Quantitative Estimation of Railway Vehicle Regenerative Energy Saving: "A Case of Addis Ababa Light Rail Transit (AALRT)"

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Abstract- A rapidly growing demand and shortage of electric energy require mankind to efficiently use it, recuperate and store it from the existing system, when possible, for further applications whenever the need arises. Electric trains figure among big energy consumers and among different railway transportation services; light rail transit trains are characterized by frequent stoppings to entrain and detrain passengers. In their operation, traction drives are made to keep on braking in order to meet their service requirements between closely spaced passenger stations. The modern service braking system used is regenerative braking, which acts as an electric energy generator during the braking period. The objective of this paper is to estimate the magnitude of regenerative energy that can be recuperated as a percentage of train energy consumption on East-West (Ayat to Tolhailoch) and West-East (Tolhailoch-Ayat) directions of Addis Ababa Light Rail Transit. Mathematical equations have been used to calculate the energy consumed between stations followed by the quantification of regenerative energy at each passenger station. Considering the current average running speed (24km/h) of the line, it resulted that 26.31% and 28.18% of energy consumption for East-West and West-East directions respectively are saved through regenerative braking energy recuperation. From the above results, it was observed that the magnitude of regenerative energy strongly depends on the speed at which the train is running and the efficiencies of inverter and traction induction motor.

Keywords: Electric train, energy consumption, speed, regenerative braking.

I. Introduction

Regenerative braking energy is a form of electric energy obtained in electric vehicles resulting in the loss of kinetic energy of the vehicle. This energy can be recuperated and stored when proper arrangement are put in place. The stored energy can be fed back to provide power to traction motors or to supply auxiliaries. In railway transportation systems, modern traction systems are equipped with regenerative brakes and the latter are used as service brakes.

Studies show that up to 40% of energy consumed by a train can be fed back to third rail through regenerative braking [1]. In Japan, flywheels have been used for regenerative braking energy saving since 1970 with the reported energy saving of 12% [2]. According to Sharma [3], regenerative energy technologies could potentially reduce the energy consumption of urban rail between 10% and 45%, depending on the track gradients and the service characteristic. The research results according to Sengor [4] reveal that in the light of calculation and measurements, 35-40% of consumed energy can be regained. The research results according to Su [5] reveal that 32% of energy consumed can be regained through regenerative braking energy recuperation and saving. Numerous researches carried out present different values of energy saving depending on the line alignment, stops spacing, gradient, power profile, frequency of service, electric network configuration, rolling stock, geographical conditions of the area and the running characteristics of the train. According to Fazel [6], 31.5% of energy consumption can be recuperated through regenerative braking energy saving and fed back to the grid when trains are run in metros.

During regenerative braking, energy losses are minimum because recent reports show that the efficiency of traction converters (mainly GTO and IGBT), DC traction motors, induction traction motors, and also gear system are 98.5-99.5%, 90-94%, 93-95%, and 96-98%, respectively [6]. Around the world, industries are undergoing competition in producing energy-efficient units with higher potential of energy saving techniques [7]. Different systems have been put in place to make the regenerative braking energy useful. Examples of successful projects include: Metro of Los Angeles which has installed a flywheel energy storage system at the Westlake/MacArthur Park Subway, and energy consumption has decreased by around 20%, yielding 540 MWh yearly saving [8]. In 1988, a flywheel at Keihin Electric Express Railway at Zushi post in Japan is installed for storing regenerative braking energy. It is reported that the 25 kWh, 2000 kW flywheel was capable of saving 12% of total energy consumed and is still operational up to date [9]. In 2000, a flywheel of power rating 1MW was installed at London Underground line to store regenerative braking energy. Before its installation, electricity consumption was £195000 whereas the power consumption was reduced by 26% or £50000 yearly after it was operated. The purchase and maintenance costs of the flywheel were £210 000 and £2500 per year respectively, which would mean that the capital investment was recovered within 5 years [10].

In October 2002, the University of Texas at Austin Center for Electro-mechanics (UT-CEM) developed an Advanced Locomotive Propulsion System (ALPS) as part of the Next Generation High-Speed Rail program sponsored by the Federal Railroad Administration (FRA).

The deliverable energy of the flywheel design is 360 MJ (100 kW-hr), providing a capability of 2MW rated power for a duration of 3 minutes [9]. In April 2014, VYCON Inc. installed a flywheel energy storage system for the Los Angeles County Metropolitan Transportation Authority to recover the braking energy from trains. The rail subway service connects downtown to San Fernando Valley through six-car trains with AC or DC traction systems. The flywheel can recover 66% of the braking train energy. The collected data, after six months of operation showed that 20% energy saving (approximately 541 MWh), which is enough to power 100 average homes in California [11]. New York City Transit/ Metropolitan Transportation Authority has a 2.4MW flywheel for storing regenerative braking energy. The flywheel is capable of supplying power for 30 seconds and the design was funded by New York Power Authority (NYPA), New York State Energy Research and Development Authority (NYSERDA) and US Department of Energy (DOE) for the Long Island Railroad [11].

To make use of regenerative braking energy for DC traction railway systems, different solutions have been proposed. The proposed systems are broadly classified in three categories:

a. By direct feeding of regenerative braking energy to the supply network: By recuperation of regenerative braking energy, there are many competing technologies with no clear leader, each technology offering advantages but also with associated disadvantages. It is already known that the regenerative energy flows in opposite direction to the driving energy [12]. In these systems, different configurations are in current use and they consists in directly feeding the regenerated energy back to the supply network as shown on the diagram below:

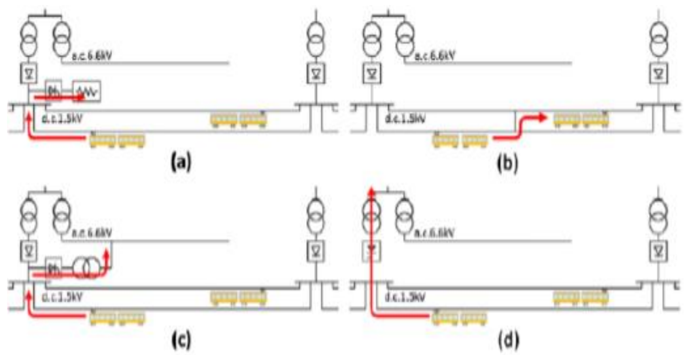


Figure 1: Illustration of methods of feeding the regenerative braking energy to the supply electrical network [13].

In Figure $1_{(a)}$, a resistance is used to dissipate regenerative energy from the braking train. This energy is not used to produce useful work, instead, it is wasted in the resistor as heat. It is clear that during braking, the gate of the thyristor in series with the resistor is triggered, thus allowing current to flow in that series combination instead of flowing back to the diode rectifier circuit which is reverse biased. It is because of the unidirectional conduction nature of the diode.

In figure $1_{(b)}$, called the Tie feeding system, it claimed to be cost effective but difficult to realize. It is achieved by time table optimization whereby the braking of the braking train is synchronized with the acceleration of another train running on the same feeding bus bar. In this configuration, the regenerative energy from the braking train is used to energize the accelerating train. In figure$1_{(c)}$, a reverse substation scheme connected in parallel with the feeding substation is presented. The regenerative DC energy is inverted to produce AC power, which is stepped up by a transformer to a feeding grid voltage. The fed energy can be utilized by other customers connected on the grid.

Depending on the grid ownership, the amount of regenerative energy can be quantified and deducted from the electricity bill. In figure1$_{(d)}$, the configuration is similar to that in figure1$_{(c)}$ but the regenerative energy is immediately fed back to the grid without reverse substation [9]**.** The system advantages include possibility of selling electricity to main grid, it can be used for all trains running on the line, maintenance and repair do not impact train operation, and lower safety constraints. The resulting setbacks are no voltage stabilization and analysis requirements to choose the right location [14].

b. Mobile storage applications: Regenerative braking energy is not always directed to feeding network, instead, it can be stored for future use. By using these systems, energy storage systems are mounted on the vehicle roof; every system working for one vehicle. It can also be installed underneath but this is costly because space is not readily available [14]. This energy can be used to supply the vehicle when it accelerates or to power its auxiliaries (heating, cooling and lighting) [15]. Advantages associated with mobile storage applications include possibility of catenary-free operation; reduction of voltage drop and improved efficiency. The associated drawbacks include high cost due to placement of energy storage system on vehicle, high safety constraints due to on-board passengers, standstill vehicle for maintenance and repair [14]**.**

c. Stationary storage applications: Wayside energy storage application consists of one or more energy storage systems placed along the track. Energy storage devices in common use include batteries and supercapacitors. The can recover energy from any braking train within the area of influence of the system as shown on the following figure:

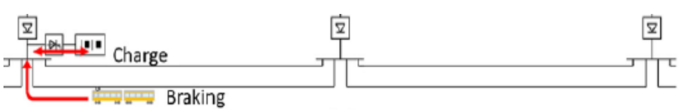


Figure 2: Illustration of regenerative braking energy recuperation for saving (batteries, supercapacitors and flywheels can be used as storage devices) [13].

The corresponding benefits of the system are the mitigation of voltage sag, maintenance and repair do not impact the train operation and the energy storage system can be used by any train moving on the line (within same section).

This system of energy storage offers drawbacks including the analysis requirements to choose the right sizing and location, increase of overhead line losses due to absorption and release of energy over the traction line [14].

II. Materials and Methods

The estimation of the magnitude of regenerative energy and its comparison as percentage of electric energy consumption requires mathematical models that take into account train static and dynamic parameters track alignment.

Both mathematical expressions of energy consumption and regenerative energy are developed before data specific to Addis Ababa Light Rail Transit are applied to the empirical equations. Data required to achieve results are presented in the following table:

Table 1: Data specific to Addis Ababa light rail transit

No	Quantity	Value
1	Vehicle weight (empty)	43000 kg
2	Vehicle weight(fully loaded)	59240 kg
3	Vehicle frontal area	10 m^2
4	Maximum design speed	70 km/h
5	Current running speed	24 km/h
6	Average starting acceleration	0.9 m/s^2
7	Maximum acceleration	1 m/s^2
9	Service brake deceleration	1.1 m/s^2
10	Motor efficiency	87%
11	Inverter efficiency	90%
12	Gearbox efficiency	96%
13	Air density	1.2 kg/m^3
14	Rolling resistance coefficient (f_r)	0.0071
15	Aerodynamic drag coefficient	0.5
16	Number of axles per cable car	6

A. Modelling of train movement and energy consumption

In the previous sections of this work, it was mentioned that the regenerative energy saving is taken as the percentage of train energy consumption after a particular track section. Therefore, it is important to initially understand the train dynamics to find the equations for train energy consumption estimation for the 21 interstation for East-West and West-East directions of AALRT.

Before the mathematical modelling of the train motion is put in place, the following symbols will be used:

Table 2: Symbols used for calculation of energy consumption

No	Quantity
a	train acceleration
D'	distance during acceleration and free running
Ea	energy to overcome acceleration
Er	energy to overcome rolling resistance
Et	total energy from driving axles
Fe	force to overcome acceleration when considering effective mass
Fg	force to overcome gradient
Fr	force to overcome rolling resistance
F_t	train total tractive force
G	percentage gradient
g	acceleration due to gravity
Me	Train effective mass
R	Train resistance
r	Train specific resistance
W	Train weigh
θ	Slope angle

When a train is in motion due to tractive effort applied, resistive forces oppose its forward motion. These resistive forces are due to interaction and friction between train parts, track irregularities as well as atmospheric resistance [16]**.**

A train is put into motion when the tractive force has overcome acceleration, gradient and friction.

a. Force to overcome acceleration: When a train has a stationary mass M and has to run with constant acceleration a, the force required to overcome this acceleration is given by the product of train mass and acceleration. Since the train has rotating parts like wheels, axles, motor armature and gearing, its effective mass or accelerating mass M_e is more about 8-15% than its stationary mass [17]. These parts have to be given angular acceleration at the same time when the train is running. Hence:

$$F_e = M_e \, a \tag{1}$$

When the mass is expressed in tones and the acceleration in km/h/s, then:

$$F_e = 277.8 \, M_e \, a \tag{2}$$

b. Force to overcome gradient: when studying the train dynamics, the gradient comes in when the train is moving on a sloped track. For better understanding, let's consider the following figure which show a train wheel moving upwards:

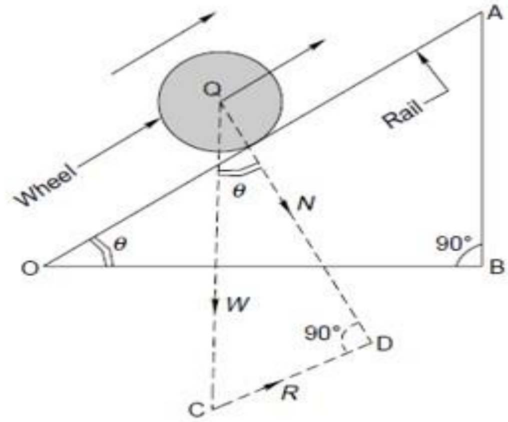


Figure 3: Forces acting on a train moving over an ascending gradient [16].

Considering an upward moving wheel of weight W, the following forces act on it: the weight of the wheel W which acts downwards (perpendicular to OB), normal pressure N on the rail which acts perpendicular to OA, resistance which acts parallel to AO in opposite direction to motion. The force that has to be overcome by the train tractive force is the one which moves opposite to the train motion which is given by:

$$F_g = W\sin\theta = M \, g \sin\theta \tag{3}$$

In railway practice, gradient is expressed as the rise (in meters) of a track distance of 100m and is called "percentage gradient".

$$\%G = \frac{AB}{OB/100} = 100\frac{AB}{OB} = 100\sin\theta \tag{4}$$

Back in the equation of F_g, the result after substitution of the value of sinθ is:

$$F_g = Mg\frac{G}{100} \tag{5}$$

When the mass is expressed in tones, the force to overcome gradient is:

$$F_g = 98MG \tag{6}$$

c. Force to overcome resistance to train motion: the train resistive force (F_r) comprises the mechanical and wind resistance. The mechanical train resistance include internal (friction at journals, axles and buffers) and external (friction between wheel and rail, flange friction) components. The mechanical resistance depends on weight rather than vehicle speed. If r is the specific resistance (resistance offered per unit mass), the force to overcome resistance is:

$$F_r = Mr \quad (7)$$

where M is in tones and r is the specific resistance expressed in Newton/tone. Hence, the expression for total tractive force is given by:

$$F_t = F_a \pm F_g + F_r = 277.8M_e a \pm 98MG + Mr \quad (8)$$

In equation (8), when calculating the force to overcome gradient, a positive sign is used for a train moving upwards while a negative sign is used for a train moving downwards.

The power and energy from driving axles are calculated based on the trapezoidal speed/time curve which is typical for light rail trains as presented in the following figure:

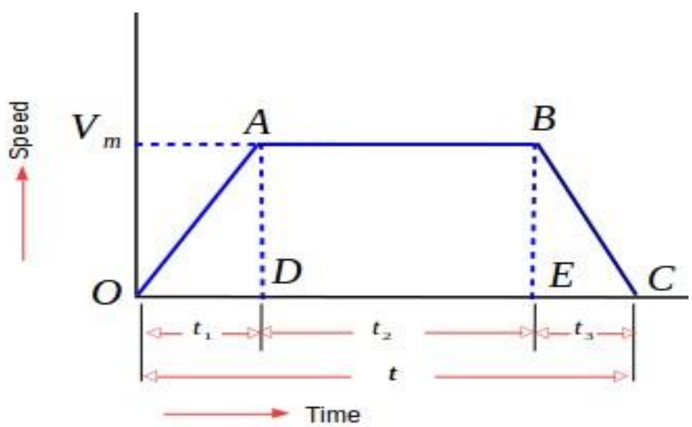


Figure 4: Trapezoidal speed/time curve for light rail trains.

In the above figure, t_1 represents the acceleration time, t_2 represents the free running time while t_3 stands for the deceleration.

The total energy output from driving axles is the energy output during acceleration and free running.

E= Energy during acceleration + Energy during free running.
From the above figure, E = $F_t *$ Area OAD + $F_t' *$ Area ABED

$$E = \frac{1}{2}F_t V_m t_1 + F'_t V_m t_2 \quad (9)$$

Where F_t and F'_t are tractive forces during acceleration and free running respectively. Incidentally F_t will consist of the three components of the tractive force expression while F'_t consists of gradient and resistance components of tractive force. In details, the energy output to supply acceleration, gradient and resistance requirements are separately described below:

i. **Energy to overcome acceleration (E_a):** As seen from the above figure, the energy required to overcome the acceleration is given by:

$$E_a = F_a * \text{Area OAD} = 277.7\,a\,M_e + \frac{1}{2}V_m t_1 \quad (10)$$

The development of equation (9) in watt-hour gives:

$$E_a = 0.01072V_m^2 M_e \quad (11)$$

ii. **Energy for overcoming gradient (E_g):** Considering that D’ is the distance over which power remains ON (acceleration OA and free running AB), and taking its maximum value from the above figure as OABE, the energy in joules to overcome gradient is given by:

$$E_g = F_g D' = 98MG(1000D') = 98000MGD' \quad (12)$$

The same energy in watt-hour becomes:

$$E_g = 27.25MGD' \quad (13)$$

iii. **Energy required to overcome resistance (E_r):** this energy is also computed considering the travelled distance when the power is ON.

$$E_r = F_r D' = Mr1000D' \quad [J] \quad (14)$$

$$E_r = 0.2778MrD' \quad [Wh] \quad (15)$$

The total energy output from driving axles becomes:

$$E_t = E_a + E_g + E_r \quad (16)$$

By replacing each term with its equivalent, the energy output from driving axles becomes:

$$E_t = 0.01072V_m^2 M_e + 27.25MGD' + 0.2778MRD' \; [Wh] \quad (17)$$

The expression for train energy consumption E_c is calculated by taking into account the efficiencies for gearbox, traction motor and inverter [17]. Its expression in Wh is given by the equation:

$$E_c = \frac{0.01072V_m^2M_e + 27.25MGD' + 0.2778MrD'}{\eta_{inv}\eta_{motor}\eta_{gear}} \quad (18)$$

where V_m is expressed in km/h; M and Me are expressed in tones; r is expressed in N/tone

B. Train resistance

The total resistance against the train movement is given by Davis equation:

$$R = 1.3W + 29N + cAV^2 \quad (19)$$

Where R: total resistance in lbs,
W: train weight in tones,
N: number of train axles;
V: train speed in miles/hour,
c: drag coefficient,
b: experimental friction coefficient
A: cross section of train frontal area (square feet).

For a passenger car, b=0.03 and c=0.00034.

At current running speed (24km/h), R=1674.1N and hence the specific resistance is 28.25 N/tone.

C. Modeling of regenerative energy

The development of an empirical formula for regenerative braking takes into account a number of parameters ranging from vehicle dynamics to power flow stages [18]. The meaning of symbol that will be used in subsequent sections is presented in table 3.

In order to develop the general expression for regenerative energy, it is essential to know the vehicle parts involved and their effect on the magnitude of regenerative energy. The latter being primarily developed from the vehicle wheels to the catenary through the gearbox, traction induction motor and the inverter as illustrated in fig. 5.

Table 3: Symbols used in regenerative braking energy empirical formula

Symbol	Meaning
A	Projected frontal area of the vehicle
B	Vehicle losses
C_w	Drag coefficient
Ftrac	Tractive force
F_{rr}	Rolling resistive forces
F_{gr}	Gradient force due to slope (inclination)
G	Acceleration due to gravity
F_{ar}	Force to overcome aerodynamic resistance
Me	Effective mass of the train
f_r	Rolling resistance coefficient
Vmax	Imposed train velocity
α	Inclination angle
d	Train average deceleration
T_a, ω_a	Torque and angular velocity at each axle of the train's car respectively
T_G; ω_G	Torque and angular velocity upstream the gearbox respectively
Eregen	Regenerative energy during deceleration
E_T	Total energy during a train complete cycle
Pelec	Electric power of train during a cycle
P_m	Mechanical power
P_{regen}	Regenerative power of train during deceleration
t_o	Starting time of powering mode
t_c	Starting time of coasting
t_d	Starting time of braking mode
t_s	Time when the train stops
Vmax	Maximum speed of the train just before it starts decelerating

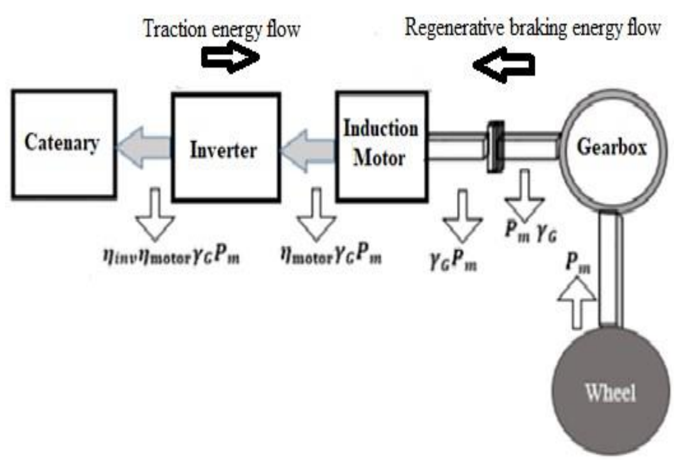


Figure 5: Traction power and regenerative braking energy flow stages [18].

By applying Newton's second law of motion, which states that the summation of forces acting on a moving object is equals mass times acceleration; the vehicles under study are acted upon by traction force from inductions for propulsion and the resistive forces. The fact that resistive forces act opposite to the traction force, they are taken negative. Therefore;

$$F_{trac} - \sum F_{resistive} = M\frac{dV}{dt} \quad (20)$$

$$\sum F_{resistive} = F_{ar} + F_{rr} + F_{gr} \quad (21)$$

where:

$$F_{rr} = MgCos\alpha \quad (22)$$

$$F_{ar} = \frac{1}{2} C_w A\rho V^2 \quad (23)$$

$$F_{gr} = MgSin\alpha \quad (24)$$

By replacing equations (22), (23) and (24) into equation (20),

$$F_{trac} = MgCos\alpha + \frac{1}{2} C_w A\rho V^2 + MgSin\alpha + M\frac{dV}{dt} \quad (25)$$

Assuming that the torque will be equally distributed among the train cars and considering the fact that each car has 6 axles, the torque and speed for axle can be calculated as:

$$T_a = r\frac{F_{trac}}{4n_c} \quad (26)$$

$$\omega_w = \frac{V}{r} \quad (27)$$

In order to assure high torque at wheels; a gearbox is used to increase the torque from induction motor shaft. Hence for determining the torque and speed of induction motor shaft, the following equations is used [18].

$$T_G = \frac{T_a}{\gamma_G} + \frac{B}{\gamma_G} \quad (28)$$

$$\omega_G = \omega_w \gamma_G \quad (29)$$

The sign in equation (28) depends on whether the train is motoring (the sign is positive) or braking (negative sign). The vehicle losses can be quantified by the following equation:

$$B = T_a(1 - \eta_G) \quad (30)$$

In the following equations, regenerative energy is calculated up to the point of connecting inverter. According to [18], the mechanical power can be represented as:

$$P_m = T_g \omega_G \quad (31)$$

Since there are 6 axles per car,

$$P_{regen} = 6n_c \eta_{inv} \eta_{motor} P_m \quad (32)$$

By substituting (20), (21), (22), (23), (24), (25), (26), and (27) in (32), it results in:

$$P_{regen} = 6n_c \eta_{inv} \eta_{motor} P_G \omega_G \quad (33)$$

If P_G and ω_G are replaced by their representative expressions and by correct rearrangement of the equation (33), the regenerative braking power is quantified by:

$$P_{regen} = \eta_{inv}\eta_{motor}[\left(F_{rr} + F_{gr} + \frac{1}{2} C_w A\rho V^2 + M\frac{dV}{dt}\right) - \frac{6Bn_c}{r}]V \quad (34)$$

By setting $K_1 = F_{rr} + F_{gr} + F_{rr}$; $K_2 = \frac{1}{2} C_w A\rho V^2$

And by expanding the term $\frac{6Bn_c}{r} = \frac{6\, n_c T_a(1-\eta_G)}{4n_c r}$ (35)

$$\frac{6Bn_c}{r} = \frac{6\, n_c F_{trac}(1-\eta_c)}{r} \quad (36)$$

$$\frac{Bn_c}{r} = F_{trac}(1 - \eta_G) \quad (37)$$

Then equation (34) becomes:

$$P_{regen} = \eta_{in}\eta_{motor}[F_{trac} - F_{trac}(1 - \eta_G)]V \quad (38)$$

If $K_3 = (1 - \eta_G)$, equation (38) yields

$$P_{regen} = \eta_{inv}\eta_{motor}(K_1 V + K_2 V^3 + MV\frac{dv}{dt})(1 - K_3) \quad (39)$$

The acceleration and deceleration are calculated from: $a = \frac{V_{max}}{t_c - t_0}$ and $d = \frac{V_{max}}{t_s - t_c}$

From the speed-time curve of the train, deceleration by brake application starts at t_d and ends when the train stops at t_s. Hence, the resulting energy (braking energy) is given by:

$$E_{regen} = \int_{t_d}^{t_s} P_{regen}\, dt \quad (40)$$

$$E_{regen} = \eta_{inv}\eta_{motor}(1 - K_3)\int_{t_s}^{t_d}(K_1 V + K_2 V^3 + MV\frac{dv}{dt})dt \quad (41)$$

After integration and necessary replacement, the magnitude of the regenerative braking energy is approximated by the following equation:

$$E_{regen} = \eta_{inv}\eta_{motor}(1 - K_3)[\frac{dK_1}{2}(t_s - t_d)^2 + \frac{K_2 d^3}{4}(t_s - t_d)^4 + \frac{M}{2}V_{max}^2] \quad (42)$$

III. Results and Dicussion

The determination of the percentage saving through regenerative braking energy recovery is achieved by using equation (18) to determine the energy consumption between passenger stations. This is followed by the calculation of regenerative braking energy at each passenger station using equation (42), from which, it is clear that the magnitude of regenerated energy depends on a combination of many factors including efficiencies of inverters and motors, braking time, acceleration, train mass, maximum operational speed, air density, frontal area of the train, drag coefficient, rolling resistive force and resistive force due to gradient. The transit line in the study case is an urban rail transportation system in Addis Ababa, operating two lines (East-West and North-South) with a total of 39 passenger stations. The E-W line is 17.4 km long stretching from Ayat to Tolhailoch while the N-S line is about 16.9 km long from Menelik II Square to Kality Depot. Both lines have a 2.7 km common track section from Stadium to St. Lideta. The AALRT was originally to have a total of 41 passenger stations on its two lines and each train was planned to have a capacity of 286 passengers. The minimum distance between stations is 435m while the longest is 2362. This results in an average spacing of 1398.5 m. It is a standard gauge rail running trains at maximum operational speed of 70km/h but the current operational speed is 24km/h. The line is supplied from 15kV line from Ethiopian Electricity Company. There are four gas insulated substation four ends of the rail network. The gas, Sulphur Hexafluoride (SF6) is chosen because it has higher breakdown strength allowing the substation to have closely spaced high voltage bus bars and this results in the overall reduction in space occupied by the substation. These substations receive power at 132 kV at the primary of transformers and output 15kV at their secondaries. The 15kV is distributed along the track as the primary voltage of the transformer of the power feeding stations. The transformer secondary outputs 590V which is rectified and filtered to provide 750VDC for overhead catenary voltage. The spacing between stations are recorded from [19] and distance D' during which the power is ON was calculated using the data from table1 and the speed-time curve of figure4.

Table 4: Spacing between passenger stations and distance for which power remains on

Interstation	D (km)	D' (km)
Ayat-Meri	2.3629	2.2
Meri-CMC	1.0922	0.921
CMC-St. Michael	0.8492	0.678
St.Michael-C.S.College	0.8452	0.674
C.S.College - Mgt.Institute	0.7245	0.553
Mgt.Institute-Guldashora1	0.9708	0.8
Guldashora1- Guldashora2	1.0549	0.884
Guldashora2 - Meganagna	0.8563	0.686
Meganagna - Lem Hotel	0.7992	0.628
Lem Hotel - Hayahulet1	0.7826	0.611
Hayahulet1- Hayahulet2	0.6853	0.514
Hayahulet2-St.Urael	0.9535	0.782
St. Urael - Bambis Hotel	0.6995	0.528
Bambis Hotel-Estephanos	0.5902	0.779
Estephanos-Stadium	0.6073	0.436
Stadium-Leghar	0.4121	0.2414
Leghar-Mexico Square	0.6634	0.493
Mexico Square-Tegbared	0.6356	0.465
Tegbared-Lideta	0.7684	0.597
Lideta-Cocacola	0.7286	0.557
Cocacola - Tolhailoch	0.7209	0.55

The expressions (18) for energy consumption and (42) for regenerative braking energy are applied to East-West and West-East directions.

The East-West portion (Ayat to Tolhailoch) of the line has 21 passenger stations and the results obtained are presented in the following table:

Table 5: Energy consumption and regenerative braking energy results for east-west direction

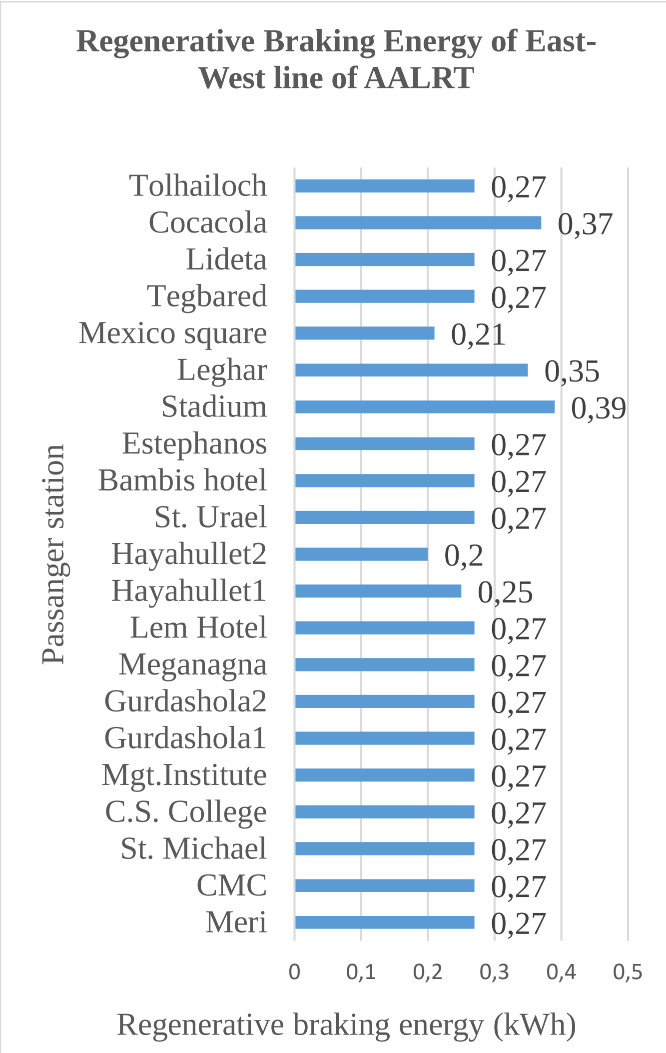
Interstation	Energy consumption (kW)	Passenger Station	Regenerative braking energy (kWh)	% of energy saving
Ayat-Meri	1.96	Meri	0.27	14.0
Meri-CMC	1.13	CMC	0.27	24.3
CMC-St. Michael	0.95	St. Michael	0.27	28.8
St.Michael-C.S.College	0.97	C.S. College	0.27	28.2
C.S.College - Mgt.Institute	0.88	Mgt.Institute	0.27	31.1
Mgt.Institute-Guldashora1	1.01	Gurdashola1	0.27	27.3
Guldashora1-Guldashora2	1.11	Gurdashola2	0.27	24.9
Guldashora2-Meganagna	0.96	Meganagna	0.27	28.
Meganagna-Lem Hotel	0.90	Lem Hotel	0.27	30.6
Lem Hotel-Hayahulet1	0.90	Hayahullet1	0.25	28.3
Hayahulet1-Hayahulet2	-0.09	Hayahullet2	0.20	-226
Hayahulet2-St.Urael	-3.79	St. Urael	0.27	-7.3
St.Urael-Bambis Hotel	0.844	Bambis hotel	0.27	32.8
Bambis Hotel-Estephanos	1.044	Estephanos	0.27	26.5
Estephanos-Stadium	0.808	Stadium	0.39	48.6
Stadium-Leghar	3.18	Leghar	0.35	11.2
Leghar-Mexico Square	4.35	Mexico square	0.21	4.8
Mexico Square-Tegbared	-1.95	Tegbared	0.27	-14.
Tegbared-Lideta	0.90	Lideta	0.27	30.5
Lideta-Cocacola	5.58	Cocacola	0.37	6.6
Cocacola-Torhailoch	0.89	Tolhailoch	0.27	30.8
	22.62		**5.953**	**26.32**

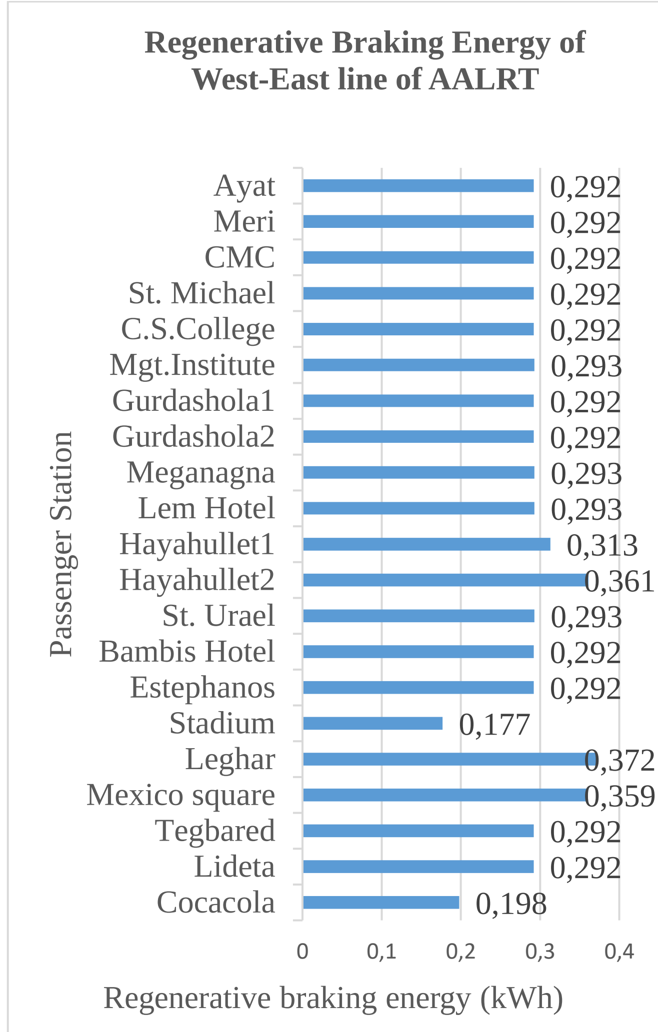
Similarly, the results found for the West-East line (Tolhailoch-Ayat) are presented in the following table:

Table 6: Energy consumption and regenerative braking energy results for west-east direction

Interstation	Energy consumption (kWh)	Passenger Station	Regenerative braking energy (kWh)	% of energy saving
Torhailoch-Cocacola	0.956	Cocacola	0.198	20.71
Cocacola-Lideta	0.949	Lideta	0.292	30.77
Lideta-Tegbared	-5.31	Tegbared	0.292	-5.5
Tegbared-Mexico Square	0.915	Mexico square	0.359	39.23
Mexico Square-Leghar	4.777	Leghar	0.372	7.79
Leghar-Stadium	3.572	Stadium	0.177	4.96
Stadium-Estephanos	-5.16	Estephanos	0.292	-5.65
Estephanos-Bambis Hotel	1.108	Bambis Hotel	0.292	26.35
Bambis Hotel-St-Urael	0.936	St. Urael	0.293	31.3
St.Urael-Hayahullet2	1.149	Hayahullet2	0.361	31.42
Hayahullet2-Hayahullet1	5.042	Hayahullet1	0.313	6.21
Hayahullet1-Lem Hotel	2.413	Lem Hotel	0.293	12.14
Lem Hotel-Meganagna	1.03	Meganagna	0.293	28.45
Meganagna-Gurdashola2	1.085	Gurdashola2	0.292	26.91
Gurdashola2-Gurdashola1	1.173	Gurdashola1	0.292	24.89
Gurdashla1-Mgt.Institute	1.097	Mgt.Institute	0.293	26.71
Mgt.Institute-C.S.College	0.99	C.S.College	0.292	29.49
C.S.College-St-Michael	1.034	St. Michael	0.292	28.24
St. Michael-CMC	1.021	CMC	0.292	28.6
CMC-Meri	1.197	Meri	0.292	24.39
Meri-Ayat	1.908	Ayat	0.292	15.3
	21.88		**6.164**	**28.18**

For better understanding, let take an example of Ayat-Meri track section from the east-west line results table. The energy consumption for of the section is 1.967 kWh and when the train is approaching Meri passenger station, the energy resulting from the application of regenerative brakes is 0.227 kWh. If this energy is recuperated and stored, it makes a saving of 14.08% of energy consumption. By applying the same principle for the whole track section, the overall saving is 26.32%.





Similarly, for the West-East line, the train on the track section Tolhailoch - Cocacola consumes 0.956 kWh and when it approaches Cocacola passenger station, the regenerative braking produces 0.198 kWh resulting in a saving of 20.71% of energy consumption for this particular track section. This interpretation is applied to other interstations and passenger stations. The overall saving for one way is 28.18%

As mentioned earlier, the research was carried on one line for both of its directions. If a train from East-West direction is ascending a gradient; in the reverse direction, the gradient will be descending. Logically, the energy consumption to overcome the gradient is different in both cases. On ascending gradient, the electric power is flowing from overhead catenary to the train and in this case the energy to overcome gradient is taken negative. On the other side, when a train is descending a gradient, the driver keeps on braking to meet the line speed requirement. The application of brakes produces electricity which flows from train to catenary and in this case the energy consumption is taken negative (because it flow in opposite direction to traction power). The effect of considering the gradient type is the sign of the cumulating energy consumed by the train. Cases arise when the energy consumption becomes negative; an indication that the portion of the track on which the train was moving is predominantly descending. Supported by an example, on East-West direction, track section Hayahulet1-Hayahulet2 has a train energy consumption of -0.092kWH; Hayahulet2-St.Urael, the train has consumed -3.792kWh. This means that the only energy consumption from the catenary is used to overcome the acceleration and friction whereas energy to overcome gradient is flowing from train to catenary (taken negative). Depending on the magnitude of negative and positive energy consumptions, the total energy can be either positive or negative. Similar observation can be applied to Wes-East direction, specifically on Lideta-Tegbared and Stadium-Estephanos interstations. The equation (18) was developed assuming that the train is moving an ascending gradient, which is not always the reality. If it was made to move over a descending gradient, the sign on the term of energy consumption to overcome gradient would be taken negative.

Conclusion

The results found in the development of this research article took into account parameters related to train dynamics and design, data specific to track alignment and weather conditions of the area. It was observed that the magnitude of regenerative energy was sensitive to the train running speed and the efficiencies of traction inverter and induction motor. The speed/time curve used is trapezoidal and is characterized by acceleration, free running and deceleration stages. In this research, the results presented in this paper were calculated by considering the current average speed at which the trains moves (24km/h) though the line was designed to accommodate trains running at maximum operational speed of 70km/h. Therefore, the more the running speed, the more the regenerative energy saving.

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