the existing Colombo-Matara Road and the Southern expressway. Much of the 130 buses presently serving this sector can be replaced.

The electrified train system has electrical power on board the train for the convenience of passengers. It can be provided with good lighting, air conditioning, sound systems and cooking to serve warm meals. More passengers including tourists can be attracted to travel by this service if electrification is implemented through a determined effort to improve the customer service and the image of Sri Lanka railways.

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