



**ADDIS ABABA UNIVERSITY**  
**SCHOOL OF MECHANICAL AND INDUSTRIAL**  
**INSTITUTE OF TECHNOLOGY**  
**(SMIE)**

**Analysis of Regenerative Braking System in the Reduction  
of Energy Consumption in Addis Ababa Light Rail Trains**

**A Thesis Submitted to the School of Graduate studies Addis Ababa  
University in partial fulfillment of the requirements for the Degree of  
Masters of Science in Rolling Stock Engineering**

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**September, 2014**

**ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES  
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ENGINEERING (SMIE)  
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## **ABSTRACT**

Regenerative braking system is a system which converts mechanical energy to electrical energy during braking action. It is an important system for the vehicle such as hybrid and electric train. This paper which mainly concerned about the potential of regenerative braking system on the reduction of energy consumption.

This study will start with literature review about the Regenerative Braking System (RBS). The important components used in RBS will be determined such as electric motor, motor controller and pantograph.

The methodology used to creating the simulation of the regenerative braking system at different positions of the track levels of stations of the East-west line of Addis Ababa LRT by using MATLAB software.

In general regenerative braking system generates a reusable energy about **3.7%** of the consumed energy of the system in the east-west line with in 22 stations and five of the stations are elevated. This energy can be generated in one tripe of the train movement from Ayat to Tor-hayloch.

**Keywords:** - Regenerative braking, Regenerative Energy and Simulation of Energy

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## Nomenclature

$E_k$	kinetic energy (KJ)
$v$	train speed or velocity (m/s)
$m$	mass of the vehicle (Kg)
$W_T$	total power energy consumption (KWH)
$T$	force in tones due to tractive effort (ton)
$d$	distance travelled at the speed range (Km)
$P_a$	power consumption by all auxiliaries
$\eta$	motor efficiency
$P_{out}$	output power (KW)
$P_{in}$	input power (KW)
$E_a$	total energy consumption for auxiliary equipment (KWh)
$t_a$	train operating time (sec)
$P_{am}$	electric power per locomotive (KW)
$n_m$	number of locomotive
$P_{at}$	electric power per trailer (Kw)
$n_t$	number of trailer
$B_T$	total braking force (KN)
$B_e$	electric braking force (KN)
$B_f$	friction braking force (KN)
$\eta_B$	regenerative system efficiency
$P_r$	electric power of regenerative braking (KW)

$F_a$	aerodynamic resistance
$\rho$	Air density ( $\text{kg/m}^3$ )
$C_D$	coefficient of aerodynamic resistance
$A_{fr}$	frontal area ( $\text{m}^2$ )
$V_{wind}$	wind speed (m/s)
$F_R$	rolling resistance (KN)
$C_R$	coefficient of rolling resistance
$M_{tot}$	total mass of train (kg)
$g$	acceleration of gravity ( $\text{m/s}^2$ )
$\alpha$	angle of the gradient
$F_{acc}$	acceleration resistance (KN)
$a$	acceleration ( $\text{m/s}^2$ )
$F_g$	gradient resistance (KN)
$F_B$	braking force (KN)
$T$	torque (Nm)
$r$	wheel radius (m)
$G$	gear ratio
$E$	total consumed energy (KJ)
$P_{regen}$	Regenerated power (KW)
$P_{Provided}$	Consumed power (KW)
RBS	regenerative braking system

## Definitions and explanations

Catenary	Cable over the track that supplies trains with electric power via the current collector (pantograph) on the train roof.
Degree of regeneration	Percentage of full regeneration since it is sometimes not possible for the train to regenerate all available power back to the catenary.
Pantograph	Device that is collecting electrical current and voltage from the overhead wiring (also known as catenary). Usually located on the roof of the train.
Regeneration	In the context of this study it is the percentage of the accumulated input energy regenerated to the catenary.
Regenerative braking	using the electric motors as generators, transforming the train's kinetic energy to electricity and, with the exception of losses, feed it back to the catenary.
Electric power	Electric energy
Energy consumption	energy utilization or energy usage. Energy cannot be consumed only utilized or converted to other form of energy.

# CHAPTER ONE

## 1 INTRODUCTION

### 1.1 Light rail transit (LRT)

A lightweight metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive right-of-way at street level. These vehicles are usually powered by overhead electrical wires, and offer a frequent, fast, reliable, comfortable and high quality service that is environmentally sustainable [37].

LRT is often identified by its right-of-way and vehicle weight and size. When compared with a regional railway or metro, the system is lighter in terms of actual system weight. However, when compared with modern low-floor trains, LRT is heavier because the vehicles are usually wider or there are two to three vehicles coupled together. The terms 'heavy' or 'light' do not solely refer to weight, but also to the flexibility of a system to deal with different types of right-of-way and to the ability to be integrated into a variety of urban streetscapes[40].

The flexibility in the definition of LRT alludes to its significant advantages. The ability to be operated as a traditional tram with a shared right-of-way in outer parts of the city and also as a tram on a separate railroad with segregated or exclusive right-of-way in the city Centre makes LRT one of the most flexible transit systems available. Because of the flexibility of LRT systems, they can be easily integrated with the existing streetscape. Designated LRT stations or stops can provide easy access, convenient stay and personal safety, something that is considered completely different when compared with underground systems. LRT is also designed to operate in a variety of environments. These can include, but are not limited to, on-street, highway medians, railroad right-of-way (operating or abandoned), and pedestrian malls, underground or aerial structures and even in the beds of unused canals. This characteristic is one that clearly distinguishes LRT from other types of rail modes. The design flexibility makes LRT one of the most readily adaptable, permanent systems and thus, is often less costly to build and operate than other fixed-railway nodes [37] [40].

## **1.2 Regenerative braking system**

Regenerative braking is used in vehicles (trains) that make use of electric motors, primarily fully electric vehicles (trains). One of the more interesting properties of an electric is that, when it's run in one direction it converts electrical energy in to mechanical energy that can be to perform work (such as turning the wheels of a train), but when the motor is run in the opposite direction, a properly designed motor becomes an electric generator, which converts mechanical energy in to electrical energy. This electrical energy can then fed in to the supply power or energy storage unit for the perspective trains. Once the motor has been reversed, the electric energy generated by the motor is fed back to wire supply (power supply) or to the sub-stations, where it can be used to accelerate the train. Sophisticated electronic circuitry is necessary to decide when the motor should reversed, while specialized electric circuits rout the electricity generated by the motor in to the train sub-stations or to the main power supply [14],[20].

Regenerative braking system is a technology that can be implemented with all the vehicles in order to improve its efficiency, saving power (energy) and low emission of **CO<sub>2</sub>** to the environment. This technology was first discovering by Toyota motors in 2004. The electric regenerative brakes used by the trains have a great potential in this area. However, in most trains today it cannot be used to the extent that might be desirable. They do not have the capability to brake fast enough to be used as the main service brake, especially not at higher speeds and in urgent braking cases, with short braking distance. The deceleration will be too low and the train will risk running late. There is simply a conflict where a more ecological and economic driving will result in longer travel times which will risk making the railway system less attractive for passengers. Also, the braking distance may be too long to suit the pre-warning distance in the signaling system. To solve this it would be necessary to make the electric regenerative brakes more efficient and practical both at higher speeds and for cases involving harder braking [21]&[24].

The objective of this research is to determine the benefits of regenerative braking system over the other braking. In this paper when the driver applies brake in the vehicle (train) to stop its motion a considerable kinetic energy is lost in the form of

---

heat which is created by the friction between wheel and rail. So regenerative braking system is very important to regain the generated electrical energy at the time of braking and stored in the sub- stations or it return to the main power supply wire. Regenerative braking a mechanism that reduces vehicle speed by converting some of its kinetic energy into a storable form of energy instead of dissipating it as heat as with a conventional brake. The captured energy is stored for future use or fed back into a power system for use by other vehicles. Electrical regenerative brakes in electric railway vehicles feed the generated electricity back into the power supply system or to the main grid line. Figure 1.1 shows that when a train is in braking it generates electrical energy and charges the generated energy to the energy storage unit and discharges the stored energy to the accelerating train. This process is called a direct charging and discharging of energy from the braking train to the accelerating train [23] [Wikipedia].

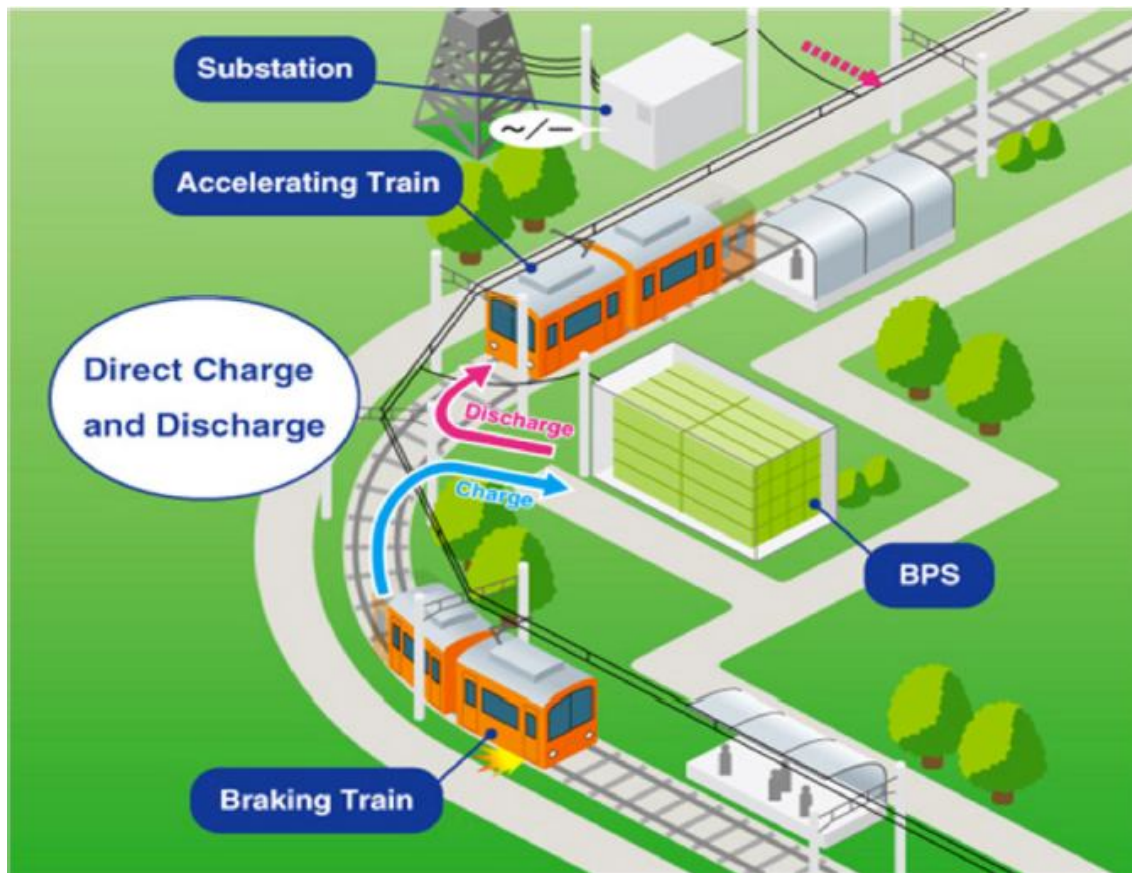


Fig1.1 Schematic for Regenerative Braking in Rail Vehicles.

### **1.3 Working principle of regenerative braking system**

All electric vehicles create power to the power supply or to the sub-stations of the energy storage unit through a process are known as regenerative braking. It is explained what regenerative braking is and how the process works in general terms, but many folks are interested in the deeper nuts and bolts of electricity generation. They understand that in all electric vehicles the word “regenerative” in terms of regenerative braking, means capturing the vehicle’s kinetic energy and turning it into electricity that regenerates the sub-stations as the vehicle is slowing down and/or stopping. In all electric trains the motor is the sole source of locomotive [2, 3, and 5].

During braking, the traction motor connections are altered to turn them into electrical generators. The motor fields are connected across the main traction generator (MG) and the motor armatures are connected across the load. The MG now excites the motor fields. The rolling locomotive or multiple unit wheels turn the motor armatures, and the motors act as generators, either sending the generated current through onboard resistors (dynamic braking) or back into the supply (regenerative braking). For a given direction of travel, current flow through the motor armatures during braking will be opposite to that during motoring. Therefore, the motor exerts torque in a direction that is opposite from the rolling direction. Braking effort is proportional to the product of the magnetic strength of the field windings, times that of the armature windings [Wikipedia, the free encyclopedia].

As the current from the power supply line is switched off by the driver instead of a current being applied to the motor to turn the rotors, the rotors are turned by the wheels due to inertia. As a result the rotors experience opposing torque as current is induced in the motor coils & this opposing torque slows or even stops the vehicle & the current induced in the system will be stored in the power saving devices [6].

The diagram below shows as the permanent magnet inside the motor rotates due to the moment created by the rotating wheels the coil inside them will be energized and electric current will be induced. Therefore the motor is now served as a generator.

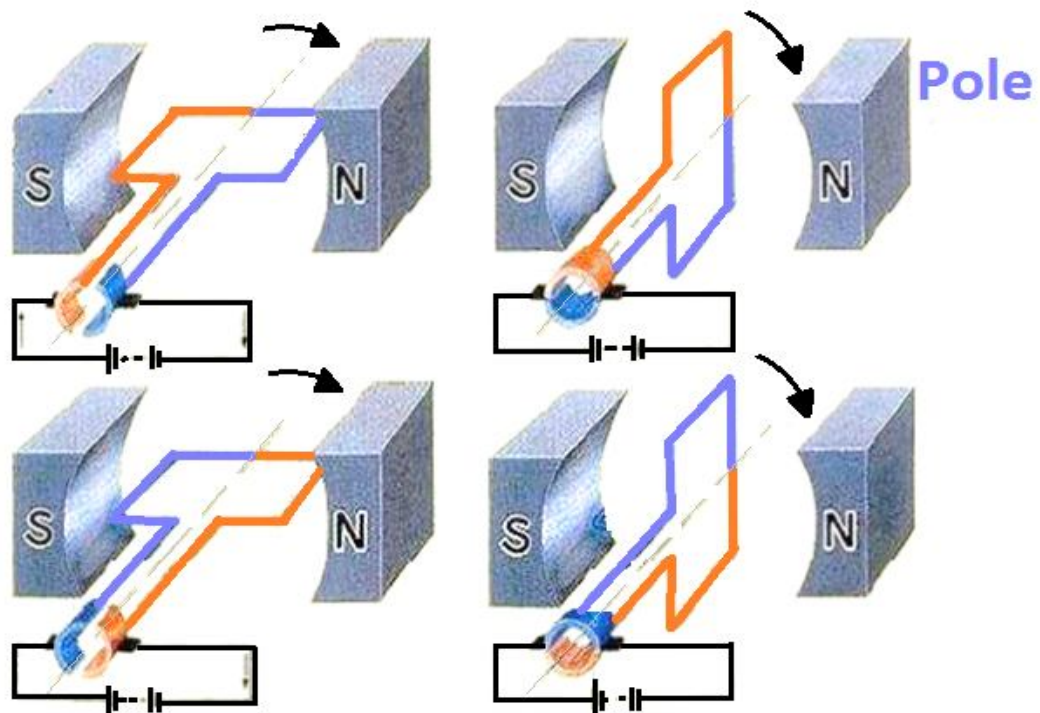


Fig.1.2 principle of generating electric current

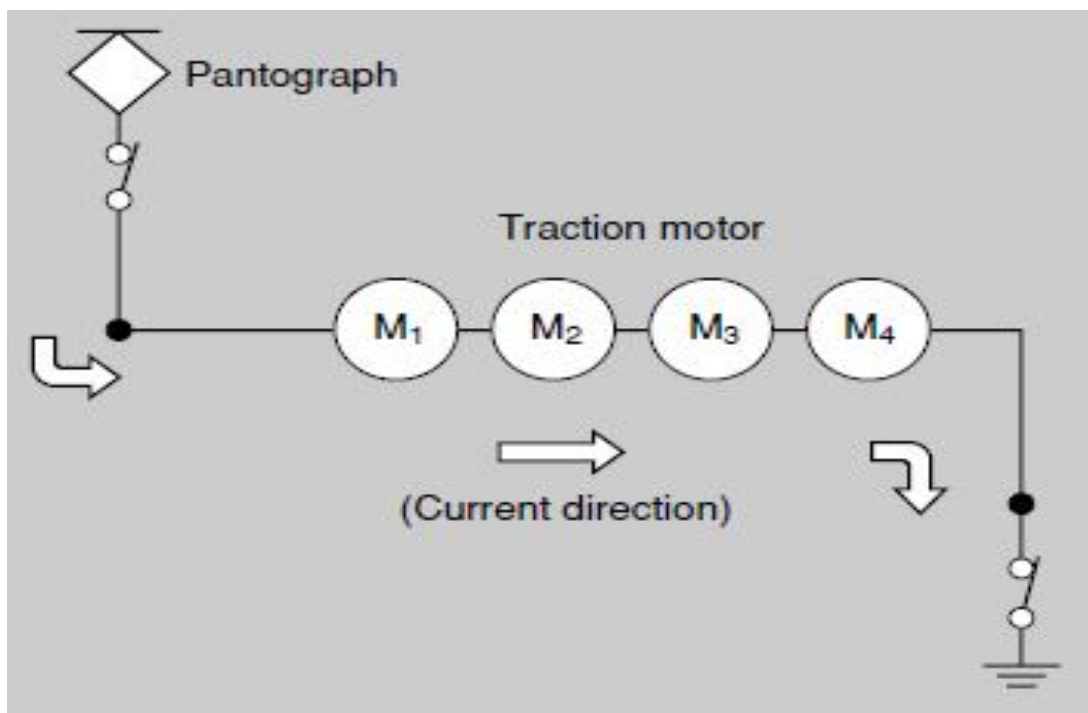


Fig1.3 electric traction [5]

Electric trains are powered by electric motors connected to electric supply line as shown in the figure 1.3. For a given direction of travel, current flow through the motor armatures during braking will be opposite to that during motoring as shown in the fig 1.4 [5].

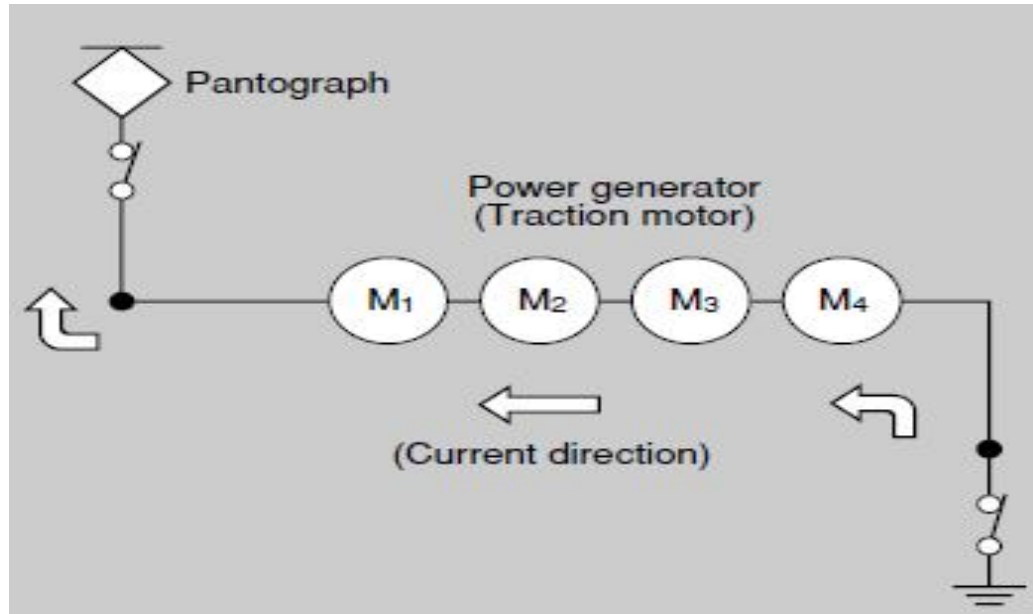


Fig1.4 electric regenerative[5]

Therefore, the motor exerts torque in a direction that is opposite from the rolling direction. That is when decrease or decelerate the train speed the driver disconnects the line between the power supply & electric motor, then the whole process goes into reverse. That is instead of a current being applied to the motor to turn the rotors and then the wheels, the rotors are turned by the wheels due to inertia. As a result the rotors experience opposing torque as current is induced in the motor coils & this opposing torque slows or even stops the train.

From the above paragraph since the rotors of the motor are turned by the rotating wheels so the motors are working like generators and start producing electricity instead of consuming or dissipate to the environment. Power flows back from these motor-generators to the power supply line to use by the other powering train on that line or save on the capacitors & power supply sub-station as shown in figure 1.5. In practice, regenerative brakes take time to slow trains down, so most trains that use

## Analysis of regenerative braking system in the reduction of energy consumption in A.A LRT

them also have ordinary (friction) brakes working alongside (that's also a good idea in case the regenerative brakes fail). That's one reason why regenerative brakes don't save 100 percent of our braking energy [5].

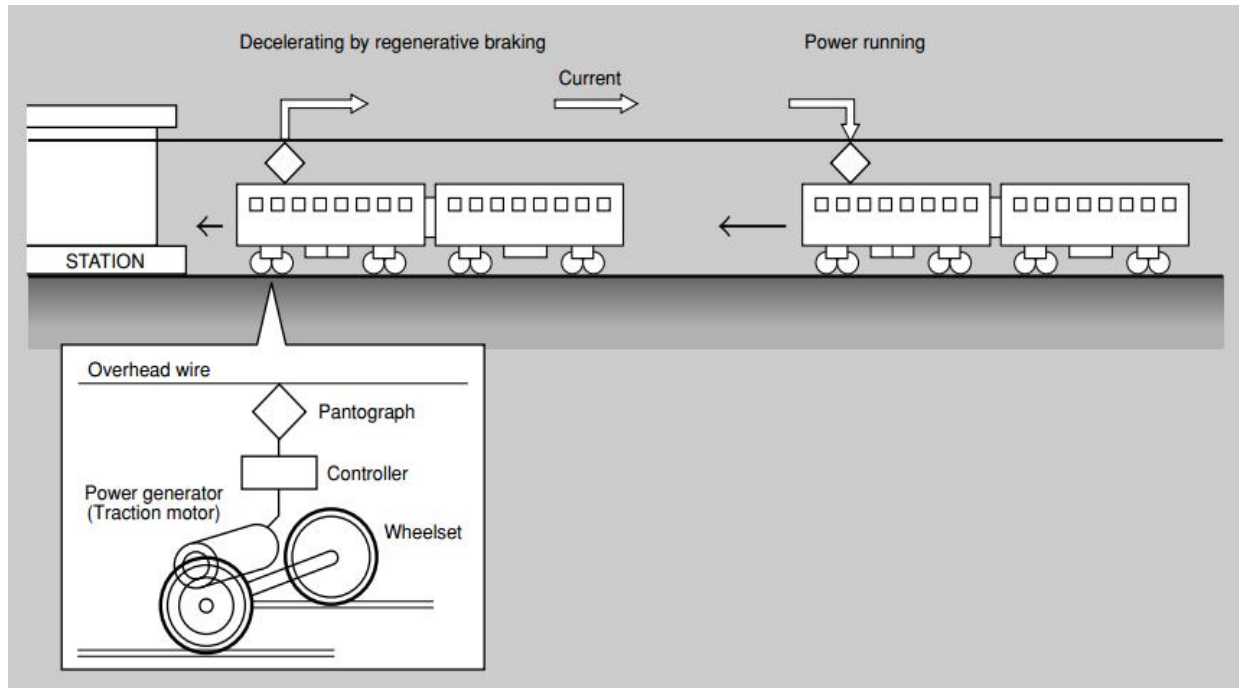


Fig1.5 recycling regenerated electric power

Returns to the overhead wire but not dissipated to the environment in the form of heat.

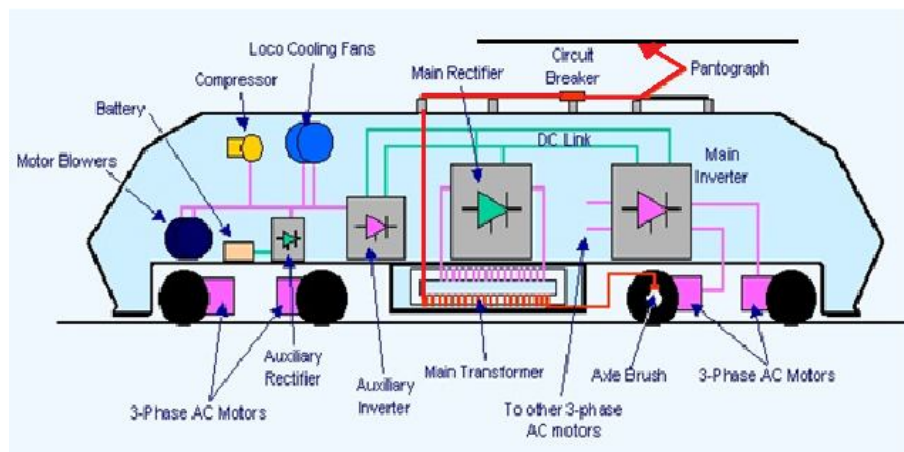


Fig 1.6 the energy generated by the regenerative braking system returns to the main power supply or to the main grid through the pantograph [Wikipedia].

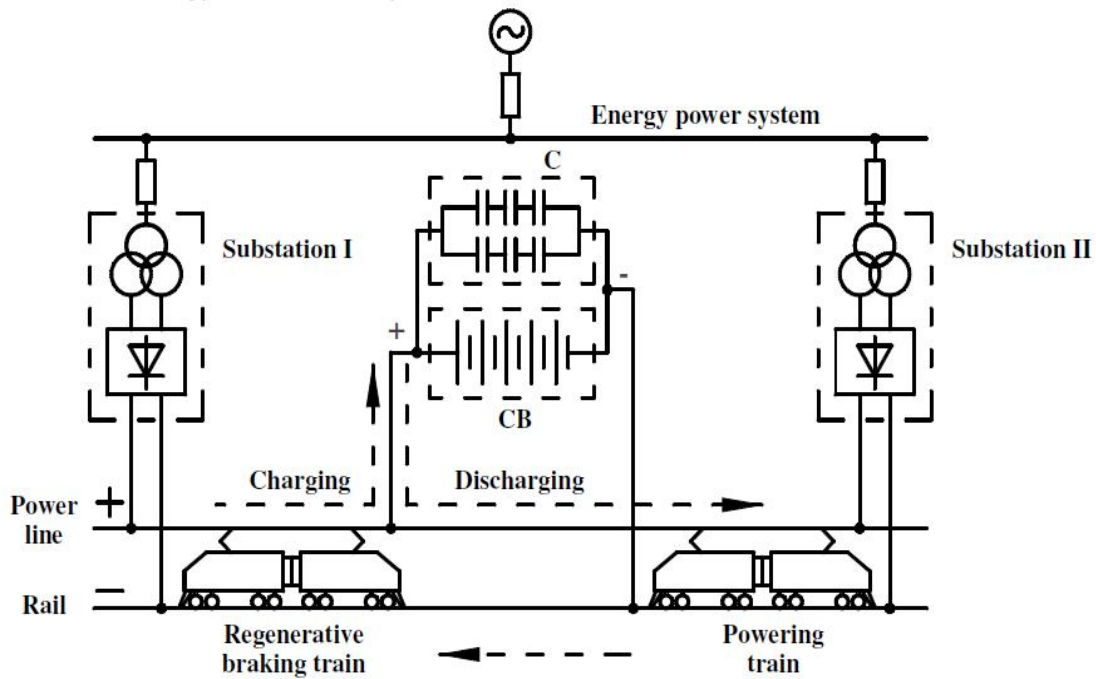


Fig1.7 regenerative braking [Wikipedia]

From figure 1.7 the braking train generates energy by regenerative braking system and charges to the substation energy storage and discharges the regenerated energy from the substation to the powering or accelerating train.

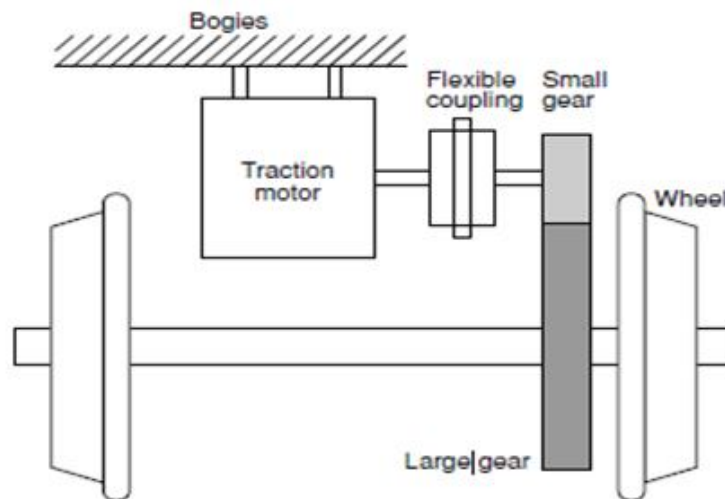


Fig1.8 Transmission of force (power) from the power source to the wheel sets [5].

#### **1.4 Regenerative braking slowing the vehicle and generating electricity**

This is really what the regenerative mode is all about. With the electronic throttle closed and the vehicle still moving, all of its kinetic energy can be captured to both slow the vehicle motion and recharging its sub-station power supply. As the onboard computer signals the battery to stop sending electricity via the controller relay and start receiving the electricity through a charge controller, the motor/generator simultaneously stops receiving electricity for powering the vehicle and starts sending current back to the sub-stations (power supply).

Remember electromagnetism and motor/generator action: when a motor/generator is supplied with electricity it makes mechanical power, when it's supplied with mechanical power it makes electricity. But how does generating electricity slow the vehicle? The armature of the motor/generator is slowed by the force of inducing current in the windings as it passes over the opposing poles in the magnets at the stator (it's constantly battling the push/pull of the opposing polarities). This magnetic friction that slowly snaps the vehicle's kinetic energy and helps to brake it.

#### **1.5 Advantages of regenerative braking systems**

- Energy saving potential

Feeder routes to iron ore or coal mines where loaded train moves down the hill provide substantial savings potential (up to 200%) through regenerative braking as train moving up the hill are usually empty.

- Reduced greenhouse gas (GHG) emission

In spite of limitations, regenerative braking can immensely contribute to overall energy efficiency of Railway systems. With demand side management, it helps to improve overall energy intensity and bridge the gap between demand and supply. With the reduction in energy requirement, GHG emission gets reduced which helps developed nations contain emission in line with 'Kyoto protocol' and developing one to earn carbon credits thus generating additional revenue.

In view of ever increasing electricity demand, world will be immensely benefited by green energy through regenerative braking. It would effectively lower cost of transport in general and railway transport in particular and help it attract more traffic from inefficient modes such as road. This would enable conservation of fossils; reduce global warming and extreme events caused by climate change.

- Brake wear savings

While growing environmental concerns have resulted in the promotion of energy recovery as the principal benefit of regenerative braking, demand on friction brakes gets reduced significantly, in addition to operational advantages due to reduced maintenance time and costs. Incidentally, brake pad replacement and brake gear maintenance is one of the biggest constituent of maintenance cost in friction based braking.

On a three-phase drive trains operating on the 25 kV AC on commuter services characterized by frequent stops, disc pad life of 18 months reduce to just 18 days when the electric braking is switched off. With advent of 'Pure electric braking' it may be possible to eliminate brake wear.

- Extra peak power

In addition to saving energy, storage units can reduce line voltage fluctuations and provide peak power when it is most needed. This can be used to improve the acceleration of trains during peak periods, especially in situations where traffic has grown and the existing supply can barely cope up. Alternatively, where a line is being extended, it is possible to space the substations further apart and locate energy storage units halfway between them, with a view to installing rectifiers at these locations later on when traffic built up.

On the hybrid trains, battery power alone accelerates from a standstill [1]. With adequate peak power available, energy management system blends power from the vehicle's diesel engine as the speed reaches 30 km/h. Thus energy management system ensures the engine to run at its most efficient speed, with excess power not required for traction being diverted to the charge the battery. The energy

management system automatically draws on the battery when more power is needed, either on an adverse gradient or for further acceleration.

- Improved fuel economy – dependent on duty cycle, powertrain design, control strategy and the efficiency of the individual components.
- Emissions reduction – engine emissions reduced by engine decoupling, reducing total engine revolutions and total time of engine operation (engine on/off strategy).
- Improved performance.
- Reduction in engine wear – engine on/off strategy.
- Reduction in brake wear -reducing cost of replacement brake linings, cost of labor to install them and vehicle down time.
- Smaller accessories – hybrid powertrain offers potential for eliminating (electric starter) or downsizing (fuel tank) some accessories, thus partially offsetting the increased vehicle weight and cost due to the hybrid hardware additions.
- Operating range is comparable with conventional vehicles – a problem not yet overcome by electric vehicles.

## **1.6 Disadvantages of regenerative braking systems**

- Added weight/bulk – extra components can increase weight increasing fuel consumption, offset by smaller engine operating at its best efficiency.
- Complexity – depends on control necessary for operation of regenerative braking system.
- Cost – of components, engineering, manufacturing and installation. Mass production would bring costs down to a more reasonable level.
- Noise – dependent on system.
- Safety – Primary concern with any energy storage unit of high energy density. There must be very little chance of dangerous failure during normal vehicle operation. Passengers must be protected from risk that may be caused by the failure of the hybrid system.
- Added maintenance requirement – dependent on complexity of design.

## **1.7 Components of regenerative braking system**

There are four elements required which are necessary for the working of regenerative braking system, these are [38]:

- Energy Storage Unit (ESU)
- Continuously Variable Transmission (CVT)
- Controller
- Regenerative Brake Controllers

### **1.7.1 Energy Storage Unit (ESU):**

The ESU performs two primary functions

- To recover & store braking energy
- To absorb excess engine energy during light load operation

The selection criteria for effective energy storage include:

- I. High specific energy storage capacity
- II. High energy transfer rate
- III. Small space requirement

### **1.7.2 Continuously Variable Transmissions (CVT):**

The energy storage unit requires a transmission that can handle torque and speed demands in a steeples manner and smoothly control energy flow to and from the vehicle wheels.

### **1.7.3 Controllers**

An “ON-OFF” engine control system is used. That means that the engine is “ON” until the energy storage unit has been reached the desired charge capacity and then is decoupled and stopped until the energy storage unit charge fall below its minimum requirement.

### **1.7.4 Regenerative Brake Controllers**

Brake controllers are electronic devices that can control brakes remotely, deciding when braking begins ends, and how quickly the brakes need to be applied. During the braking operation, the brake controller directs the electricity produced by the motor into the batteries or capacitors. It makes sure that an optimal amount of power is received by the batteries, but also ensures that the inflow of electricity isn't more than the batteries can handle [38].

In the regenerative braking system, the braking controller is the heart of the system because it controls the overall process of the motor [38]. The functions of the brake controller are monitor the speed of the wheel, calculate the torque, rotational force and generated electricity to be fed back into the energy storage system. During the braking operation, the brake controller directs the electricity produced by the motor into the batteries or capacitors.

The most important function of the brake controller, however, may be deciding whether the motor is currently capable of handling the force necessary for stopping the car [38]. If it isn't, the brake controller turns the job over to the friction brakes. In vehicles that use these types of brakes, as much as any other piece of electronics on board a hybrid or electric car, the brake controller makes the entire regenerative braking process possible.

## **1.8 Objective of the research**

### **1.8.1 Major Objective**

The major objective of this research is to show the potential of the regenerative braking system in the reduction of energy consumption and implementing of the technology from developed country to our home country since railway is a new technology to our country.

### **1.8.2 Specific Objectives**

- To calculate the resistance forces & clearly understand the working principle and to define the function of all the components used in regenerative braking system.
- To calculate the generated energy during regenerative braking system from Ayat to Tor-hiloch of the braking stations.
- Make a comparison of the energy consumption between different braking types.
- To simulate the system using MATLAB software at different braking positions.

### **1.9 Statement of the problem**

In train (railway) braking system the main problem is the wastage of energy. However, regenerative braking system is the one which is efficient in energy storage or capturing energy instead of dissipating energy and it is used to produce green environmental condition. Therefore, saving energy of the vehicles during braking time and produces low environmental pollution will be the first priority to the advantage of regenerative braking system. Depending on the braking position of the rails, the regenerative energy produced during the braking time is different. Due to this, there are different questions to be answered, like:

- What is the potential of regenerative braking system in the reduction of energy?
- How it is generated what are the advantages of this over the other braking types?
- How to simulate the system at different positions of the track level?

Such and other kinds of questions divert the interest of most researchers to direct their attentions to the area of regenerative braking systems of trains, especially to the role of regenerative braking system in the reduction of energy consumption problems.

### **1.10 Scope and limitations**

The scope of this study is to calculate the generated energy from Ayat to Tor-hailoch of the east-west line of Addis Ababa LRT of the stations. In this line there are 22 train stations. This calculated generated energy is only in one tripe of the train movement from Ayat to Tor-hailoch that means it does not include the whole day of the train working hours. But to activate this paper some limitations can be happen because of new type of transport to our country like

- Lack of real data's to compare with this simulated results
- Lack of experienced person with this field
- Enough Resources are not available

### **1.11 Methodology**

The methodology that will be applied by the study has been chosen in order to acquire information and deduce conclusions about the development and the role of regenerative braking system simulation on that field of specialization.

#### **1.11.1 Data collection / research materials**

For the purpose of this research, and in order to achieve the objectives listed in the sub topic of specific objective of the research the data will be collected through secondary data collection method:

- By browsing different published papers and journals
- By browsing different regenerative braking systems related books and
- By visiting to the Addis Ababa LRT manufacturing work shop found on Leghar if their braking system is regenerative. and
- From the information that we have learned in class i.e. lecture notes

#### **1.11.2 Research procedures / analysis plan/ methods**

In this sub topic the overall procedure of the research work is stated as clear as possible as in the following manner sequentially having in minds that specific question to answer.

- Data collection as stated in the data collection sub topic
- Understanding clearly the existing working principle of railway regenerative braking system.
- Reading other recent related research works that have been done before by other researchers.
- Analyzing appropriate simulating tools to solve the complexity stated in the statement of the problem sub topic. like
  - MATLAB-Simulink: for modeling and simulating purpose
  - CATIA: to simply show the complete schematic diagram of the train
- Understanding these simulating tools in-depth to perform the stated tasks under each tool.
- After understanding these simulating tools performing the tasks under them.
  - Modeling the system with appropriate software and then
  - Simulating the system by feeding some known parameters to MATLAB Simulink
- Observing the effect or the result of simulation at different braking positions
- Writing conclusions and
- Writing recommendations or future development to investigate further more by other researchers later on.
- At this stage brief summary or abstract of the research is written after completing the research work.
- Acknowledge for the materials used to prepare the research or for any one who helps to facilitate my work.
- Finally edit the overall paper to submit.

## **1.12 Comparison of regenerative braking system with dynamic braking system and convectional brakes**

Dynamic (rheostat) brakes, unlike regenerative brakes, dissipate the generated electric energy as heat by passing the current through large banks of variable resistors. The electrical characteristics of modern, rectifier electric locomotives and multiple-unit cars do not permit the return of power to the distribution system. Such rolling stock is equipped for simple dynamic braking.

Convectional braking systems are systems which dissipates the electrical energy in the form of heat instead of return to the main power grid. But when we use regenerative braking system the energy generated during the braking of the trains either powering to the accelerating train if not returns to the main power supply.

## **CHAPTER TWO**

### **2 LITERATURE REVIEW**

#### **2.1 Introduction**

This is one of the portions of the paper that reviews the previous related works which are basic guide for the introduction of the current work. Some of them may have a direct relation with this work whereas the others may have indirect relations. But the main principles they have used and the major methodologies and approaches they precede will be selected generally and applied for the formulation of specific model and analysis.

Generally there are many journals, conference papers, proceedings, design works and books related to the railway engineering, railway vehicle dynamics and particularly regenerative braking, storing energy, less environmental pollution etc. but to save time and to manage the paper work the review of literatures mainly considers more related works to the paper. This intensifies the deep analysis of the previous related works and selection of appropriate conditions, approaches and methodologies for the successful accomplishment of the paper.

#### **2.2 Electric braking**

Electrical braking is needed in many applications and used instead of mechanical braking. The advantage of electrical braking is virtually no wear and tear is experienced. Electrical braking may be seen in modern cars, traction motor control, train services, alternators and in automotive industries [14].

The main theory of electrical braking is to use a DC (direct current) injection to provide magneto motive resistance to the running rotor [14]. If a DC flux is provided to the rotor and rotor cuts through it, it eventually slows down because DC injection effectively produces an electrical (or more accurately, magnetic) resistance as described below. During braking it is obvious that we will remove AC supply from the stator. Rotor will be rotating due to its inertia. The larger the angular momentum, the larger time it takes to stop rotation. Now, after removing the AC supply from the

stator, if we apply a DC voltage to the stator, a large DC current will be induced in the rotor. This induction happens because the rotor still rotates in a DC field. This large DC current will heat up the rotor coil (resistance of rotor coil, truly) and energy is dissipated in the form of heat. So, we see, applying a DC voltage to the stator makes a good method of braking. This method is used in dynamic braking. In regenerative braking, rotors kinetic energy is converted to electrical energy and fed back to main supply or other loads.

### 2.3 Regenerative brake system

A regenerative brake system (RBS) converts the kinetic energy, caused by the deceleration of the vehicle body, into another type of energy (e.g. Electric, rotational kinetic) instead of dissipating it as heat through friction brakes [11].

Madan Singh (January 2013) [1] said that when a motor turns faster than the commanded speed as set by its drive, the motor in effect acts as a generator. During regenerative braking vehicles' electric motor is reconnected as a generator and its output is connected to an electrical load, which provides the braking effort see the figure 2.1. The current thus generated could be employed regenerative braking [1].

It has been shown that the driving range of electric vehicles (EV) can be increased by 8%-10% if using a RBS so that for pure inner-city driving the driving range is estimated to be extended by 14% to 40%. [5, 11, 12].

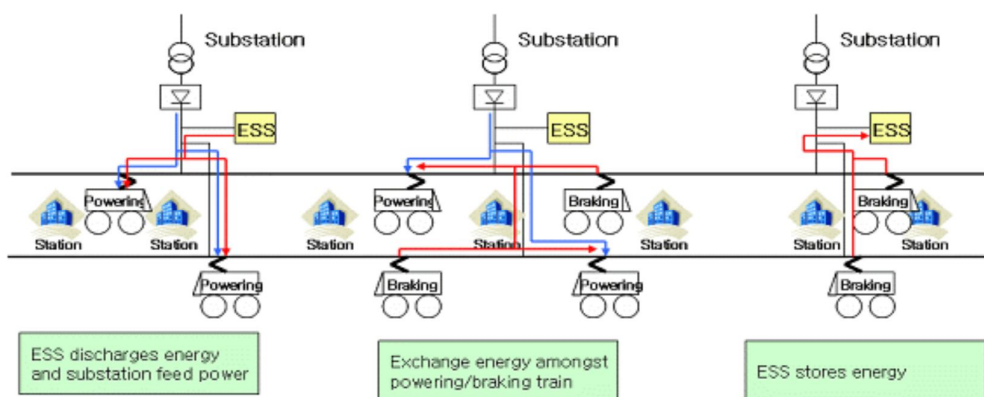


Fig 2.1:- working principle of regenerative brakes in electric trains [41].

Regenerative Braking Systems (RBS) provide an efficient method to assist hybrid electric buses achieve better fuel economy while lowering exhaust emissions [2]. Deceleration of a vehicle with a traditional braking system requires that the kinetic and potential energy of the vehicle be converted into thermal energy or heat through the action of friction. Studies show that in urban driving about one third to one half of the energy required for operation of a vehicle is consumed in braking [3].

In regenerative braking system the electricity generated by the braking is not consumed by the main resistor. Instead it is transmitted to the overhead wire. The flow of this electricity is controlled by a controller under the pantograph that opens and closes with split-second timing. The regenerative brake system is even more economical because the electricity generated from the train's kinetic energy is transmitted to the overhead wire, and become available to power other rolling stock as stated in the figure 2.1 [5].

In order to understand the concept of a RBS and its impact on vehicle energy performance, a simple example is presented: Consider a 300 kg (~ 661lbs) vehicle moving at an initial speed of 72 km/h(~ 45mph).Now, on braking the vehicle to a speed of 32 km/h(~ 20 mph) the amount of energy spent is around 47.8 kJ using the equation given below, [5]

$$E_k = \frac{1}{2}mv^2 \quad \dots\dots\dots (2.1)$$

Where  $E_k$ : Kinetic Energy of the vehicle; m: Mass of the vehicle and v: Velocity of the vehicle. Ideally, this is the amount of energy available for capturing at each instance of braking. If regenerative braking was used on such a vehicle it would be able to capture this amount of energy and reuse this same energy which would otherwise have been lost in the form of heat, sound etc. Now, even if we suppose that the efficiency of the brake is 25% of this, there would still be an amount of 11.85 kJ (25% of 47.8kJ) of energy available at each braking instance, which shows the amount of energy that can be utilized for beneficial causes. This energy is roughly, neglecting all losses, enough to accelerate a car from 0 km/h to around 32 km/h (using equation (2.1)). This stored energy using RBS can be reutilized for different purposes, either to help improve performance or

fuel efficiency, in either case assisting in 'Load Sharing'. 'Load sharing' or 'Load averaging' can simply be defined as sharing of the power requirements of the vehicle between a primary and secondary propulsion/energy storage unit [6, 7].

A recent electric train uses electric brakes which converts mechanical to electric energies and sends the regenerated energies to other trains on the same route. It is called regenerative brakes [12]. Conventional mechanical brakes using frictional force have to be used with the regenerated brake at high speed. Since regenerative braking force is less than simultaneous service braking force at high speed. The response of mechanical brakes is much slower than electric brakes. The source of mechanical braking force is the friction which strongly depends on environment. It worsens ride quality for a change of frictional force. Furthermore, mechanical brakes cost a lot of time and money for maintenance. In this paper, the authors propose pure electric brakes [8] [9] [10] which mean ordinary brakes by only the regenerative brakes without any mechanical brakes at high speed. The advantage of the proposed braking concept is evaluated under the assumption of regenerative substations in a modern DC-electrification system. In addition, the authors evaluate the effect of increasing sending voltage at substation.

A regenerative brake is a mechanism that reduces vehicle speed by converting some of its kinetic energy into another useful form of energy [14]. This captured energy is then stored for future use or fed back into a power system for use by other vehicles. For example, electrical regenerative brakes in electric railway vehicles feed the generated electricity back into the supply system. In battery electric and hybrid electric vehicles, the energy is stored in a battery or bank of capacitors for later use. Other forms of energy storage which may be used include compressed air and flywheels. Regenerative braking should not be confused with dynamic braking, which dissipates the electrical energy as heat and thus is less energy efficient.

Traditional friction-based braking is still used with electrical regenerative braking for the following reasons [14]:

- The regenerative braking effect rapidly reduces at lower speeds; therefore the friction brake is still required in order to bring the vehicle to a complete halt.

- The friction brake is a necessary back-up in the event of failure of the regenerative brake.
- The amount of electrical energy capable of dissipation is limited by either the capacity of the supply system to absorb this energy or on the state of charge of the battery or capacitors.
- Under emergency braking it is desirable that the braking force exerted by the maximum allowed by the friction between the wheels and the surface without slipping, over the entire speed range from the vehicle's maximum speed down to zero.

For these reasons there is typically the need to control the regenerative braking and match the friction and regenerative braking to produce the desired total braking output [21 22].

Regenerative braking is also known as feedback braking. The braking of traditional automotive is to convert the vehicle's energy by the friction of the brake into unrecovered heat energy and then dissipate into the environment. The motor for a hybrid electric vehicle can be converted into the generator running state under certain conditions [6, 12, and 23].

## **2.4 Models for estimating energy consumption of electric trains**

Energy resources are quite scarce in many countries. One of the most important energy sources is electricity. Railway operators are heavy users of electricity resource with the increasing use of electric trains [39].

To implement energy cost reduction programs and study economical train operation strategies, a precise energy model for estimating train electricity consumption is required. Estimating the train energy consumption it requires detailed train running states outputted from train performance simulator (TPS) or speed profile generator, including train velocity, running time, corresponding tractive effort and braking force. The model employs numerical integration method to estimate the overall energy consumption of a single train operation [39].

Energy saving is always an issue that draws much attention from rail authority. Previous researches and demonstrations have confirmed that energy consumption

can be reduced through appropriate operation strategies [39]. In Paul's study (Paul, 1999), 5% extension on run time can produce energy savings up to 20% on a suburban system. Tomii (2003) develops a model which estimates power consumption at high precision with 2% deviation from real situation. It is found that reducing maximum speed and tactfully performing coasting can reduce energy consumption about 7% ~ 20%.

TMG International Consultants proposes an optimal train performance simulator which gains a 13.7% reduction in traction energy consumption by the timetable optimization process without increase in running time. The simulator shows a reduction in traction energy consumption from 576 kWh per unit to 497 kWh per unit as a result of the timetable optimization process.

In order to study energy saving problems, an accurate energy estimation model is necessary. As early as in 1985, Majumdar proposes four main stages of train movement including:-

- acceleration,
- balancing,
- coasting, and
- Deceleration.

The Equation below is the summary of his ideas for calculating energy consumption. It shows that the total energy consumed in train operations is the product of force and displacement. Coefficients in the equation are energy efficiency and factors for converting the work done in ton-km into electric power units. This approach is an actual measurement and thus, contributes less function in energy saving [39].

$$W_T = \left[ \frac{2.725}{0.814} (\sum T_A \times d_A + \sum T_B \times d_B) \right] + \left[ \frac{P_a}{0.964} \times \left( \frac{\sum d_c}{v_c} + \frac{\sum d_D}{v_D} \right) \right] \dots \dots \dots (2.2)$$

Where  $W_T$  =total power energy consumption (kWh)

$T$  =force in tones due to tractive effort (ton)

$d$  =distance traveled in km at that speed range (km)

$P_a$  =power consumption by all auxiliaries (kWh)

A, B, C, D = Acceleration, Balancing, Coasting and Deceleration stage, respectively

Goodman (1987) develops single train and multi train simulation programs. The voltage received by a train will vary with position and the simultaneous action of other trains in multi train model, while it remains a constant in single train model. This is the main difference between two models in estimating energy consumption. Goodman considers detailed factors in his model, including substation, feeder cable and volt-drop, etc.

Recently, different researchers (Caputo in 2000) develop a model that considers not only power supply parameters, but also energy storage devices, such as accumulator, flywheels or capacitors. The expected benefits of the energy storage devices are the reduction in energy consumption as well as line peak loads. This becomes a new trend in saving electric energy for train operations.

Estimation of energy consumption can be categorized mainly into electric-power approach and kinematics approach. Generally, the electric-power method calculates electric energy that is directly imported into the train. The kinematics method estimate energy consumption via kinetic energy and efficiency factor. The two models are explained more detailed in the following subsections.

### 2.4.1 Electric-Power Based Model

This model was proposed by Wardrop in 1989. The basic calculation, as shown in the equation 2.3, requires line voltage, current and motor combination code, etc. The k value is the number of parallel motor circuits. According to the equation 2.3 this method contains an assumption that energy consumption has a linear relationship with the proportion between actual traction and maximum traction.

$$E_m = \int \frac{1}{1000 \times 3600} \times V I_m \times k \times r_T dt = \frac{1}{3.6 \times 10^6} \times k \times V \int I_m \times r_T dt \dots\dots\dots (2.3)$$

Where  $E_m$  =main power energy consumption (kWh)  
 $V$  =voltage (V)  
 $I_m$  =motor current (A)

k =motor combination code,  $k \geq 1$

$r_T = \frac{T_{actual}}{T_{max}}$ , the proportion between actual traction  $T_{actual}$  and maximum traction

$T_{max}$  ,  $0 \leq r_T \leq 1$

t =operation time (s)

### 2.4.2 Kinematics Based Model

As shown in the figure 2.2, after electric power inputs to rolling stocks, it will go through converter, motor, and mechanic devices to output traction power for train movements [39]. The entire procedure involves more or less energy loss. The motor efficiency is defines as the division of output power over the input power. In equation (2.4), motor efficiency, train traction, and speed are inputs for estimating input power. Energy consumption is estimated via equation (2.5).

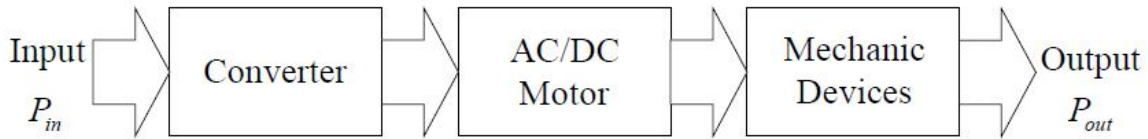


Figure 2.2 Energy Consumption Sketch Map

$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.27 \times T \times V}{P_{in}} \dots \dots \dots (2.4)$$

$$E_m = \int P_{in} dt \dots \dots \dots (2.5)$$

- Where
- $\eta$ = motor efficiency,  $0 < \eta < 1$
  - $P_{out}$  =output power (Kw)
  - $P_{in}$  =input power (Kw)
  - T=tractive effort (KN)
  - V=train velocity (km/h)

Different researchers develop Energy Management Model and Train Operations Model which use above approach. Piotr (2001) presents a model on MATLAB environment. His study also utilizes kinematics based model. In addition, special attention is given to wheel slippage. Coefficients measured from real data are considered in his study to develop a customized model for SJ RC4 locomotive.

## **2.5 Simulation model**

As described in the previous section, the computation of energy consumption requires the integration of input power over time, no matter which model is applied [39]. Since the power does not have specific function form, the integration is usually solved numerically. In train simulation programs, the estimation of energy consumption is usually based on train movement module. In order to obtain the parameters for calculating energy consumption at every time step, a train dynamic model is required.

According to JyhCherng JONG & En-Fu CHANG (2005) [39] research scientists a complete energy estimation model for electric trains includes at least three parts, i.e.

- The energy used by the traction motors,
- The energy consumption of auxiliary equipment's, and
- The energy produced by regenerative braking.

These three modules are introduced in the following sections:

### **2.5.1 Energy Model for Traction Motors**

The energy consumed by traction motors is utilized to produce sufficient tractive effort for train movements [39]. It is the majority of total energy consumption of electric trains. In the proposed model, the kinematics based approach is selected to estimate energy consumption. The reason is that the input data of electric-power based model implies the concept of motor efficiency. Through suitable transformation, the input of electric-power model can be converted into a single efficiency curve. Section 3.4 will explain the mechanism in more detailed.

According to Equation (2.4), (2.5), energy consumption is calculated from train traction, speed, and motor efficiency at every time step. These variables are obtained from train performance simulator or speed profile generator except motor efficiency. Usually, motor efficiency is a function of tractive effort and velocity as shown in equation (2.6). After twice interpolations, efficiency value for a specific traction and velocity can be acquired. Whenever the tractive effort or velocity cannot

be covered by the curves, boundary value is adopted instead of extrapolation to avoid unreasonable efficiency.

$$\eta = f(T, v) \dots \dots \dots (2.6)$$

### 2.5.2 Energy Model for Auxiliary Equipment's

Auxiliary equipment's include lighting, air conditioning, etc. In general, their energy consumption rate is considered as a constant. Assume that auxiliary equipment's work all the time in the simulation. Then the power consumption can be calculated by

$$E_a = \frac{P_a \times t_a}{3600} = \frac{(P_{am} \times n_m + P_{at} \times n_t) \times t_a}{3600} \dots \dots \dots (2.7)$$

Where  $E_a$  =total energy consumption for auxiliary equipment (kWh)

$P_a$  =total electric power for auxiliary equipment (kW)

$t_a$  =train operating time (sec)

$P_{am}$  =electric power per locomotive car (kW)

$n_m$  =number of locomotive cars.

$P_{at}$  =electric power per trailer cars (kW)

$n_t$  =number of trailer car.

### 2.5.3 Energy Model for Regenerative Braking

Modern electric trains are usually equipped with regenerative braking. During braking period, electric power is generated from kinetic energy of the train. Note that the braking force of the train is composed of friction braking force and motor braking force. Only the latter can be used to produce electricity. Thus, equation (2.8) must be applied to determine the electric braking force first. Then the product of the motor braking force, velocity and regenerative efficiency yields the electric power produced by the regenerative braking, as expressed in equation (2.9).

$$B_T = B_e + B_f \dots \dots \dots (2.8)$$

$$P_r = (1/3.6) \times B_e \times v \times \eta_B \dots \dots \dots (2.9)$$

Where  $B_T$  =total braking force (KN)  
 $B_e$  = electrical (regenerative) braking force (KN)  
 $B_f$  = friction braking force (KN)  
 $V$  = speed of the train (m/s)  
 $\eta_B$  = regenerative system efficiency  
 $P_r$  =electric power of regenerative braking (kW)

The logic behind the model is similar to the energy model for traction motors. However, this model is only optional since not all electric trains equipped with regenerative braking. Moreover, the power energy produced by regenerative braking is not utilized by the train itself unless it is equipped with energy storage devices, like accumulator or capacitors.

On the other hand Mikael Sjöholm (2011) from Royal Institute of Technology (KTH) preparing research and development in the benefits of regenerative brakes for new high-speed trains in Sweden. The purpose of his study is to investigate the effects of regenerative braking and eco driving with regard to energy consumption and wear of the mechanical brakes. He states that the electric regenerative brakes can thus be used as normal service brake with minimum time loss.

He performs the consumed energy and the generated energy using a simulation program by Simulation of Train Energy Consumption (STEC) created in the Microsoft Excel, energy consumption for different cases of high-speed train operations is procured. Simulations include both “normal driving techniques” and “eco driving”. The driving styles were decided through interviews with train drivers and experts on energy optimized driving systems.

His simulation results shows that more powerful drive systems reduce both energy consumption and travel time by permitting higher acceleration and energy regeneration while braking.

Finally he concludes that Eco driving techniques can help to further reduce the energy consumption and mechanical brake wear than normal driving techniques. From the simulation results of the train the consumed energy is reduced about 30%.

During eco driving style the regenerated energy is more efficient than the normal driving style. In this driving style the generated energy in the high speed trains from the simulation results of Train Energy Consumption (STEC) is regenerated 30% of the kinetic energy.

## **CHAPTER THREE**

### **3 ANALYSIS OF THE REGENEATIVE BRAKING SYSTEM ENERGY**

#### **3.1 Train energy consumption**

Balance of efforts applied on trains is the first approach found in the literature to estimate the electric consumption of light rail trains. An interesting general formulation of running resistance as a function of train characteristics like mass, number of bogies, inter-vehicle gap, number of pantographs, etc. The maximum running speed is generally lower than 70 km/h. The second step of the model review is to gather knowledge on the method to convert the force developed by the train (based on a physical model) in the energy consumption [17, 25].

To estimate the energy consumption, the train is considered as a point with a mass  $M$  [16]. Newton's second law is applied on this point. The total force to the drive wheels provided by the electric motor is computed. This force times the velocity gives the power required by the train. Then, as explain by Jeunesse and Rollin [17], the electric consumption is deduced by using a ratio that illustrates the efficiency of the traction system which includes the electric motor and the mechanical traction finally; this power is integrated to obtain energy consumption.

#### **3.2 Technical specifications of the LRT**

Despite the numerous categories and types of LRT systems, they are comprised of the following basic elements [40]: (1) Rolling Stock: a fleet of railcars that are used to carry passengers along the track ways, and designed so that they can be combined to make longer trains; (2) Infrastructure: comprised of the track ways, stations and maintenance/storage yards, including any associated structures such as tunnels, bridges and subsurface infrastructure; (3) Fixed Equipment: includes the operations center, power supply infrastructure, signals and communications facilities as well as road-side infrastructure (Boorse, 2000).

**Table3.1 Addis Ababa LRT Technical specifications of the light rail train.** [Addis Ababa LRT]

Specification	Values
Track gauge (standard)	1.435m
Vehicle weight (empty, average)	43,000kg
Vehicle weight (full, average)	64,000kg
Single vehicle height (with pantograph)	5m
Single vehicle length (average) (constrained by intersection spacing)	29.7m
Single vehicle width	2.65m
Horizontal vehicle clearance (total)	1.0m
Vertical vehicle clearance (minimum)	4.5m
Maximum running Vehicle speed in m/s	19.44m/s
Passengers (seated/standing, total)	64/286,350
Average starting Acceleration	0.9m/s <sup>2</sup>
Service brake Deceleration	1.1m/s <sup>2</sup>
Emergency brake deceleration	2.5m/s <sup>2</sup>
Longitudinal impact rate	0.75m/s <sup>3</sup>
Wheel diameter	0.66m
Frontal area of the vehicle	10m <sup>2</sup>
Motor efficiency	0.87
Wheel rail rolling coefficient	0.0071

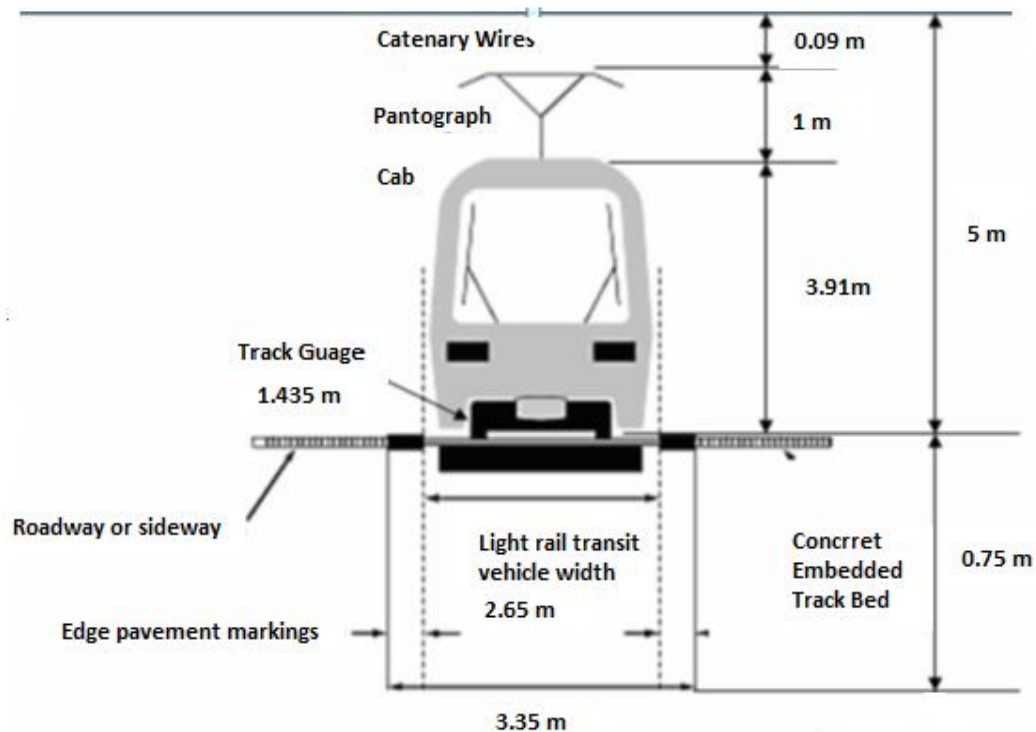


Figure 3.1 System Specifications Diagram outlining average LRT vehicle measurements [from ERC LRT project].

### 3.3 Braking force

This force must overcome the vehicle resistance to the movement, which is composed by the sum of the different forces that act against its movement [25]. This braking effort has to accomplish the following:

- overcome the rolling resistance;
- overcome the aerodynamic drag;
- provide the force needed to overcome the component of the vehicle's weight acting down the slope;
- Decelerate the vehicle, if the velocity is not constant.

The rolling resistance force,  $F_{r0}$ , is due primarily to the friction of the vehicle wheel on the rail, but friction in bearings and on the gearing system must also be considered [25]. The aerodynamic force  $F_a$  is consequence of the friction of the

vehicle body moving through the air. The hill climbing force  $F_{dr}$  is the force needed to drive the vehicle up a slope. It may have a negative impact on the movement of the vehicle, acting indeed as a resistance force but also a positive impact, if the vehicle is going down a hill. A force has to be applied in addition to the forces already mentioned if the velocity of the vehicle is changing, to overcome its inertia. The acceleration force  $F_{acc}$  will provide the linear acceleration of the vehicle (Ehsani et al., 1997; Larminie & Lowry, 2003; Malcolm A. Weiss, John B. Heywood & Andreas Schafer, 2000). The mathematical equations that define all those forces are listed below. The total braking force is the sum of the above mentioned forces.

The most important driving resistances are: aerodynamic and rolling, and depend on a variety of factors [25]. The techniques for calculating these factors and their relative importance for a variety of train types are described in an accompanying report (Lindgreen and Sorenson, 2005). The basic principles are reviewed here. The aerodynamic resistance is dependent on the frontal area of the train, its shape and its speed. In addition, atmospheric factors as air density and wind direction have an effect:

### 3.3.1 Aerodynamic resistance

The mathematical equations that define the aerodynamic resistance can be calculated as

$$F_a = 0.5 \times \rho \times C_D \times A_{fr} \times (v + v_{wind})^2 \dots \dots \dots (3.1)$$

$$F_a = 0.5 \times 1.2 \times 0.4 \times 10 \times 1183.4 = 2840N$$

- Where
- $F_a$  = total aerodynamic resistance in N
  - $\rho$  = the air density in kg/m<sup>3</sup> (1.2 kg/m<sup>3</sup>)
  - $C_D$  = aerodynamic resistance coefficient (0.4)
  - $A_{fr}$  = frontal area in m<sup>2</sup> (10m<sup>2</sup>)
  - $V$  = is the train's speed in m/s
  - $V_{wind}$  = is the wind speed in m/s (15m/s)

The drag coefficient is a geometrical property of the vehicle body design and it varies in a range of 0.3 to 0.52 for passenger cars and 0.5 to 1 for heavy duty vehicles such as container carriers and trucks [25].

### 3.3.2 Rolling resistance

The rolling resistance is a function of the total mass of the train and the rolling resistance coefficient.

$$F_R = C_R \times m_{tot} \times g \dots\dots\dots (3.2)$$

$$F_R = 0.0071 \times 64000 \times 9.81 = 4395N$$

The rolling resistance coefficient can be calculated

$$C_R = (0.0041 + 0.000041 \times V \times 2.24) \times ch$$

- Where  $F_R$  is the total rolling resistance in N
- $C_R$  is the rolling resistance coefficient (0.0071)
- $m_{tot}$  is the train mass in kg
- $g$  is the acceleration of gravity (9.81 m/s<sup>2</sup>)
- $ch$  is the road surface coefficient (1.2)

### 3.3.3 Gradient resistance

The gradient resistance is dependent on the weight of the train and the size of the gradient to which the train is exposed.

$$F_g = m_{tot} \times g \times \sin\alpha \dots\dots\dots (3.3)$$

$$F_g = m_{tot} \times g \times \frac{\Delta h}{X} \times 1000 \dots\dots\dots (3.4)$$

- Where:  $F_g$  is the total gradient resistance in N
- $m_{tot}$  is the train's mass in kg
- $g$  is the acceleration of gravity (9.82m/s<sup>2</sup>)
- $\alpha$  is the angle of the gradient
- $\Delta h$  is the height difference [m] over the horizontal distance  $x$  [m]

### 3.3.4 Acceleration resistance

The acceleration resistance can be calculated as

$$f_{acc} = m \times a \dots\dots\dots (3.5)$$

$$f_{acc} = 64000 \times 0.9 = 57600N$$

Where  $F_{acc}$  is the acceleration resistance in N  
 $m$  is the mass of the train or vehicle kg  
 $a$  is the acceleration in  $m/s^2$

The braking force is the sum of the above resistance forces.

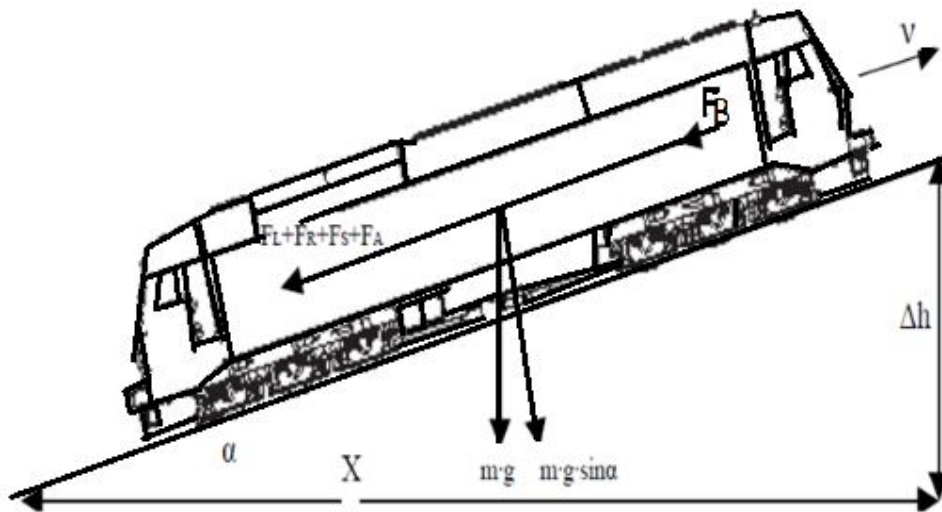


Figure 3.2 Sketch of driving resistances [25].

Using Newton's 2<sup>nd</sup> law in the opposite direction of travel, the connection between the driving resistances and motion is given as:

$$M \times a = -F_B - (F_g - F_R - F_a) = -F_B - F_g - F_R - F_a$$

$$F_B = -(F_{acc} + F_g + F_R + F_a)\dots\dots\dots (3.6)$$

Where  $F_B$  = is the locomotive's braking force at the wheels in N.

- $F_g$  = is the total gradient resistance in N
- $F_a$  = total aerodynamic resistance in N
- $F_R$  = is the total rolling resistance in N
- $F_{acc}$ =is the accelerating resistance in N

### 3.4 Torque, power and motor speed

The torque can be expressed by  $F_B \times r$ , where  $r$  is the radius of the wheel, and  $F_B$  is the braking effort delivered by the powertrain. Assuming  $G$  as the gear ratio of the transmission system connecting the motor to the axle, and  $T$  the motor torque (Larminie & Lowry, 2003), it can be calculated according to:

$$T = \frac{F_B \times r}{G} \dots\dots\dots (3.7)$$

- Where
- $T$ = is the torque in Nm
  - $F_B$ = is the tractive effort in N
  - $r$ =is the wheel radius in m
  - $G$ =is the gear ratio

After calculating the tractive force, it is necessary to know the amount of power required for each instant of the driving cycle. This power can be calculated as a function of the vehicle torque and motor speed, according to (Ehsani et al., 1997):

$$P = \frac{T \times \eta_m \times \pi}{3000 \times \eta_m \times \eta_c} \dots\dots\dots (3.8)$$

- Where
- $P$ = is the power in kW
  - $T$ = is the torque in Nm
  - $\eta_m$ = is the motor speed in rpm
  - $\eta_c$ =is the controller efficiency (92%)
  - $\eta_m$ = is the motor efficiency (89%)

The motor efficiency ( $\eta_m$ ) is calculated by the given formula below

$$\eta_m = -3(10 - 8) \times (V^2 \times m) + 0.0002 \times V_m + 0.638 \dots\dots\dots (3.9)$$

The motor speed  $v_m$  in revolutions per minute can be calculated taking into account the linear speed, the perimeter of the wheel and the transmission gear ratio:

$$n_m = \frac{v \times 30 \times G}{\pi \times r} \dots \dots \dots (3.10)$$

Where  $n_m$ = is the motor speed in rpm  
 $v$ =linear speed in m/s  
 $2. \pi. r$  =perimeter of the wheel in m  
 $G$ =gear ratio

### 3.5 Developed power and consumed power

The force  $F$ , provided by the electric motor, times the velocity gives the power to be provided by the train consumed energy:

$$P_{Consumed} = F_B \times V \dots \dots \dots (3.11)$$

The electric consumption is deduced (the generated energy) by using a ratio:

$$P_{regen} = \frac{P_{Consumed}}{\eta} \dots \dots \dots (3.12)$$

- $\eta$  is the efficiency of motor system. As a first approximation, this efficiency is considered as constant.
- $P_{regen}$ =regenerated power
- $P_{Consumed}$ =consumed power
- $F_B$ =braking force
- $V$ =velocity of the train

### 3.6 Consumed energy and regenerated energy

#### 3.6.1 Consumed energy

The total energy consumption can be calculated in several ways.  
 Based on knowledge of driving resistance (first and foremost aerodynamic and rolling resistance), the energy consumption can be calculated by integrating the instantaneous force over the traveled distance:

$$E = \int_{x_1}^{x_2} F_{tot} dx \dots \dots \dots (3.13)$$

$$E = F_{tot}(x_2 - x_1)$$

Where  $F_{tot}$  = the sum of the resistance forces  
 $x_2 - x_1$  = the distance traveled

The energy consumed at the accelerating time (when acceleration =  $0.9\text{m/s}^2$ ) at station one can be calculated as the tractive force is the summation of the resistance forces multiplied by the distance travelled.

$$E_1 = F_t \times d \dots \dots \dots (3.14)$$

Where  $E_1$  = consumed energy  
 $F_t$  = tractive force  
 $d$  = distance travelled

The tractive force is the summation of

$$F_t = m \times a + F_a + F_r \dots \dots \dots (3.15)$$

Where  $m$  = mass of the train = 64000Kg  
 $a$  = acceleration of the train =  $0.9\text{m/s}^2$   
 $F_a$  = aerodynamic resistance = 2840N  
 $F_r$  = rolling resistance = 4395N

The distance travelled at the starting time ( $a=0.9\text{m/s}^2$ ) is calculated by the equation

$$V_f^2 = V_o^2 + 2ad$$

Where  $V_f$  = final velocity  
 $V_o$  = initial velocity

From this formula distance is determined

$$d = \frac{V_f^2}{2a}, V_o = 0$$

$$d = \frac{19.4^2}{2 \times 0.9}$$

$$d = 376\text{m}$$

Then the consumed energy at the accelerating time (when acceleration = 0.9) is calculated by substituting the values in equation (3.14) for station one is

$$E_1 = (4395 + 2840 + 57600)\text{N} \times 376\text{m}$$

$$= \underline{\underline{24377960\text{J}}}$$

When the train is travelled with constant velocity (acceleration=0) tractive force is the summation of the rolling, aerodynamic and acceleration resistances.

Therefore consumed energy at station one is the product of these resistance forces and distance to be travelled

$$E_2 = (F_{acc} + F_a + F_r) \times d$$

$$E_2 = (57600 + 2840 + 4395) \times 700$$

$$E_2 = \underline{45384500J}$$

And the consumed energy at decelerating time is determined from the simulation results of the system by MATLAB Simulink.

$$E_{Consumed} = E_3 = \int_0^t P_{Consumed} dt = F_B \times d = 64835 \times 24.9033 = 1616356.3J$$

Where  $P_{onsumed} = F_B \times d$

$P_{onsumed}$  = consumed power

$F_B$  = braking force

$d$  = train travelled distance

This consumed energy determined from the simulation results of the system. The result from the simulation of the system for station one is ( $E_3 = 1616356.3J$ ).

The total consumed energy in station one is

$$E_c = E_1 + E_2 + E_3 = 24377960 + 45384500 + 1616356.3$$

$$E_c = \underline{71378816.3J}$$

For the other stations can be determined the consumed energy in the same manner and explained in table 4.2

**N.B** Assume that at the ground stations the provided degree is too small and there is no gradient resistance in a level or ground station.

### 3.6.2 Regenerated energy

The regenerated energy at each station of the east west line of Addis Ababa LRT is determined by the give formula below from the simulation results of the system.

$$E_{regen} = \int_0^t P_{regen} dt = 1857880.9J$$

Where  $E_{regen}$  = regenerated energy  
 $P_{regen}$  = generated power

But generated power is determined from equation (3.12) and all the generated energies in each station can be determined from the simulation results of the system by MATLAB Simulink in table 4.2 below.

The regenerated energy in percent for station one can be defined as

$$\%regen = \frac{\text{regenerated energy}}{\text{consumed energy}} \times 100$$

$$\%regen = \frac{1857880.9}{71378816.3} \times 100$$

$$regen = \underline{\underline{2.6\%}}$$

For the other stations can be determined in the same manner and explained in table 4.2 below.

### 3.7 Braking time

The braking time of the system is determined by the equation provided below at the time of regenerative braking system.

$$s = V_0 t + \frac{1}{2} at^2 \dots\dots\dots (3.16)$$

Where  $s$ = decelerating distance [m]  
 $V_0$ = initial velocity of the train [m/s]  
 $a$ = deceleration [m/s<sup>2</sup>]  
 $t$ = traveled time [s]

But first we can determine the distance train travelled can be defined by the equation below

$$V_f^2 = V_0^2 + 2as \dots\dots\dots (3.17)$$

Where  $V_f$  = final velocity of the train [m/s]

$V_o$  = initial velocity of the train [m/s]

$a$  = deceleration of the train [m/s<sup>2</sup>]

$s$  = traveled distance [m]

### **3.8 Simulation**

Simulation is defined as the construction of a mathematical model to reproduce the characteristics of a phenomenon, system, or process, often using a computer, in order to infer / gain information or solve problems

There are six steps to modeling any system in the simulation

- 1) Defining the System
- 2) Identifying System Components
- 3) Modeling the System with Equations
- 4) Building the Simulink Block Diagram
- 5) Running the Simulation
- 6) Validating the Simulation Results

The first three steps of this process are performed outside of the Simulink Software environment before model is begin to build.

#### **3.8.1 Defining the System**

The first step in modeling a dynamic system is to fully define the system. If you are modeling a large system that can be broken into parts, you should model each subcomponent on its own. Then, after building each component, you can integrate them into a complete model of the system. The most effective way to build a model of this system is to consider each of these subsystems independently.

The system to be simulated is defined as the system of regenerative braking system for electric light train's vehicle of Addis Ababa LRT. This system is used to reduce the dissipated energy in the time of braking trains and produces a green environment by reducing pollutant element or gas at the braking of the train.

The aim of this system is to generate energy at different braking positions of the track level that is at

- Level position
- Uphill position
- Downhill position

### 3.8.2 Identifying System Components

The second step in the modeling process is to identify the system components.

Three types of components define a system:

- **Parameters**— System values that remain constant unless you change them
- **States**— Variables in the system that change over time
- **Signals** — Input and output values that change dynamically during a simulation

In Simulink, parameters and states are represented by blocks, while signals are represented by the lines that connect blocks. For each subsystem that you identified, ask yourself the following questions:

- How many input signals does the subsystem have?
- How many output signals does the subsystem have?
- How many states (variables) does the subsystem have?
- What are the parameters (constants) in the subsystem?
- Are there any intermediate (internal) signals in the subsystem?

Once you have answered these questions, you should have a comprehensive list of system components, and you are ready to begin modeling the system.

The system components used in this simulation study of regenerative braking system are listed in figure 3.3.

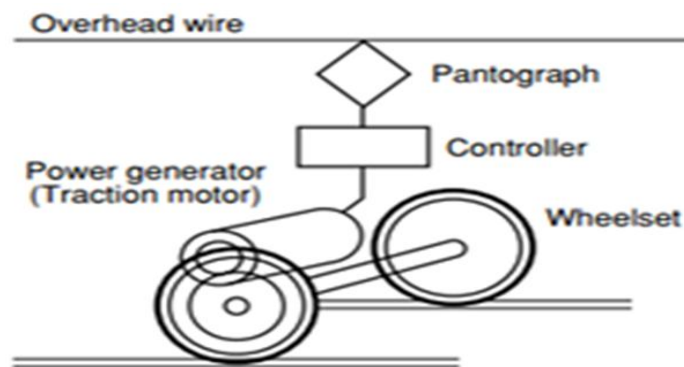


Fig 3.3 components of regenerative braking systems [5].

- Overhead power supply
- pantograph
- controller
- power generator/traction motor
- wheel sets

### **3.8.3 Modeling the System with Equations**

The third step in modeling a system is to formulate the mathematical equations that describe the system. For each subsystem, use the list of system components that you identified to describe the system mathematically.

The model may include:

- Algebraic equations
- Logical equations
- Differential equations, for continuous systems
- Difference equations, for discrete systems

We use these equations to create the block diagram in Simulink.

In modeling the regenerative braking system of train vehicles when a driver holds brake at different track level that is

- at the level position
- at the uphill position and
- at the downhill position

The mathematical equations used for the above braking conditions will be explained below

#### **3.8.3.1 Braking at level position**

When a train is accelerating in level position of the track as the driver holds a brake the mathematical equations which are used to explain the amount of regenerative energy is explained as the total force or the braking force is the sum of

- Aerodynamic resistance
- Rolling resistance
- Accelerating resistance

$$F_B = -F_{acc} - F_a - F_r \dots \dots \dots (3.18)$$

Where  $F_B$  = is the braking force at the wheels in N  
 $F_a$  = total aerodynamic resistance in N  
 $F_r$  = is the total rolling resistance in N  
 $F_{acc}$  = is the accelerating resistance in N

### 3.8.3.2 Braking at uphill position

When a trains accelerating in uphill position of the track as the driver holds a brake the mathematical equations which are used to explain the amount of regenerative energy is explained as the braking force is the sum of aerodynamic resistance, rolling resistance, gradient resistance and accelerating resistance

$$F_B = -(F_a + F_R + F_g + F_{acc}) \dots \dots \dots (3.19)$$

Where  $F_B$  = is the locomotive's braking force at the wheels in N.  
 $F_g$  = is the total gradient resistance in N  
 $F_a$  = total aerodynamic resistance in N  
 $F_R$  = is the total rolling resistance in N  
 $F_{acc}$  = is the accelerating resistance in N

### 3.8.3.3 Braking at downhill position

When a trains accelerating in downhill position of the track as the driver holds a brake the mathematical equations which are used to explain the amount of regenerative energy is explained as the braking force is the sum of aerodynamic resistance; accelerating resistance and rolling resistance mines gradient resistance.

$$F_B = -(F_a + F_r - F_g + F_{acc}) \dots \dots \dots (3.20)$$

Where  $F_B$  = is the locomotive's braking force at the wheels in N.  
 $F_g$  = is the total gradient resistance in N  
 $F_a$  = total aerodynamic resistance in N  
 $F_r$  = is the total rolling resistance in N  
 $F_{acc}$  = is the accelerating resistance in N

### 3.8.4 Building the Simulink Block Diagram

After you have defined the mathematical equations that describe each Subsystem, you can begin building a block diagram of your model in Simulink. Build the block diagram for each of your subcomponents separately. After you have modeled each subcomponent, you can then integrate them into a complete model of the system.

The proposed regenerative braking system will be simulated in three different drivers braking positions that is in:

- level position
- uphill position and
- downhill position

And it is modeled in block diagrams in Mat lab Simulink and programmed in the Mat lab M-file scripts as in the following flow charts

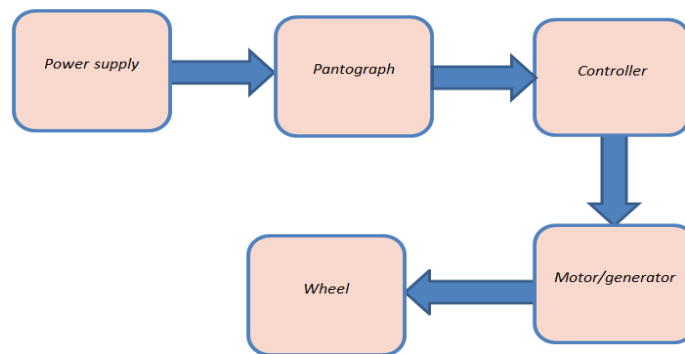


Fig 3.4 flow chart for the transmission of energy for electric trains in the acceleration

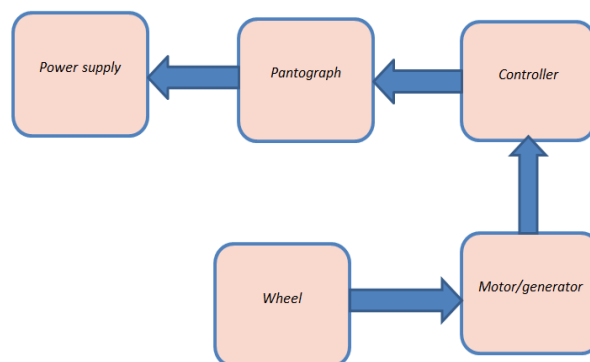


Fig3.5 flow chart for the transmission of energy for electric trains in the regenerative braking or in the deceleration.

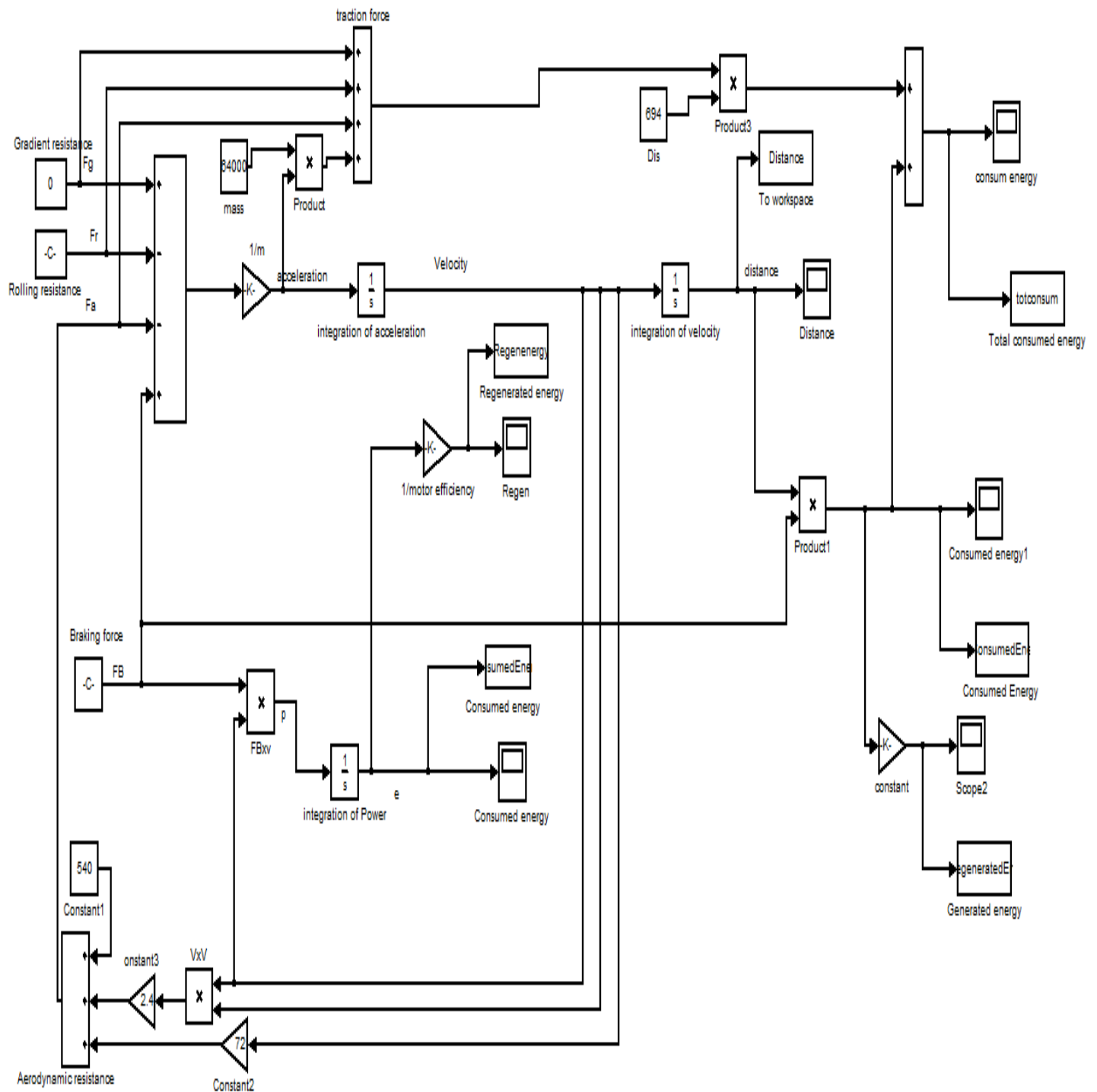


Fig 3.6 the model of regenerative braking system at a level position of the track level of the ground stations.

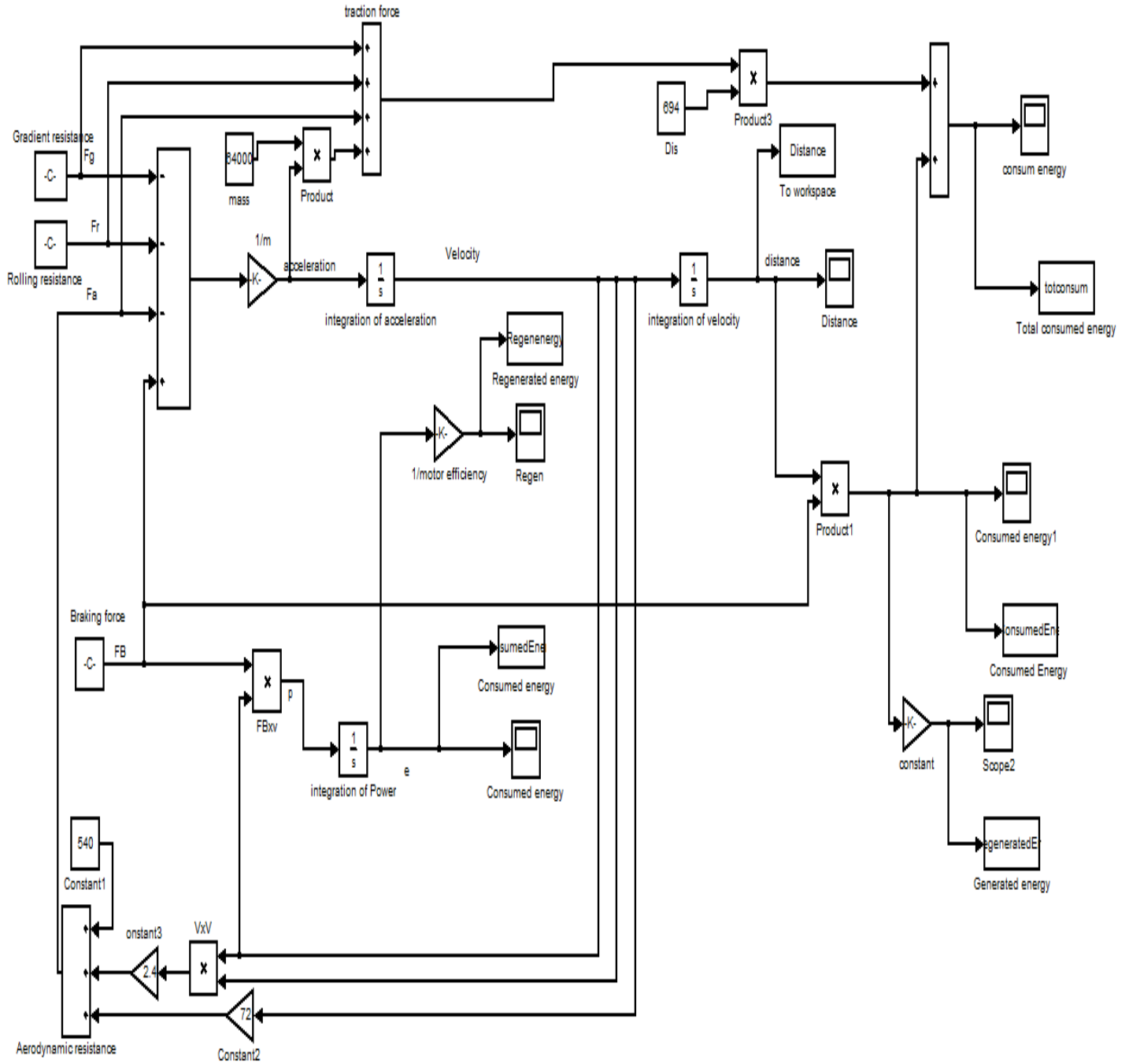


Fig 3.7 the model of regenerative braking system at uphill position of the track level of the station.

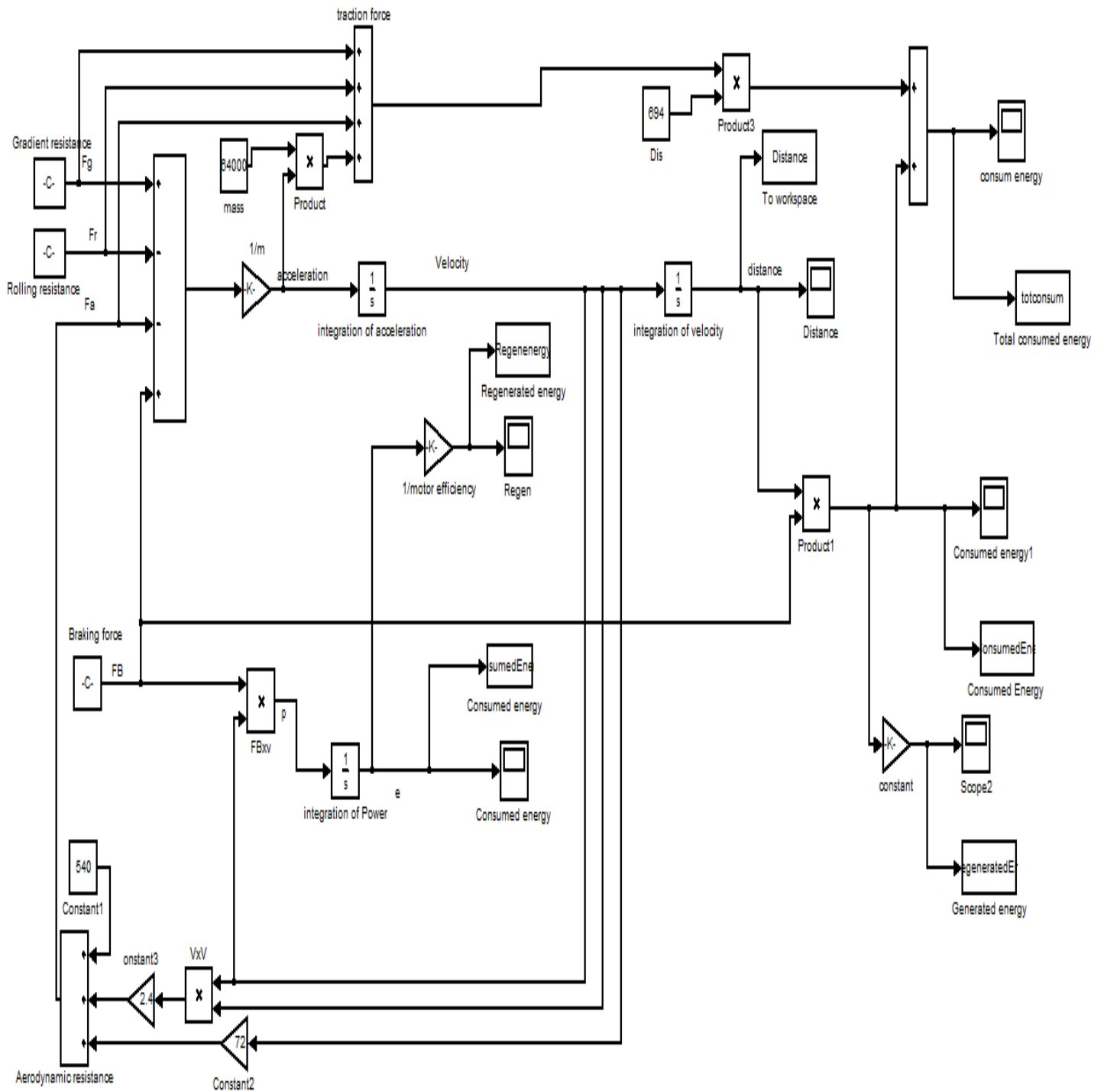


Fig 3.8 the model of regenerative braking system at the downhill position of the track level of the station.

### 3.8.5 Running the Simulation

After you build the Simulink block diagram, you can simulate the model and analyze the results. Simulink allows you to interactively define system inputs, simulate the model, and observe changes in behavior. This allows you to quickly evaluate your model.

This section shows all the results of the programs which are properly fed to the MATLAB Simulink software. The mathematical models of the system which are provided in the above chapters are properly modeled to the Simulink MATLAB program.

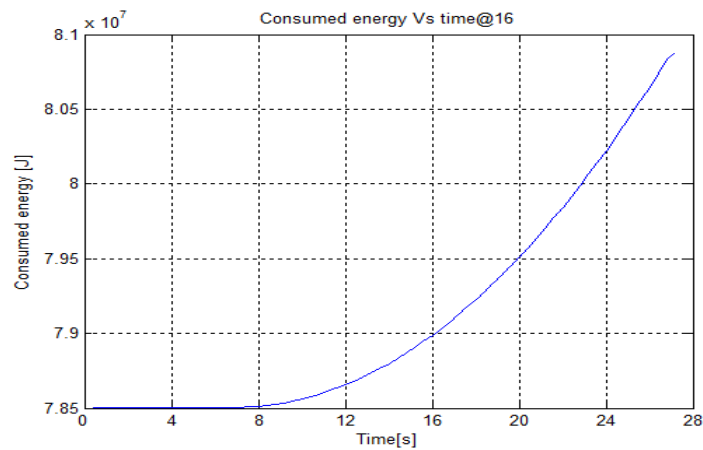


Fig 3.9 consumed energy at uphill station 16

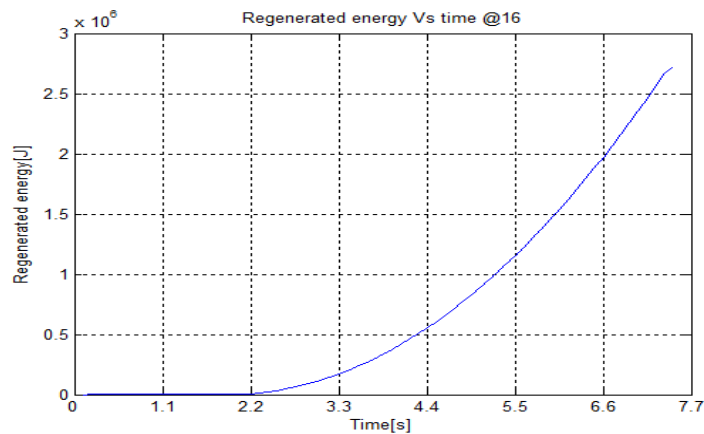


Fig 3.10 Regenerated energy at uphill station 16

## CHAPTER FOUR

### 4 RESULTS AND DISCUSSIONS

#### 4.1 Results

In this chapter the results from the simulations regarding energy consumption and energy generating calculations are provided.

Thanks to the results of the simulations in the program MATLAB Simulink software and calculations made in earlier chapters the generated energy and consumed energy of the different cases can be calculated. The generated and consumed energy is presented to allow for a comparison between the different cases in this study and should be seen as relative.

The regeneration of the accumulated input energy is also stated and is simply called “Regeneration” or “Regen. This value indicates how much energy that the electric regenerative brakes really feed back to the catenary in relation to the input energy, taking losses in the train’s propulsion system as well as the assumed degree of regeneration into account.

**Table 4.1 generated energy at the elevated stations.**

Station	Slope in degree	Gradient force (N)	Regen energy (J)	% of regen	Remark
20	2.247	24611.3	4383601.3	5.4	downhill
19	1.591	17454.0	3751306.9	3.2	downhill
17	1.901	20844.3	2066713.6	2.7	uphill
16	2.767	30324.7	2726882.9	3.4	uphill
12	1.641	17956.2	3794060.4	4.4	downhill
Total generated energy			16722565.1		

From this table the result of the generated energy at braking time of regenerative braking system using MATLAB Simulink software is 16722565.1J. At the downhill braking stations more energy is generated because the gradient force helps to generate but in the uphill stations less energy is generated due to more resistance forces applied to the train movement.

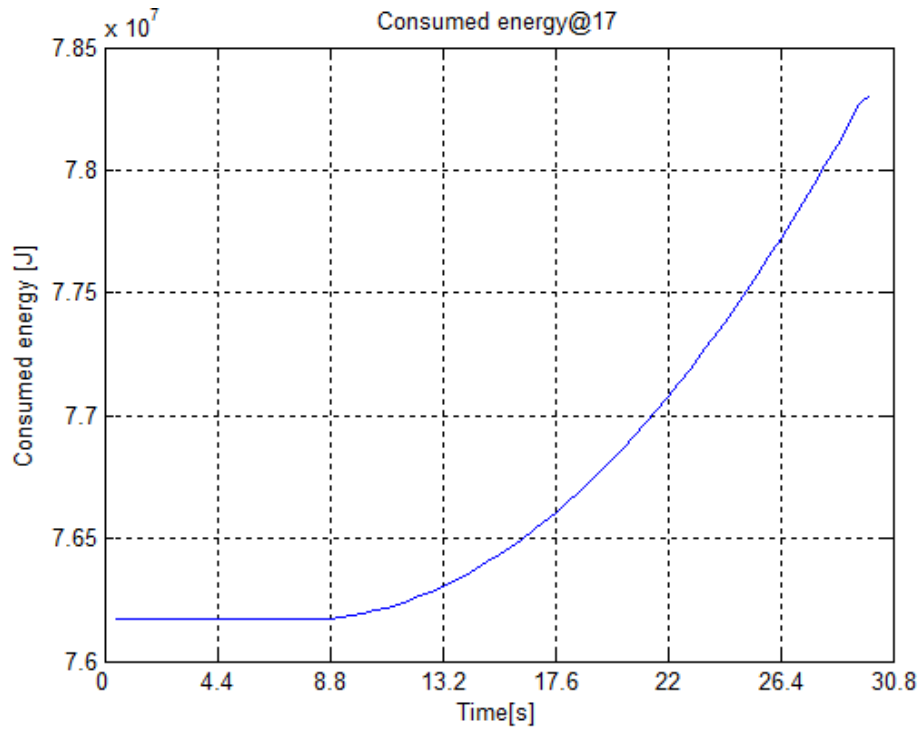


Fig 4.1 consumed energy of the system at the uphill braking station of 17.

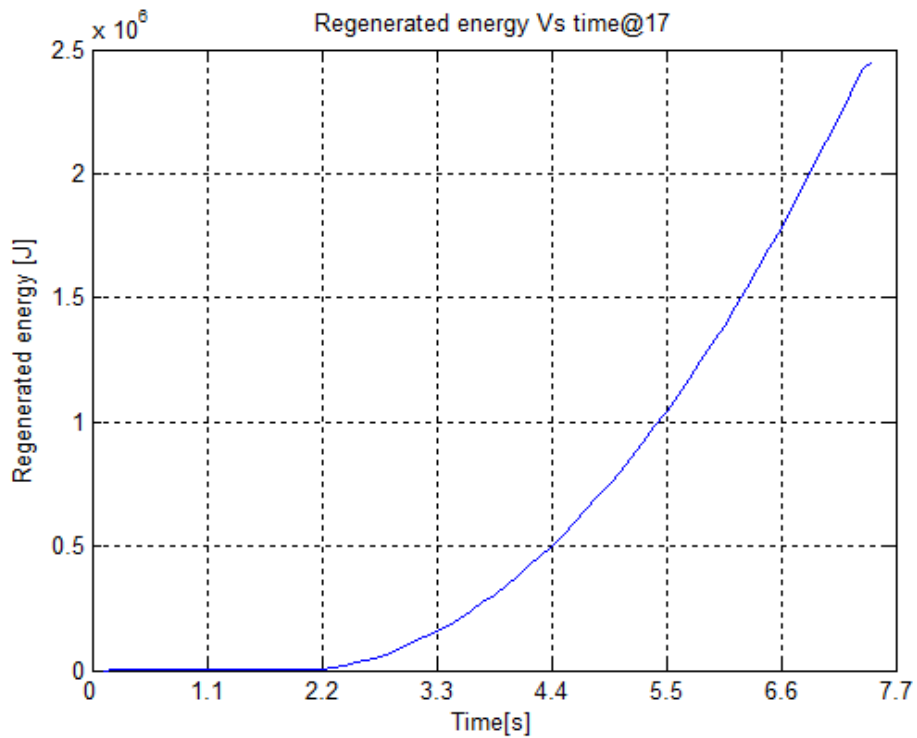


Fig 4.2 Regenerated energy of the system at the uphill braking station of 17.

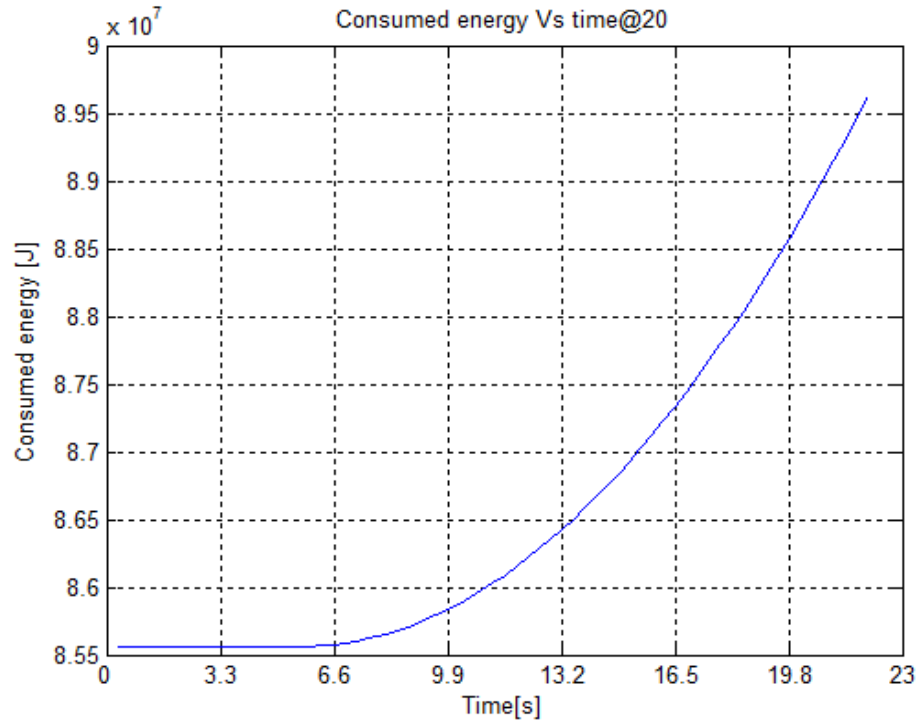


Fig 4.3 consumed energy of the system at downhill braking stations of 20.

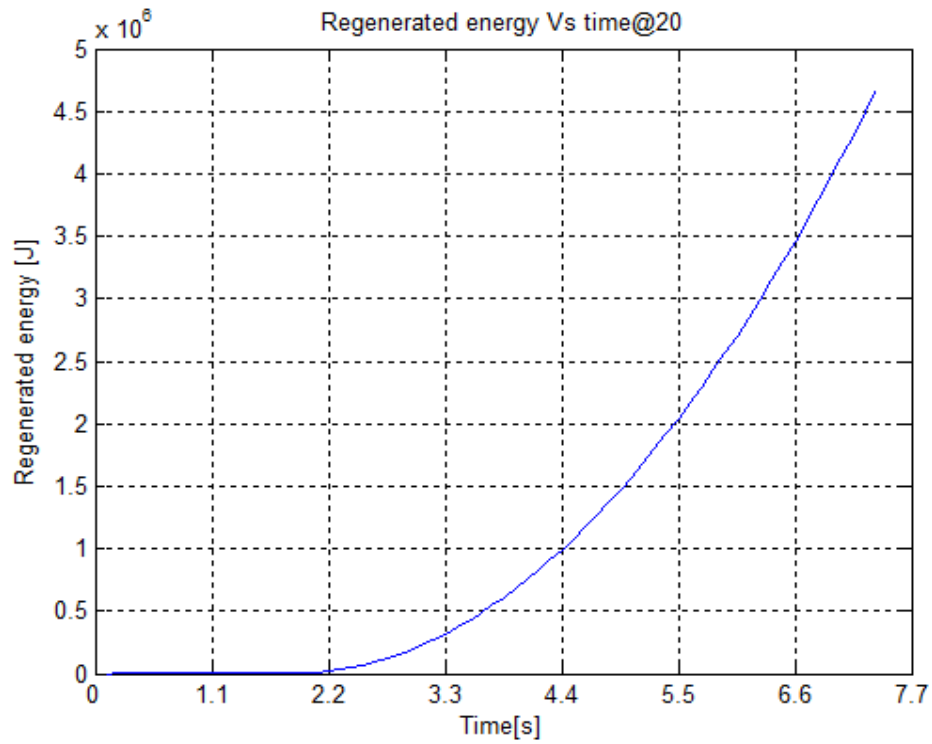


Fig 4.4 generated energy of the system at the downhill braking station 20

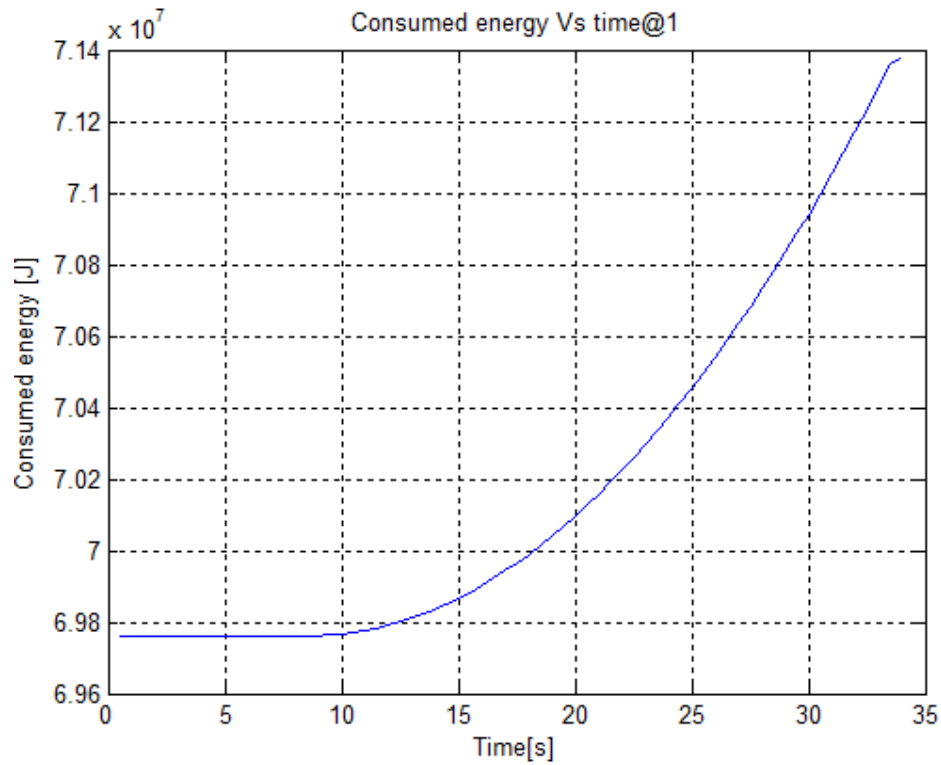


Fig 4.5 consumed energy of the system at level braking stations one

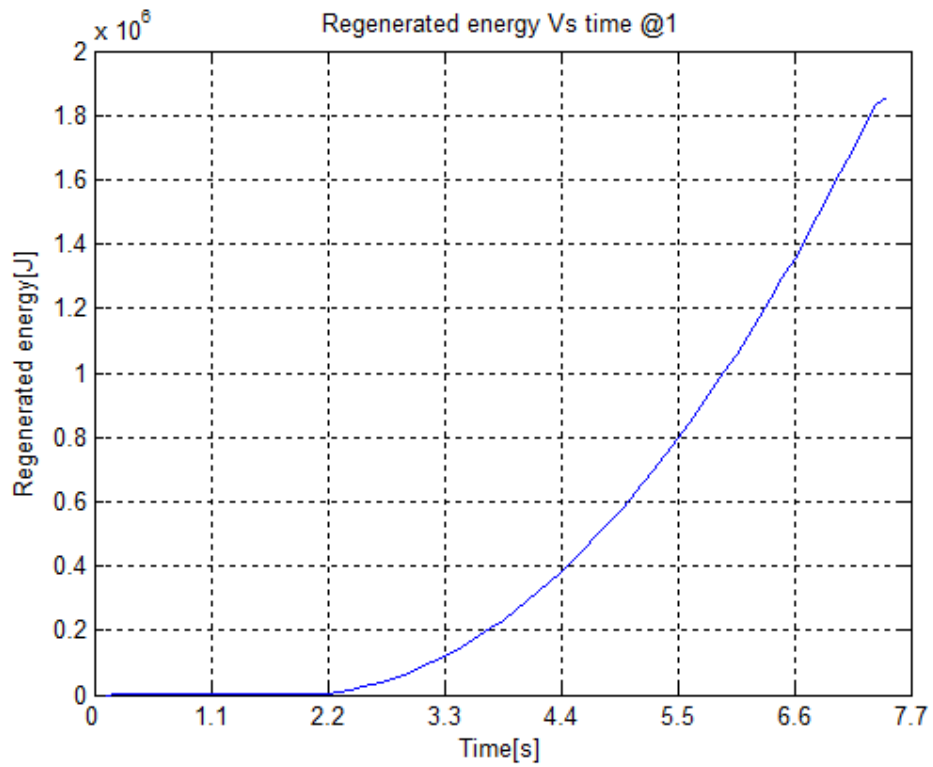


Fig 4.6 generated energy of the system at level braking stations one

**Table 4.2** the percentage of regenerative energy during regenerative braking system of the light rail transit in Addis Ababa LRT from Ayat up to Tor-hayloch.

S/N	Name of station	Type of station	Gradient/ Slope	Station spacing	Regen energy (J)	Consumed energy (J)	% of regen energy
1	Ayat 2	Ground station	0.00905°	1101	1857880.9	71378816.3	2.6%
2	Ayat 1	Ground station	0.00818°	696	1857880.9	45120641.3	4.1%
3	CMC2	Ground station	0.00917°	758	1857880.9	49140411.3	3.8%
4	CMC1	Ground station	0.00093°	696	1857880.9	45120641.3	4.1%
5	St. Michael church	Ground station	0.00958°	500	1857880.9	32412981.3	5.7%
6	Civil service college	Ground station	0.00458°	506	1857880.9	32801991.3	5.7%
7	Sahlite mihret church	Ground station	0.0079°	673	1857880.9	43629436.3	4.3%
8	Gurd shola	Ground station	0.00127°	565	1857880.9	36627256.3	5.1%
9	Meganenga/Adwa square	Ground station	0.00953°	555	1857880.9	35978906.3	5.2%
10	Lem hotel	Ground station	0.00358°	570	1857880.9	36951431.3	5%
11	Mazoria/Traffic police HQ	Ground station	0.491°	920	1857880.9	59643681.3	3.1%

Analysis of regenerative braking system in the reduction of energy consumption in A.A LRT

S/N	Name of station	Type of station	Gradient/ Slope	Station spacing	Regen energy (J)	Consumed energy (J)	% of regen energy
12	Chemical Corporation(downhill)	Elevated station	1.641°	740	3794060.4	86393246.2	4.4%
13	St.Urael church	Ground station	0.00989°	760	1857880.9	49270081.3	3.8%
14	Yordanos Hotel	Ground station	0.00849°	930	1857880.9	60292031.3	3.1%
15	St. Estifanos/meskel square2	Ground station	0.00155°	952	1857880.9	61718401.3	3%
16	Stadium/meskel square1(uphill)	Elevated station	2.767°	850	2726882.9	80879140.6	3.4%
17	Leghar(uphill)	Elevated station	1.901°	910	2066713.6	77966671.9	2.7%
18	Road Authority	Ground station	0.00102°	725	1857880.9	47000856.3	4%
19	Mexico square(down)	Elevated station	1.591°	1005	3751306.9	117328034.4	3.2%
20	Lideta (downhill)	Elevated station	2.247°	660	4383601.3	81159895.5	5.4%
21	Coca cola	Ground station	0.00998°	1150	1857880.9	74555731.3	2.5%
22	Tor-hailoch	Ground station	0.00504°	1260	1857880.9	81687581.3	2.3%
<b>Total</b>					<b>48306540.4</b>	<b>1307057865</b>	<b>3.7%</b>

## 4.2 Discussions

From this simulation of MATLAB Simulink result the generated energy is about **48306540.4J** or **48306.5404KJ** can be generated in one tripe of the train movement from Ayat to Tor-hailoch. The total length of the main line of East-West line is about **17.41km**. In this line there are **22 stations** and five of the stations are elevated and they are used for common to East-west and North-South lines of the Addis Ababa LRT. This energy is generated within 7.31 seconds of simulation time of the Simulink ADAMS software by MATLAB. This simulation time is calculated from equation 3.16. This energy has an advantage in the reduction of energy consumption and implementing the braking system gives reduction in the cost of electric power.

This energy feedbacks to the main line and used by other trains which is accelerated in the same line if not returned to the main power supply system. The regenerated energy is controlled by the regenerative braking system controller which is an electric device that controls the system remotely. In the downhill station of the braking system more energy can be generated but in the uphill station generates less energy than downhill and ground level station. Because in the uphill position the motion of the train is traveled with less speed and more resistance force are applied than the other type of the train braking systems.

Table 4.1 shows the regenerative energy at the time of braking when the train uses regenerative braking system at different slop of the stations. From this table we consider the generated energy at the uphill position of the stations is 4793596.5J of the consumed energy. This energy is the summation of the generated energy at stations **16 & 17** in the east-west line stations. The generated energy at downhill's position of the stations (**20, 19 & 12 stations**) is 11928968.6J of the consumed energy. And at the rest of **17** ground level stations of the track position is 31583975.3J of the consumed energy is generated. The summation of generated energy at the time of regenerative braking system at one tripe of the movement of the train from Ayat to Tor-hailoch is about **3.7%** of the consumed energy of the train.

From the results of the model and simulation of the regenerative braking system by MATLAB of the Simulink Adams software regenerative braking system is very

important in the saving of energy. From the results which are expressed or explained in table 4.1 and 4.2 above the regenerated energy during regenerative braking system is 3.7% of the consumed energy. Light Rail Transit (LRT) in general railway transportation system is a new type of transport in our home country (Ethiopia) it is advantageous to use regenerative braking system because regenerative braking system reduces the energy consumption of the system. Regenerative braking system saves the dissipated energy in the form of heat at the time of train brake. This shows that regenerative braking system reduces the cost of the power by generating energy and return to the main grid. This generated energy is used by the train if a train is in accelerating mode in the same network if not the regenerated energy is returns to the main power supply grid. In general regenerative braking system is very important in the reduction of energy consumption.

From the results of the Simulink ADAMS simulation of the regenerated energy by MATLAB the consumed energy of the trains in general reduced. From the figure 3.9 the consumed energy at the uphill position of the track level at station16 is 80879140.6J. This consumed energy reduced to 78152257.7J because of the regenerative braking system as shows in figure 3.10. At this track level position of the station the generated energy is about **3.4%** of the consumed energy.

From the figure of 4.3 the consumed energy at the downhill position of the track level station 20 from the simulation results is about 81159895.5J. But from figure 4.4 this consumed energy is reduced to 76776294.2J. The generated energy from the simulation results of the regenerated braking system is 4383601.3J. The generated energy in station 20 which is downhill station is about **5.4%**of the consumed energy of the system.

Figure 4.5 shows the results of consumed energy at the ground position of the track level station one. At this ground level station of station one the consumed energy is 71378816.3J. From figure 4.6 simulation results of the system this consumed energy is reduced to 69520935.4J. At this track level station of the system the generated energy is about **2.6%** of the consumed energy of the system at station one only.

In general the system can generate energy about **3.7%** of the consumed energy of the system in the whole line of one tripe of train movement in the east-west line from Ayat to Tor-hailoch.

**Table4.3 generated energy at different position of train stations.**

<b>Position of station</b>	<b>Consumed Energy</b>	<b>Generated energy (J)</b>
Ground or Level (17 station)	863330876.4	31583975.3
Uphill	158845812.5	4793596.5
Downhill	284881176.1	11928968.6
<b>Total generated energy</b>	<b>1307057865</b>	<b>48306540.4</b>

From table 4.3 the sum of the generated energy in the east-west line stations from Ayat to Tor-hailoch is 48306540.4J.

This generated energy is very important in the reduction of

- Energy consumption
- Power cost

## CHAPTER FIVE

### 5 CONCLUSION , RECOMENDATIONS AND FUTURE WORKS

#### 5.1 Conclusions

Railway transport is a modern transport and new type of transport for our country. Since Ethiopia is in developing country, it needs renewable type of energy source. To achieve this usable energy regenerative braking system is very important. Regenerative braking system generates some percentage of the kinetic energy into usable energy instead of wasting it to the environment in the form of heat. This heat energy dissipates and follows some impacts to the environment. To solve and avoid this condition regenerative braking system is the best.

With an extensive and expanding rail transit network, energy efficiency will always be an important component of environmental impact and operation costs. Electric transportation offers many advantages over conventional technologies. This includes lower driving costs, higher energy efficiency, and the possibility of lower emissions. Regenerative braking system in electric transportation railway transport is very important because it produces some percentage of the kinetic energy of the train. The sum of the average regenerative braking system produces about **3.7%** of the consumed energy of the train at different station positions of the track level. If we cannot use this type of braking this amount of energy can be dissipated to the environment in the form of heat. As designers and engineers perfect regenerative braking systems, they will become more and more common. All vehicles in motion can benefit from utilizing regeneration to recapture energy that would otherwise be lost.

The recycling of the braking energy of trains causes significant electricity savings, environmental benefits and supplementary revenues. The major factors influencing the energy consumption are respectively the weight of the train, operating frequency and the maximum acceleration. Efficient operation of the railway system is considered as an essential way of energy saving in rail transportation.

## **5.2 Recommendations**

From the simulation result of regenerative braking system in the East-west line of 22 braking stations on page 52 table4.2 above, the regenerated energy is shown clearly. The system generates in one tripe of the train movement from Ayat to Tor-hailoch about 3.7% of the consumed energy. This generated energy is advantageous in the reduction of energy consumption and power cost.

Therefore for ERC it is recommended to introduce trains that have a regenerative braking system.

## **5.3 Future works**

The proposed research requires detailed train dynamics for the reduction of energy consumption in Addis Ababa LRT. The future works of this research includes

- compare the regenerated energy using normal driving and Eco-driving styles
- The energy generated in the whole day of the working time
- Compare the simulated results with measurable or experimental by collecting real data's from the ministry of transport or from the corporation
- compare the wear of the wheel-rail in the time of braking with the other braking styles

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