Regenerative Braking in Indian Locomotives: A model involving the use of flywheel as an ESD (Energy Storage Device) in WAP-7 Locomotives

Subhadeep Kuila[1], Sudhanshu Yadav[2]

[1] *School of Engineering and Applied Sciences, National Rail & Transportation Institute, Vadodara*
[2] *School of Engineering and Applied Sciences, National Rail & Transportation Institute, Vadodara*

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Abstract - *A new mathematical model to estimate the regenerative braking efficiency of Indian locomotives, which are already installed with the 'regenerative braking system,' is discussed here. It is demonstrated for a WAP-7 locomotive that runs on Indian tracks. This paper discusses the need of having an alternate energy recovery mechanism, (Flywheel here) in the mechanical model of the locomotive. The effect of gradient on energy savings for this new model is discussed here. The drive cycle relationships have been developed to study energy estimations on the selected route of ADI-MMCT. Finally, energy savings of the model proposed is compared with the energy savings of the already existing mechanism of WAP-7.*

Key Words: Flywheel, FBESS, Mathematical Model, Regenerative Braking, OBESS

1. INTRODUCTION

One of the environmentally friendly ways of transportation is railways. It is a critical approach to meet rising transportation demands in an ecologically conscious economy. India's rail sector remains a large energy user. With a growing population and greater energy consumption, the need for rail services will continue to rise, and energy consumption will increase in tandem.[1] The energy lost as trains reach rail stations provides an obvious additional source of energy that may be used to reduce demands on electricity production facilities and improve the overall efficiency of the electrical grid in large metropolitan regions. The energy lost as trains reach rail stations provides an obvious additional source of energy that may be used to reduce demands on electricity production facilities and improve the overall efficiency of the electrical grid in large metropolitan regions. The quantity of energy wasted every day in our civilization is startling. The causes vary from inefficient systems like single-pane windows in homes to vital but inelegant systems like friction brakes on nearly every mode of transportation.

The theory of regenerative braking captures the energy expended when cars use their brakes to slow down, and it provides a practical way to use otherwise dissipated energy. Using lost energy to boost energy supply to the electrical grid without incurring additional production expenses can improve the electrical grid's overall efficiency. The otherwise squandered braking power may be effectively and cheaply gathered and utilized to replenish the neighbouring electrical grid by using electrical generators positioned on train rails at appropriate locations to provide the deceleration forces necessary for braking.

1.1. CURRENT SCENARIO OF REGENERATIVE BRAKING IN INDIAN RAILWAYS

The Indian Railways have been particularly attentive about energy conservation and efficient utilization. Electric traction has a unique function called 'regenerative braking,' which converts the train's energy in motion to electric energy upon braking and giving it back to the feeder services. This function has been successfully implemented in the WAG-9, WAP-7, and WAP-5 locomotive classes, saving up to 20% and on all new electrical multiple units (EMU) that can save up to 30%. While this function saves energy, it also extends the life of the wheels and enhances the Locomotive's availability for driving trains, making electric traction more cost-effective.[3]
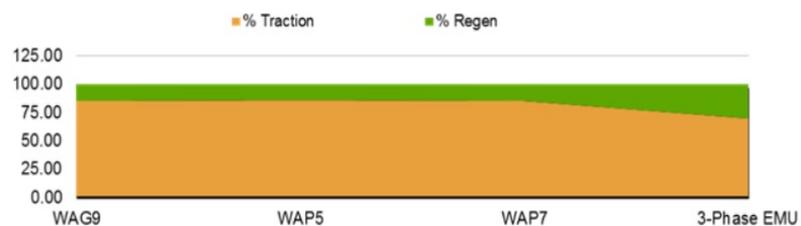
Figure 1: *The regeneration values of 3-Phase electric rolling stock of Indian Railways*

The figure above depicts the regeneration and traction values of 3-Phase electric rolling stock used by Indian Railways in WAG-9, WAP-5, WAP-7, and EMUs (Electric Multiple Units). It could be seen that the regeneration capabilities of EMUs are more significant than the rest of the categories mentioned. While it is very appreciable to note that Indian Railways has successfully achieved a regeneration saving of above 20% on the locomotive classes of WAG-9 and WAP-5, it is also crucial to increase regeneration efficiency in these areas classes of locomotives to compensate for energy losses. [3]

Railways have reduced Specific Energy Consumption (SEC) by roughly 18.9% during the previous five years through different energy conservation strategies. According to the BEE evaluation for 2014-2015, energy usage in traction applications improved by 3.3 per cent from a year earlier.

Over several years, Indian Railways has also received 87 energy conservation awards.

1.2 COMPARATIVE ANALYSIS OF REGENERATIVE BRAKING ENERGY SAVINGS: CASE OF INDIAN RAILWAYS NCR & UNITED KINGDOM SWR

We have tried to compare the case of Indian Railways' North-Central Region and United Kingdom's South-West Region running trains with Regenerative Braking capabilities to conclude with what measure Indian Railways should rely upon for achieving an excellent energy-saving index.

NCR has saved over 15 million power units by running these trains with three-phase induction traction motors with regeneration capabilities.[4] Cutting down to numbers, we have 400 electric locomotives running across NCR, out of which 100 have regenerative capabilities, and the 15 million kWh saving of electricity is due to these 100 three-phase induction traction motors fitted locomotives only.

More than 200 electric trains on the South-West Trains network have had equipment installed as part of the scheme. These trains serve Guildford, Alton, Portsmouth, Reading, Southampton, and Weymouth in the London suburbs. They've all been upgraded to include the new energy-saving technologies. The technique saves 50 million kWh of electricity each year, enough to power around 11,500 UK households for a year.[5]

We could conclude, from the figures below that despite having double the number of trains equipped with Regeneration capabilities, the energy saving is almost 3.5 times that of the NCR region. The track on which these figures have been taken has approximately the same track length, which Trains running in SWR Class 458 Class 444 Figure 3: Proportion of 3-Phase ITM locomotives from NCR makes the comparison fair enough to decide what extra technologies UK's SWR uses that make it such energy efficient. We will be talking about that part in later sections of our paper.

1.3 MODERN ELECTRIC RAIL VEHICLE: OVERVIEW & POWER FLOW IN WAP-7 LOCOMOTIVE

WAP-7 is the 7th generation of WAP class locomotives, where W stands for broad gauge (Wide), A stands for AC Electric locomotive, and P for Passenger locomotive. WAG-9 is the 9th generation of WAG class locomotives, where W stands for the same broad gauge (Wide), A stands for AC Electric locomotive, and G for Goods or freight locomotive.

The major components of this WAP-7 locomotive are a) Pantograph, which collects the high tension current (25 kV) from the contact wire, b) Voltage Regulating Equipment, where the main transformer, consists of an Autotransformer with 32 taps and a stepped-down transformer with two distinct secondary windings, steps down the high OHE voltage to a low voltage, c)Silicon Rectifiers, which converts the alternating current provided by secondary windings of the main transformer is into direct current utilizing two silicon rectifiers (RSI), one each supplying to set off three

traction motors, d)Traction Induction Motor, which is the prime mover of the locomotive. Generally, a three-phase Induction motor is used as the primary traction motor due to its Electromagnetic properties.[6]
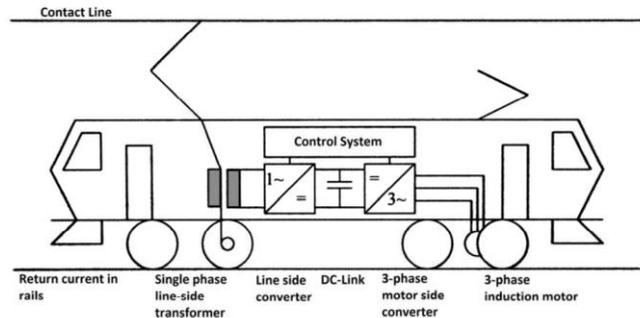
Figure 2: *Main Components of a Modern Electric Rail Vehicle*

The power flow through the locomotive happens wherein, the "traction sub-station," a single-phase step-down transformer is linked to the three-phase utility system, which feeds energy to the overhead line (high-voltage) and the rail ("ground"). The pantograph captures the AC power and is then provided to the vehicle. The Locomotive is fitted with appropriate equipment to enable the loco pilot to manage the train's speed according to requirements by regulating the applied voltage to traction motors. The 25KV, single-phase AC power is gathered from the OHE by a roof-mounted pantograph and stepped down by a transformer in typical locomotives. Before being supplied to the traction motors, this supply is converted to DC using a full-wave silicon rectifier and related smoothing filter. The variation of the AC input voltage to the rectifier via an on-load tap changing arrangement on the primary winding of the locomotive transformer is used to manage torque and speed.[7]
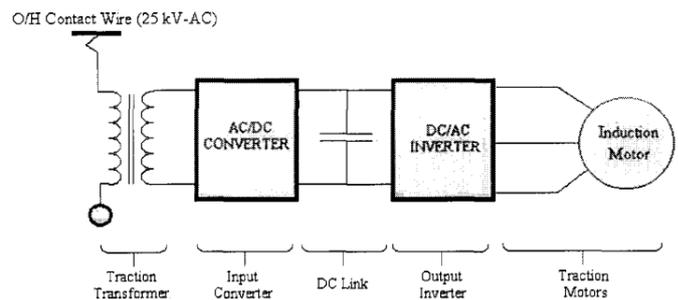
Figure 3: *Simplified view of power flow in a WAP-7 locomotive*

The Locomotive's primary transformer steps down the 25 kV overhead AC supply. It feeds it to a front end (line) dual 4-quadrant line converter, which converts the AC to DC using Pulse Width Modulation (PWM) to achieve a unity power factor. This supply is connected to an input side converter through a DC connection, which serves as an energy reservoir. The VVVF Converter transforms the DC supply

into three phases, subsequently delivered to three-phase traction motors. The output of the Drive converter (inverter) is a VVVF (Variable Voltage Variable Frequency) supply, which aids in adjusting the starting and operating torques of three-phase traction motors to meet traffic needs.

1.4 BRAKING OF A WAP-7 LOCOMOTIVE

In traction systems, there are two forms of braking: dynamic (electric) braking and classic friction braking. The produced current is used for regenerative braking when a traction motor is transferred to a generator for dynamic braking. This braking is helpful for heavy-haul diesel electric locomotives operating on routes with significant downgrades. When regenerative braking is used to decelerate the train, the current in the electric motors is reversed.[8]

In a Conventional Friction Brake, the hydraulic mechanism mainly drives the braking system. It consists of a primary, or master, cylinder filled with fluid and linked to a secondary or slave cylinder. When the brake pedal is depressed, a piston in the master cylinder depresses, forcing fluid through the circuit and into the slave cylinders at each wheel, which push the pistons to apply the brakes effectively. This system has improved over time with advancements like disc brakes, floating and multi-piston callipers, and power brakes, making braking more effective and comfortable for the driver, particularly with today's engines' more significant power outputs.[9]
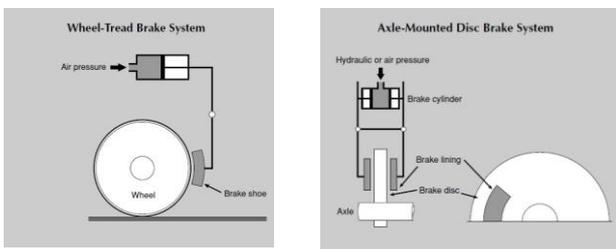
Figure 4: *Conventional Friction Braking of a WAP-7 locomotive*

Let us now look at the regenerative energy recovery mechanism used in Locomotive and the subsequent energy usage utilized by an accelerating train on the same contact line. It could be seen that the energy recovered by one train is sent back to the OHE line for other accelerating trains to feed upon it.
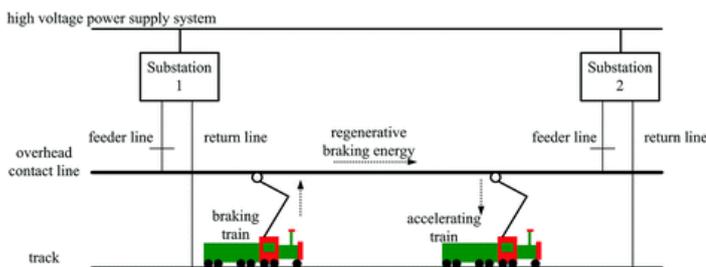
Figure 5: *Block diagram of energy recovery and usage on same OHE line by an accelerating train*

In Regenerative Braking of a WAP-7 locomotive, if we get energy back from the Traction motor, it acts as a generator,

generating electrical energy from the kinetic energy when braked upon. So, in the case of regenerative braking, and Induction Motor acts as an Induction Generator. Induction Motor acts as an Induction generator when the slip becomes negative, i.e., when the slip of motor is less than 0, then kicks in the regenerative braking capability of the motor, and when the slip is greater than 0. The motor traction capability acts upon the device.

$$slip = \frac{N_S - N_R}{N_S}$$

N_S is synchronous speed and N_R is speed of rotor

In easy words:

Slip>0, N_S>N_R: Induction Motor

Slip<0, N_S<N_R: Induction Generator

When the brakes are applied, the NS is reduced to such a level that the value of NS is less than the NR. Thus, the motor acts as a generator, generating electricity from the mechanical shaft movement due to inertia. NS could be altered as it depends upon the frequency of the Alternating Current supplied to the motor. The slip could be changed when braking is needed to make it less than 0. [10]

By reducing the frequency of AC supply, we could suddenly reduce the NS or synchronous speed, but NR or the rotor speed would not reduce suddenly due to the inertia it has gained by rotating. This is how the N_S or the slip is changed for making the motor behave as a generator. We use Variable Frequency Drives (VFD) to change the frequency of the AC being provided to the motor. A variable frequency drive (VFD) is a motor controller that controls the frequency and voltage of an electric motor's power supply.

As soon as the slip becomes negative, the motor's torque also becomes negative, i.e., it reverses the direction of applied torque. The torque of the motor tries to adjust itself by changing from negative to positive, but when the value of torque in its quest of becoming positive touches the value of 0, i.e., zero torque, the supply of current is cut down to the motor, which forces the motor to stop. We receive excess energy as an energy-saving from this regeneration mechanism. The same could be understood from the graph given below-
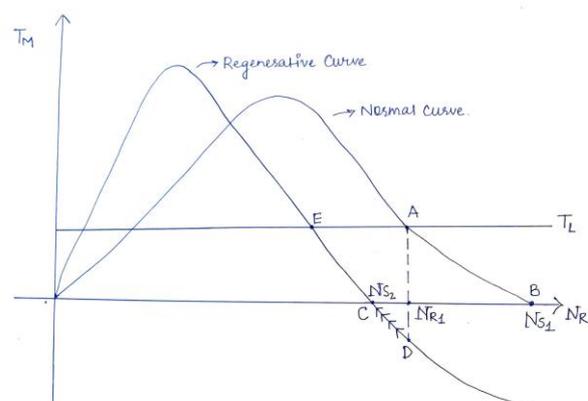
Figure 6: *Torque and Speed Characteristics of an Induction motor*

2. MATHEMATICAL MODELING OF WAP-7 TRAINS

The mathematical model for WAP7 locomotive developed in this research uses the equations of motion. The tractive effort $F_{trac.}$, track resistance force T_{res}, and the gradient force T_{grad} are considered as the three main operating force on the train's body.

$$F_{trac.} - F_{res} - F_{grad.} = M_{eff.} \cdot a = F_{a.} \qquad (1)$$

M_{eff} is the effective mass of the train, F_a is the net resultant force accelerating the train.

2.1. Equations governing train dynamics

The motion of train is majorly governed by the newtons third law of motion. The effective mass of the train is dependent upon the mass of locomotives, tare mass of the carriages and the mass of the payload.

$$M_{eff} = M_{loco} + N_{carr.} \times \left(M_{tare}^{carr.} + M_{payload} \right) \qquad (2)$$

Here, M_{loco} is the mass of the locomotive, N_{carr} Is the total number if the carriages, M_{tare} is the tare mass of the carriage and $M_{payload}$ is payload per vehicle. By using (1) and (2) we can find the acceleration as:

$$a = \frac{d^2 x}{dt^2} = \frac{F_{traction} - F_{friction} - F_{gradient}}{M_{train}} \qquad (3)$$

Tractive effort is the net force applied by the locomotive parallel to the direction of motion. The tractive effort is constrained by the motor current limits and the mechanical restriction. Values of the starting effort, continuous traction effort and braking effort is taken from the official documentation. A train's track resistance is its velocity-dependent resistance to motion. The semi-empirical Davis equation is commonly used to calculate resistance.

$$F_{res} = D_A + D_B \cdot v + D_C \cdot v^2 \qquad (4)$$

D_A, D_B, D_C are the coefficients for the various frictional force. Effect of gradient with θ as track gradient calculated as:

$$F_{grad} = M_{train} \times g \sin\theta \qquad (5)$$

2.2. Train Parameters

The focus of our study is the WAP 7 locomotive, for that we have chosen Shatabdi Express through the route ADI-MMCT (Ahmedabad Jn – Mumbai Central) would be used. This convoy is chosen because it is one of the fastest convoys on one of the busiest sections. The data used is given in the table below.

Name	Description	Unit	Value
M_{loco}	Mass of the locomotive	kg	123000
$M_{carriage}$	Mass of the individual carriage	kg	45000
$M_{payload}$	Mass of payload in a carriage	kg	
$N_{carriage}$	Number of carriages		22
$S_{\square}$	Surface area of locomotive	m^2	13.4
F_{start}	Starting force by the locomotive	kN	322.4
P_{train}	Power of the locomotive	kW	4560
V_{max}	Maximum velocity of the locomotive	m/s	50
F_{br}	Braking effort of the locomotive	kN	18600
P_{max}	Maximum power of locomotive	kW	4740

Table 1 – *Data for WAP 7 and Shatabdi Convoy*

2.3. Drive Cycle and Energy Estimation

A driving cycle is necessary to evaluate the train's energy consumption because the efficiency of a hybrid power train is highly dependent on the duty cycle as well as route parameters. We used the data available on the Ahmedabad-Mumbai route of Shatabdi express for recreating the driving cycle in simulation. The recreated driving cycle's distances and time were tested and validated against figures given by erail.in. Table (2) below shows the input used for the driving cycle, which should be read from left to right.

Sr no.	Station	waiting time (sec)	Travel Time (sec)	Distance (m)
1	Ahmedabad	0	2040	45000
2	Nadiad	120	1020	19000
3	Anand	120	1800	35000
4	Vadodara	300	2820	71000
5	Bharuch	120	2760	58000
6	Surat	300	3840	93000
7	Vapi	120	5220	140000
8	Borivali	180	3420	30000
9	MMCT	0		

Table 2 – *Route data for drive cycle*

The track's gradient data is not given, but the model can handle gradients, allowing broad dependencies on uniform gradients to be demonstrated.

Based on a modified version of the velocity-step approach (Ref. Jong J-C, Chang S), driving cycle is created. The driving cycle is set up to correspond to the distance and time requirements listed in data table provided above. The approach is modified by introducing a constant velocity part in the simulation that helps in meeting the time frame for the given distance. There are three phases to each driving section: acceleration, constant velocity motion, and deceleration as depicted in the figure given below. The acceleration (section a), constant speed (section b) and deceleration trajectory (section c).
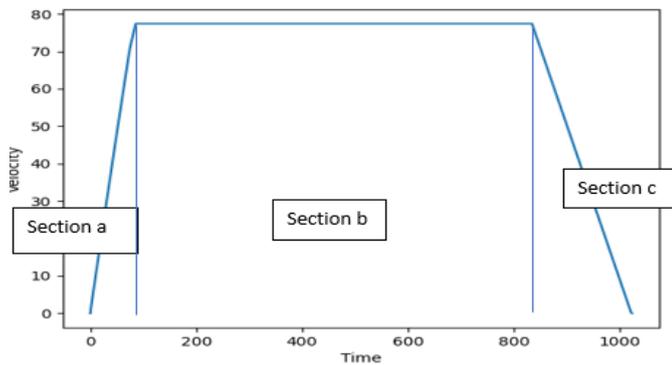
Figure 7: Drive cycle, showing the three sections

Acceleration starts at each station and establishes a constant speed, while the deceleration trajectory (section c) is dependent upon, the next arriving station, braking power and safety and comfort restrictions. Distance covered in all the three phases are computed concurrently as the velocity is increased in each step in an iterative manner. As the net distance travelled (area under the velocity time curve) matches or exceeds the driving length of the given section we stop the acceleration. Then the train travels at a constant speed for a pre decided length, and then starts to deaccelerate as it reaches the calculated braking distance. As a result, the time criteria are met precisely, whereas the distances are near accurate.

After using equation 3 for determining acceleration, we moved on to determining velocity, formula used for that is.

$$v = V_0 + a\Delta t \qquad (6)$$

The distance covered was updated using following equation.

$$x = x_0 + v\Delta t \qquad (7)$$

The data vital to this simulation is the power consumption throughout the journey. The instantaneous tractive power required by the train is determined by:

$$Power = F_{Traction} \times v \qquad (8)$$

The energy consumption and energy recovered by the regenerative braking are what we're interested in. The following is the formula for energy.

$$E = \int P\,dt \qquad (9)$$

The energy consumption during the traction will be calculated by using:

$$E_{traction} = \int P_{traction}\,dt \qquad (10)$$

The energy recovered during the braking of train will be calculated using:

$$E_{braking} = \int P_{braking}\,dt \qquad (11)$$

2.4. Implementation

In Python, numerical model incorporating all the equations discussed above was created. Driving cycle is computed after taking in the input of route profile, train parameters and other constraints. The velocity-step algorithm is applied at every section of track. Continuous computation is performed to calculate the distance traveled and braking distance required. For each velocity step, it starts with calculating the force required to overcome the force of friction and other resistances. Then it moves onto calculate the resultant acceleration using the equation (3) provided above. Further it updates the velocity and acceleration using equations 6 and 7. Next it checks the braking distance and braking time required to stop this train, after this the time for which the train will run at a constant speed is calculated. The distance travelled in all three (accelerating, constant speed, braking) phases is added up. This process is repeated until the sum of distances meet the prescribed distance of the section. After generating the drive cycle all time-dependent kinematic variables and forces are calculated, and the energy consumption is evaluated during postprocessing using the equations 10 and 11.

Below is the flow chart depicting the outline of the whole process implemented to obtain results.
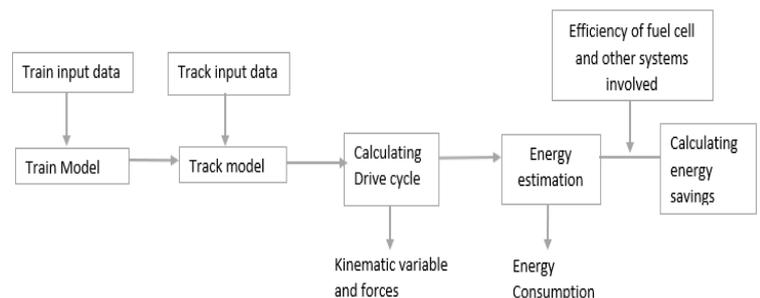
Figure 8: Basic modules and steps used in Python modelling

3. RESULTS

Below are the results and graphs obtained from the simulation. This simulation estimates the total energy consumed by the train in traction, we can use this to compute the energy taken from substation using equation 12.

$$E_{trac}^{Ac} = \frac{E_{trac}}{\eta_1} \qquad (12)$$

Here E_trac^Ac is the total energy taken from the substation, E_trac^ is the traction energy obtained from equation 10. η_1 is the induction motor's efficiency to convert the input electrical energy to output traction energy. Similarly, simulation also produces the cumulative braking energy produced during drive cycles.

We can use this to obtain the net amount of energy arriving at the flywheel by using equation (13).

$$E_{brake}^{Dc} = E_{brake} \times \eta_1 \qquad (13)$$

Recovered energy is equal to the multiplication of energy stored in flywheel with flywheel's efficiency.

$$E_{FESS} = E^{DC}_{brake} \times \eta_2 \qquad (14)$$

In the equation (13) E^{DC}_{brake} is the energy reaching the flywheel energy storage system (FESS). Multiplied with efficiency of the FESS (η_2) we obtain E_{FESS} that is the energy stored in the FESS. Since the energy must again pass through the induction motor to reach the wheels of the train, the energy recovered is equal to the energy collected by the FESS multiplied by η_1.

$$E_{recoverd} = E_{FESS} \times \eta_1 \qquad (15)$$

We also obtain the value of efficiency gain, which is defined as the ratio of energy recovered to the ratio of energy spent through-out the trip (16). As well as the value of energy recovery efficiency which is defined as the ratio of energy recovered to braking energy (17).

$$\varepsilon = \frac{E_{recovered}}{E^{AC}_{trac}} \qquad (16)$$

$$\epsilon = \frac{E_{recovered}}{E_{brake}} \qquad (17)$$

3.1. Results for zero gradient

Graphs below of passenger stock (18 LHB II Ac Coaches) being pulled by the WAP 7 locomotive on the route shown in table 1.

Velocity-Time Curve
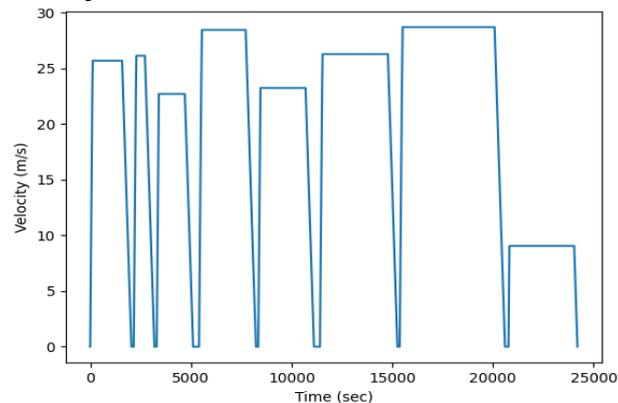
The maximum velocity attained 28.72 m/s.

Acceleration-Time curve
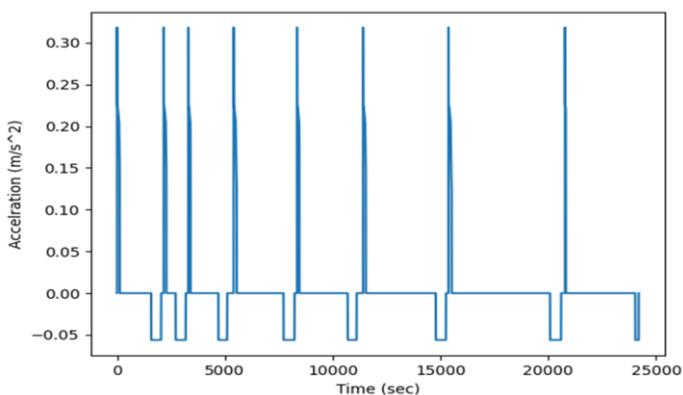
Peak acceleration for this run is 0.31m/s2, peak deacceleration is 0.051m/s².

Power-Time curve
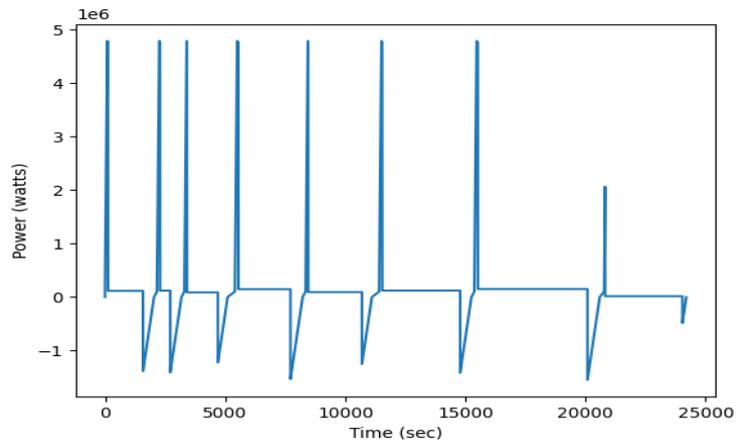
Peak acceleration power for this run is 4.79 Megawatts, peak power during deacceleration is -1.54 Megawatts.

Traction Energy-Time curve
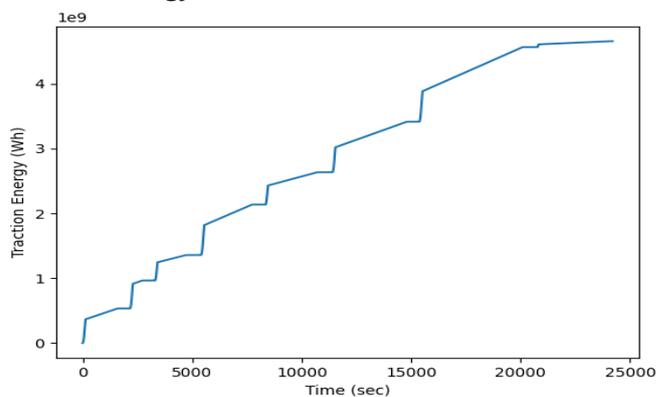
Total consumption of energy in whole travel time is 4.65×10^9 watt-hrs.

Braking Energy-Time curve
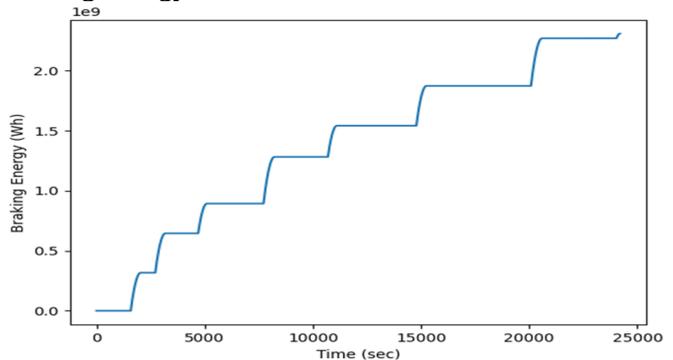
Total consumption of energy while braking is 2.304×10^9 watt-hrs.

Table below shows the various combinations of passenger stock being pulled by the WAP 7 locomotive on the route shown in table 1. The value for the efficiency of induction motor η_1 is taken as 0.88, and the efficiency of Flywheel η_2 as 0.90.

Gradient	Train Composition	$E_{traction}$ (kWh)	$E^{AC}_{traction}$ (kWh)	$E_{braking}$ (kWh)	E^{DC}_{brake} (kWh)	E_{FESS} (kWh)	$E_{recovered}$ (kWh)	ε	ϵ
0%	WAP 7 loco; 18 LHB II AC Full load	4660000	5295454.545	2304000	2027520	1824768	1605795.84	0.303240416	0.69696
	WAP 7 loco; 18 LHB II AC half load	4500000	5113636.364	2199000	1935120	1741608	1532615.04	0.299711386	0.69696
1 in 400 (0.25%)	WAP 7 loco; 18 LHB II AC Full load	5840000	6636363.636	2137000	1880560	1692504	1489403.52	0.224430667	0.69696
	WAP 7 loco; 18 LHB II AC half load	5640000	6409090.909	2042000	1796960	1617264	1423192.32	0.222058376	0.69696
1 in 300 (0.33%)	WAP 7 loco; 18 LHB II AC Full load	6320000	7181818.182	2111000	1857680	1671912	1471282.56	0.204862129	0.69696
	WAP 7 loco; 18 LHB II AC half load	6080000	6909090.909	2016000	1774080	1596672	1405071.36	0.203365592	0.69696
1 in 200 (0.5%)	WAP 7 loco; 18 LHB II AC Full load	7250000	8238636.364	2058000	1811040	1629936	1434343.68	0.174099647	0.69696
	WAP 7 loco; 18 LHB II AC half load	6990000	7943181.818	1978000	1740640	1566576	1378586.88	0.173556002	0.69696
1 in 150 (0.67%)	WAP 7 loco; 18 LHB II AC Full load	8390000	9534090.909	2049000	1803120	1622808	1428071.04	0.149785759	0.69696
	WAP 7 loco; 18 LHB II AC half load	8020000	9113636.364	1959000	1723920	1551528	1365344.64	0.149813377	0.69696
1 in 100 (1%)	WAP 7 loco; 18 LHB II AC Full load	10990000	12488636.36	2049000	1803120	1622808	1428071.04	0.114349637	0.69696
	WAP 7 loco; 18 LHB II AC half load	10430000	11852272.73	1951000	1716880	1545192	1359768.96	0.114726432	0.69696

Table 3: *Estimated recovered energy for various train configurations on route shown in table 1*

For a train consisting of 18 fully loaded LHB II AC coaches the total energy spent in traction is 5.29×10^6 kWh. The braking energy generated is 2.304×10^6 kWh. Total energy that can be recovered if on-board FESS is used 1.6×10^6 kWh, which is around 30% of total energy supplied for the traction. Similarly, for all other composition of the stock value of ε ranges from 0.29 to 0.31. Whereas the value of ϵ is constant for all the compositions.
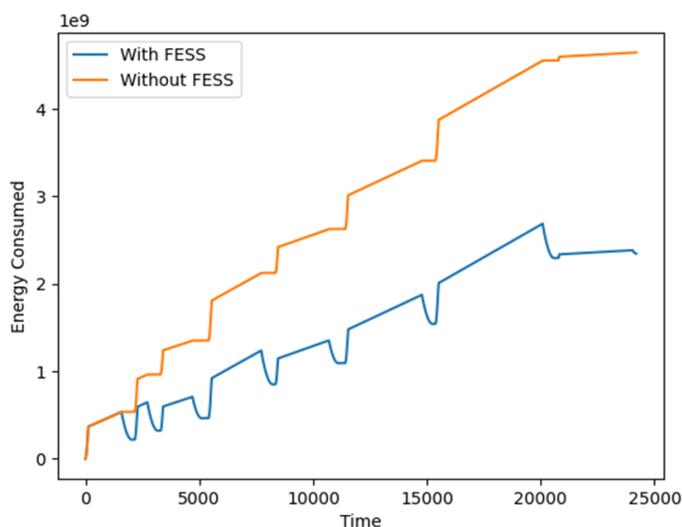
Figure 9: *Comparison of trains running with and without FESS*

Total energy consumed over the trip represented by orange curve is 4.65×10^6 kWh and for the blue curve is 2.36×10^6 kWh. Estimated energy savings by using FESS in this case is 2.29×10^6 kWh**.**

4. CONCLUSIONS

The results show that utilizing the FESS can save a significant amount of energy. The estimated energy savings varied depending on the track, payload, number of cars per train, and kind of FESS. The net recovered energy ranges from 29-31% of the total energy consumed. With increasing gradient, the energy savings from a flywheel decreased due to less requirement of braking on up-terrain.

The feasibility of a FESS for decreasing energy usage in passenger rail transportation systems is confirmed in this study. The technique and results can be applicable to various rail routes, even if the results were achieved for a specific route.

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