ADDIS ABABA UNIVERSITY ADDIS ABABA INSTITUTE OF TECHNOLOGY SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING GRADUATE PROGRAM IN RAILWAY ENGINEERING

ANALYSIS OF EFFECT OF TRAIN OVERLOAD ON ENERGY CONSUMPTION OF AALRT

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(Railway stream)

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Abstract

Railway operation are heavy users of electric energy, energy cost of a rail transportation is high especially for the traction in its daily operation. To implement energy saving programs and to study economical operation strategies, an energy estimated model is required. The models can be further extended to develop models and simulation for estimating power demand of train operation and minimizing energy consumption through different driving strategies.

In order to make analysis for train energy consumption and regenerative energy, this thesis work focuses only Ayat to Torhiloch (East Wast) line of Addis Ababa Light Rail transit (AALRT).

The main targets of this research work is to analyze the effects of train overloading in energy consumption of AALRT by comparing with different load conditions such as normal and maximum load. During peak hour the number of passengers are high, overloading affects energy consumption because it takes more energy to accelerate the train.

Mathematical modeling and simulation based analysis are presented to analyze the effects of overloading on train energy consumption. The models are formulated using train dynamics, train tractive effort and driving resistance which includes aerodynamic, gradient and rolling resistance. The methodology to evaluate energy consumption is based on power and time.

In this research work Matlab/Simulink software is developed to analyze train energy consumption and regenerative energy. The method that used to create the simulation of energy analysis at different track position such as level, uphill and downhill position.

Finally, the Simulink result shows that, there is 11.05 % additional energy consumption is used during overloading when it is compared to normal train loading, 6.22 % used when it is compared to maximum train loading condition. The result shows that during overloading the train needs high amount of energy consumption to accelerate.

Keywords: Train energy consumption, Regenerative energy, Mathlab/Simulink simulation

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Nomenclature

F_t	Train tractive effort
P	Train power P
V	Train speed
C_a	Aerodynamic resistance coefficient
f_m	Mass factor
a	Acceleration or deceleration
x_a	Acceleration distance
v_o	Initial speed
xb	Deceleration distance
v_{max}	Maximum operation speed
$\sum F$	Sum of force
F_r	Rolling resistance
F_a	Aerodynamic resistance
F_g	Gradient resistance
Fc	Curve resistance
X_L	Train level distance
X_U	Train Uphill distance
X_D	Train downhill distance
ρ	Air density
A_{fr}	The frontal area
m_{tot}	Train mass

g	Acceleration of gravity
C_R	Rolling resistance coefficient
E	Total energy consumption
t	Time
T	The motor torque
P_{out}	Output power of the motor
ω	The motor angular speed
∑R	Sum of driving resistance
η	Motor efficiency
E_{reg}	Regenerative energy

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

A transport system can be appreciated as the backbone of modern societies and involves private car, bus, truck, waterway, airway, railway, etc. transportation. Of the aforementioned transport systems rail transport service is the accustomed mode of mass and bulk transport which is a reality nearly two centuries ago, i.e., since early 1800s. Particularly, electrified railroad transport system is an admired alternative compared to other technology options-steam and diesel- mainly due to its salient features; namely: energy efficient, high power to mass ratio (kW/tonne), higher speed capability, advantageous at high traffic situation, easily controlled and integrated due to technological advances in electrical energy manipulation, environmentally friendly with low emission rate of carbon dioxide (CO_2) per passenger km or per ton of freight per km transported, etc. [20].

In these days, railways are being reevaluated as an environmentally friendly mode of transportation. The researchers develop the energy efficient railway technologies, such as energy storage system, energy efficient driving. Mass rapid transit (MRT) railways, which are an important means of public transportation in urban areas, have operational characteristics, short headways, frequent departures and arrivals. When multiple trains are operating in the same power supply system, it is important to synchronize the traction energy and regenerative energy which may be exported on deceleration. However, the regenerative energy is used mainly for the vehicle cooling-heating system and has a low reuse rate. Therefore, it is necessary to increase the reuse rate by synchronized energy saving [7].

Rail transit system are widely used to provide mass transportation. However, the frequent accelerations and decelerations for rail transit trains adversely affects in the major performance of travel time, propulsive energy consumption and braking wear between stations. This thesis work focus on effects of train overloading on energy consumption.

If a train running between two stations consumes electric energy, the energy consumption of a train can be divided into three phases: the traction phase requires high power (traction energy); the coast phase requires low or no power; and the deceleration phase may export regenerated brake power (regenerative energy).Generally, regenerative energy are equal to approximately 30~40% of the total traction energy. This principle is explained by the conversion of kinetic energy into electrical energy. That is, the kinetic energy that originates in the braking phase can be converted into electrical energy and transferred to the power supply system for use by other trains running within same power supply system. Note that if the regenerative energy is not used for other trains, it is lost [7].

The use of regenerative energy is closely related to a group of stations within a specific range of the power supply system. . The power supply system covers adjacent stations. In the power supply system, electricity flows from high to low voltage to operate trains at adjacent stations within a specific range of the power supply system. The group of stations also represents a zone within which regenerative energy can be interchanged. That is, trains with regenerative energy can provide it to other trains running within the group of stations.

1.2 Railway Transportation

Railways as a means of transportation a very old idea. Railways were mainly utilized in central European mines, with different means of traction being applied. They did not come into general use until the invention of the steam engine. Since the 18th century, railway development has accelerated, until now, in the 21st century, it has become the most efficient means of transport for medium distances, thanks to the remarkable development of high speed service.

Railroads transformed the world in the nineteenth century and supported the industrial expansion of the early twentieth century, then declined in the face of airline and highway competition. To survive, railroads were forced to rationalize their systems, develop more efficient operations, and introduce new services. At the turn of the twenty – first century, railroad remain dominate for bulk transportation, provide the backbone of rapidly growing intermodal freight service, and compete successfully with airlines in medium distance markets. Highways congestion, limited airport capacity, and environmental concerns guarantee role for rail systems in the twenty first century.

Railways reduced transportation costs and travel times by an order of magnitude, changing the economic geography of the world forever.
Railways have been playing a significant social role in ground-based mass public transportation. In spite of the discussion regarding its social role in the era of motorization in the latter half of the 20th century, electric railway systems are again growing in importance as a result of recent arguments on energy saving and environmentally friendly sustainability. In fact, globalization, climate change, and population growth require new and optimized transport systems [23].

A substantial advantage of electric railways compared to other modes of transportation is the use of electric energy, which allows the utilization of a variety of primary energy sources.

1.3 Light Rail Transit

Transport system for people with average flow rate and frequency, with driven and towed convoys in a constrained path, with movement controlled by signals and completely independent from any other type of traffic.

Light rail transit (LRT) is a particular class of urban and suburban passenger railway that utilizes equipment and infrastructure that are typically less massive than that used for metro systems and heavy rail. As such, the main difference between LRT and metro systems is the mass of the utilized equipment and infrastructure [23]. When a heavier mass of equipment and infrastructure is used, the cost of the system is higher, where one can broadly compare the costs of metro and LRT systems.

Tracks for light rail transit are generally constructed with the same types of materials used to construct “heavy rail,” “commuter rail,” and railroad freight systems. Also, light rail vehicles maybe as massive as transit cars on heavy rail systems.

- Light rail is a system of electrically propelled passenger vehicles with steel wheels that are propelled along a track constructed with steel rails.
- Propulsion power is drawn from an overhead distribution wire by means of a pantograph or other current collector and returned to the electrical substations through the rails.

- The tracks and vehicles must be capable of sharing the streets with rubber-tired vehicular traffic and pedestrians. The track system may also be constructed within exclusive rights-of-way.
- Vehicles are not constructed to structural criteria (primarily crashworthiness or "buff strength") needed to share the track with much heavier railroad commuter and freight equipment.

1.4 Addis Ababa Light Rail Transit

Transportation system in Addis Ababa has become a series issue now a days, because of increasing different infrastructure, increasing number of population and increasing economic growth of the city. It was because of different reason such as environmental friendly transportation system light rail transit system is planned, this system provides services at higher speed and capacity.

Addis Ababa Light Rail Transit (AA-LRT) Project consists of East-West and North-South lines in phase one, with the total length of main line 34.25km. The east west line is from Ayat to Torhiloch covered 17.35 kilometers and have 22 stations. The North south line is 16.9 kilometers pass through Menelikn Square to Kality have 21 stations.

These two lines operate on the same rail in downtown area for a total length of 2.662km.The ground line mode is mostly applied in rail laying, while elevated line and underground line are also applied in some sections.

1.4 Train driving patterns

A driving pattern can describe a train operation either as a function of elapsed time or the number of driven kilometers.
In general, there are four types of operation that make up driving pattern such as acceleration, constant speed operation, coasting and braking.

- Acceleration

The train's speed is increasing. This can be due to start from a station, signal or in connection with a change in speed limits. Some limiting cases would be constant acceleration, constant traction force, or constant engine power. During the acceleration, the traction force required is usually significantly larger than the aerodynamic, rolling or possibly gradient resistance.

- Constant speed operation

Since the speed is considered constant, the required traction force is equal to the sum of the driving resistances (aerodynamic, rolling and gradient). In model developed here, a minimum acceleration is defined, under which it is assumed that the acceleration is zero.

- Coasting

Both rolling and braking are portions of the operation where the speed decreases. In the case of rolling, the braking force and the traction force are both equal to 0. That is, it is alone the driving resistances that determine the speed of the train. This condition is useful for measuring the resistance parameters in a so-called "coast-down test".

- Braking

In this condition the brakes are active. That is, the traction force is 0, while both the braking and driving resistances slow the train down [27].

1.5 Electric train power transmission

The locomotive receives electricity for the electric traction motors directly from the electricity lines along the track. Electrical equipment on the locomotive adapts the electricity to that type used by the traction motors [27].

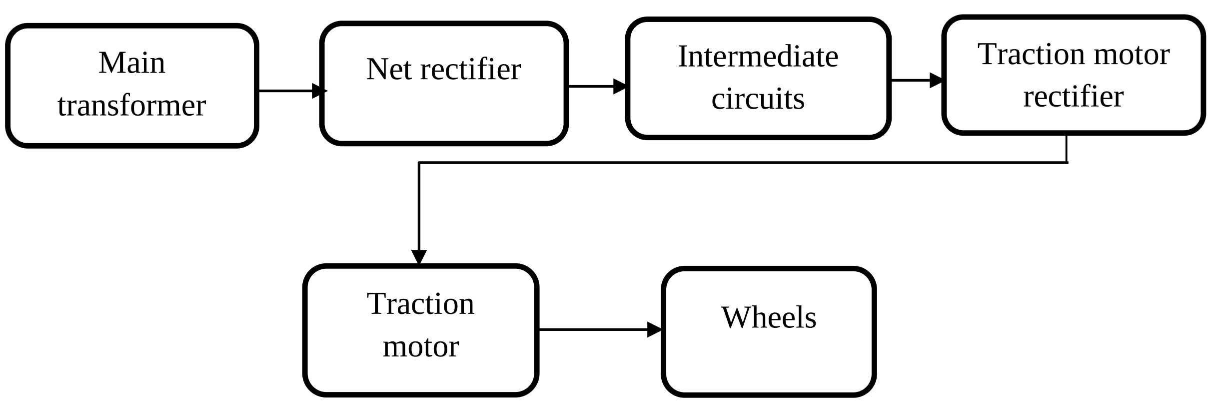

Figure 1-1 Principles of transmission for electric trains

1.7 Working principles of regenerative braking

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

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 [25].

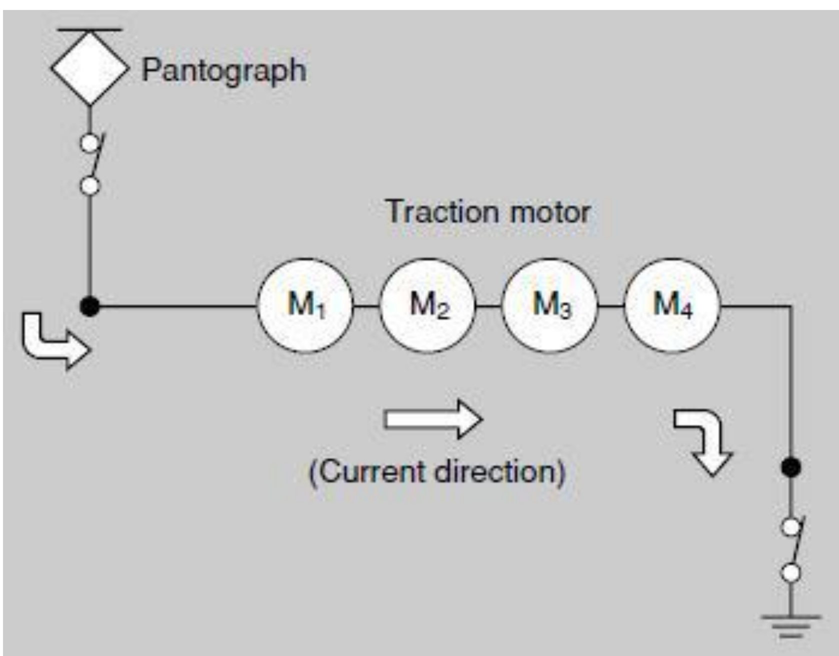

Figure 1-2 Electric traction

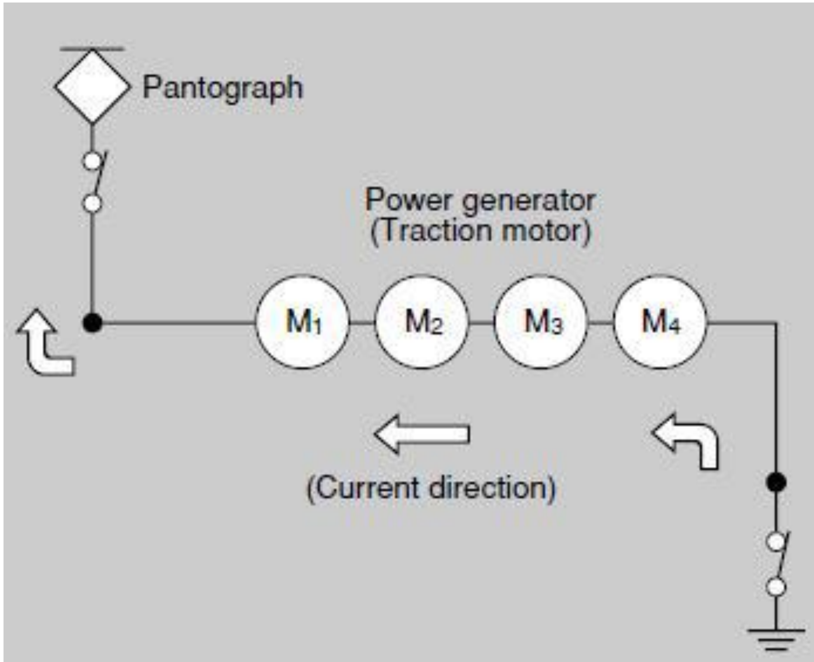

Figure 1-3 Electric regenerative

Regenerative braking technique is an energy recovery mechanism used in metro system to recover the tractive energy during braking into electricity [28].

1.8 Statement of the problem

Nowadays energy consumption is an important issue on transportation sectors. Power usage of train is varies on time and place, rail transport is very high energy consume during operation and energy loss happened; it affects rail company growth as well as environment.

Train movement during peak hour consume high energy because of train overloading capacity. Effects of overload capacity in rail traffics includes environmental, social and economic losses. This thesis work shows that energy consumption of train at difference loading capacity of AALRT.

1.9 Research Question and/ or Hypothesis

On this research work, starts from many different approaches to the problem were considered until the method that was used to decide. The aim of this thesis is build a mathematical model and simulate to get the specified train energy consumption at different train loading capacity. Some research questions that were to be answered were:-

- How to calculate energy consumption of the train?
- What kinds of method follow to evaluate all parameters?
- How to determine the traction energy consumption of train?
- How to analyze energy consumption and regenerative energy at different load conditions?
- How to save the regenerative energy?
- What kinds of method used to formulate the appropriate energy analysis for train?
- How to build a Mathlab/Simulink software for train energy analysis?
- How can simulate train energy consumption using software? Etc
- How to show the simulation result using graphically?
- How to compare energy consumption and regenerative energy at different load condition in percentage?

1.10 Conceptual frame work

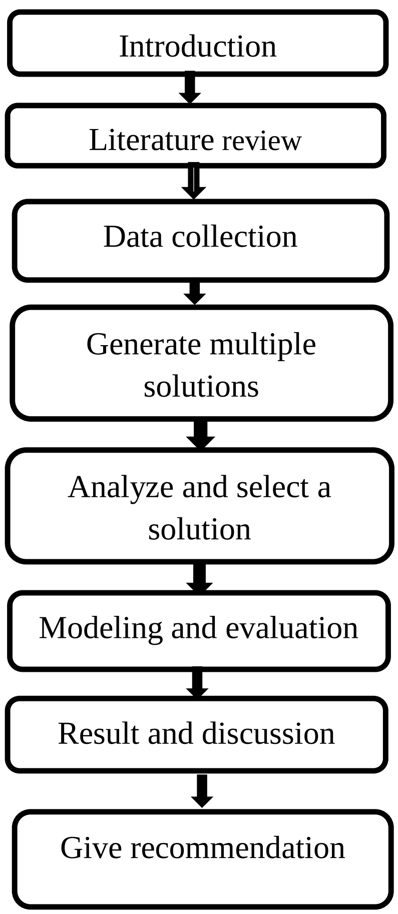

Figure 1.4 Research flow diagram

1.11 Objectives

1.11.1 General objectives

The main objectives of this research is to determine the effect of overload capacity on energy consumption of the Addis Ababa LRT especially E-W (Ayat to Torhiloch) line.

1.11.2 Specific objectives

- To determines the amount of traction/regenerative energy consumed/produced by train running between stations
- Determine all the require force and resistance acting on the train
- To calculate total energy consumption of the train at different load capacity
- Mathematical modeling of train energy consumption
- Build a Mathlab/Simulink loop to determine traction, speed holding and regenerative energy of AALRT train at level, uphill and downhill track position at different load condition.
- Simulate energy consumption of train using Simulink
- Compare energy consumption of the train at different load condition

1.12 Scope and limitation of the research

The aim of this thesis work is used to determine the effect of train overload capacity in energy consumption of the train and also used to determine train regenerative energy at different load capacity.

In this paper use a mathematical model to determine energy consumption and regenerative energy by considering different train parameter including train dynamics motion, driving resistance and tractive effort.

The train energy consumption is analyzed in one direction of the train movement from Ayat to Torhailoch. In this thesis the train energy consumption is analyzed the energy used only from regenerative energy such that the regenerative energy from braking trains can be more effectively used to accelerate trains.

1.13 Research Methodology

- **Research design**

This thesis work is observational studies type to achieve the objectives, which is based on previous research journals, all the parameters that will be used in this research simulation is from LRT and rail standard specification.

- **Research area**

This research shall address train energy analysis using different load condition, the energy consumption of LRT.

- **Data collection**

Data collection methods of this research work is

- ✓ By browsing energy consumption of scientific journals
- ✓ Different energy consumption related books
- ✓ From National Railway Standard specification
- ✓ From Ethiopian railway corporation specification data and by visiting LRT project

- **Issues of reliability and validity**

Now a day power usage for electric train is a critical issue, which is play important role for rail transport, environmental friendly, cost reduction of energy, growth of economies for the company.

- **Method of Analysis**

- **Input data**

On this research work the input data is the data which is previously analyzed, interpret and mathematically modeled of collected data used to give the required output parameters.

- **Modeling**

Analyze the energy consumption of rail vehicles; it is include deriving a mathematical model for the system and using the simulation to get the result hence to predict energy consumption.

- **Parameterization**

On this research work all the required parameters are determined by the vehicle mathematical modeling and computer simulation to identify the required parameters.

- **Discussion**

This thesis present energy consumption concept that play important role on energy saving of train, develop mathematical model that can show train power usage.

Finally, this paper organized as follows:-

- The first step after collecting of data,
    - Gives brief description on introduction and background and literature of energy consumption of electric train.
- Next step deals with formulates the mathematical model for energy consumption systems, describes the procedures for determination of the parameters for these model.
- Use computer softer ware for simulation program of consumption energy modeling and determination of the parameter. Clear understanding and analyzing appropriate simulating tools to solve the problem which is stated on this research.
    - SIMULINK software is used for this thesis work.
    - Modeling and simulating the system by feeding the parameters.
- On this section gives brief discussion the simulation results
- Finally, present conclusion, recommendation and direction of future study.

CHAPTER TWO

2. Literature review

2. 1 Train dynamics

In order to investigate how the energy consumption of train calculated, it is essential to first study the theory of train motion dynamics.

2.1.1 Tractive effort

The trains are moving along a route involves many force components, including tractive effort (TE), resistance braking force and train weight. Tractive force provides a necessary force to move a train, resistance known as drag and consisting of the force acting on the wheels and externally on the train body, opposes the movement and speed of the train. To accelerate or decelerate the train, the tractive force must be transferred between wheels and the running surface of the rail through a friction force called adhesion [13].

F**t** induced tractive effort is generated by the locomotive or the power equipment of the multiple units. Which is the only internal effort from the train itself to control the train and it is related to the train power P (W) and speed (m/s).

$$F_t = \frac{P}{v} \dots\dots\dots\dots\dots\dots\dots 2.1$$

2.1.2 Resistance effort

Train resistance effort, it refers to the resistance caused by [13] [14]

- Gradient resistance
- Curve resistance
- Aerodynamic resistance
- Internal mechanism resistance or rolling resistance

2.2 Train motion behavior

When the train run on rail track, four kinds of possible basic motion behavior can be identified in practices, such as

- Acceleration
- Cruising

- Coasting and
- Braking

During acceleration phase, a train tractive force effort should be higher than the resistance force. Cruising phase means that the train is running at a constant speed. In this case, the traction effort and resistance effort equals.

The coasting phase means that the train is running without any effort from the engine in roll out case where traction effort is zero. In this case the train will not consume any energy and its speed may increase or decrease depending on the gradient of the section and the value of train resistance. The braking phase of train means that the train is reducing speed with traction force $F_{traction} < 0$. However, from a practical usage point of view it can be classified as

- Normal braking (comfortable braking) and
- Emergency braking.

Normal braking is used in normal situation, and its deceleration effort is smaller than that of the emergency braking in order to make passenger feel more comfortable, while emergency braking is used in unexpected situations and its objective is to make the train from moving to standstill as soon as possible.

2.3 Train Control Regimes

Train control for most transit operations represents a cycle of different motion regimes, including acceleration, cruising, costing and braking.

Four basic train controls and their motion regimes are

- Control I: Acceleration, then braking must apply;
- Control II: Acceleration, cruising, then braking must apply;
- Control III: Acceleration, cruising, coasting, then braking must apply; and
- Control IV: Acceleration, coasting, then braking must apply.

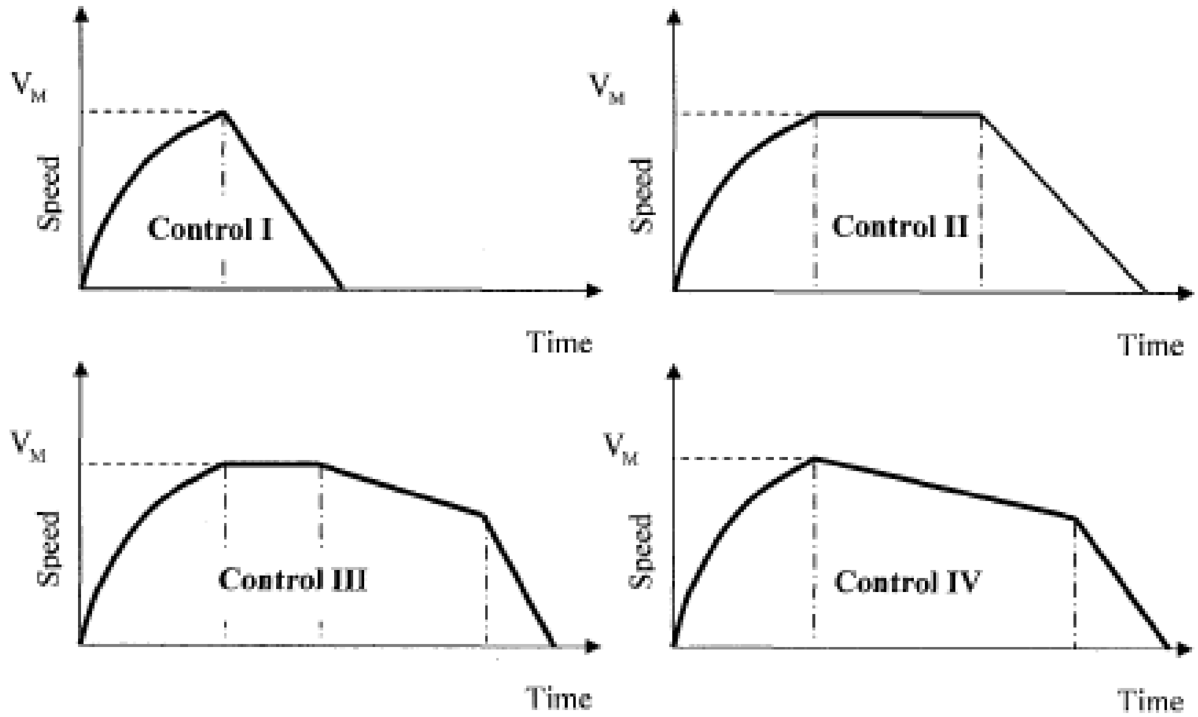

Figure 2-1 Four cases of inter-station train control regimes [13]

The figure above contains a set of motion regimes such as acceleration, cruising, coasting and braking which affected by maximum operating speed (V_M), acceleration or deceleration rates and station spacing. Controls I and II are used to achieve the least travel time for station spacing, in control II, a train accelerates until the velocity reached at maximum, and then maximum velocity is maintained until a brake must be applied to stop at the next station. It is obvious that control II operation drives shorter travel time but consumes more energy, compared to those in controls III and IV. Control III operation is commonly used for reducing energy consumption, which consists of an acceleration interval to reach at maximum velocity, cruising at that speed, coasting, and then braking. By using Control IV operation, the consumed energy can be further reduced, albeit the longest travel time [13].

2.4 Energy use by rail passenger trains

Rail passenger train energy efficiency depends on many variables. In large part, through an analysis of energy consumption in passenger transportation begins with four basic factors such as

- Surface contact friction (rolling wheels)

- Air drag (wind resistance)
- Mass and weight (which influence acceleration/deceleration requirements and contact friction) and
- Load factor (the percentage of occupied seats or space).

Surface friction is a source of rail's advantages in transport energy efficiency.

Air drag is minimal at very low speed, but it rises rapidly with increasing speed. In fact, drag is related to speed cubed, and affects all vehicles.

Mass affects energy consumption because it takes energy to accelerate the vehicle and its passengers, and most of this energy is subsequently wasted as heat in the braking system when the vehicle slow. Weight also increasing rolling friction.

Weight reduction the weight of any motor powered vehicle is essential to its performance, as it is directly related to motor's energy consumption. Weight reduction is a widely used method to lower electric input for traction. As the purpose of the train is to transport people, railway researches have established mass per seat as the most relevant measurement of energy efficiency. Thus, the lower the mass per seat is, the less energy it would require to achieve its target velocity [22].

The weight reduction of railway vehicles has different impacts. One result is the energy saving. Simulations have shown that the potential for savings through reduction of vehicle mass is dominated by the characteristics of the service profile. There is a particularly high potential for savings with service profiles that have short distances between the stations and low maximum speeds. As the maximum speed increases, the proportion of energy needed to overcome aerodynamic resistance increases and the potential for savings goes down [24].

The lightweight design of railway vehicles leads to numerous primary as well as secondary advantages. The primary effects are e.g. energy reduction and adherence of the maximum load per wheel set. Secondary effects include reduction of wheel sets itself what leads to a weight reduction of the trains and the aerodynamic resistance. A comparison of road and rail vehicles reveals that rail vehicles must move more mass per passenger than road vehicles. Reasons for this include high requirements on static and dynamic loads and a configuration of the vehicles for greater mileage.

Car body weight and the required drive power are mutually influencing. If operational requirements (train schedule) demand a specific acceleration capability, then the required drive power will increase proportionally to vehicle mass. This implies that a secondary effect of a lower vehicle weight is a reduction of the installed drive power, resulting in additional energy savings [24].

The past few years many researchers have addressed ways to reduce energy consumption by railroads. In a study of the energy savings with train operations, due to the huge amount of energy it consumes every day, highly-efficient operation of a metro system lead to significant energy savings.

Sergey E.Galushine et al. They proposed that design a realistic performance of passenger train [11]. The main goal of their research work is to design a realistic performance of a passenger train for regional service and study its energy consumption and running time. On this research a mathematical of the train has been developed, to determining time evolution of the speed, acceleration, energy consumption and distance travelled of the train. Running times defined for different braking modes allowed as to develop an optimal schedule in order to meet time window constraints for terminal and intermediate stations. Their result shows that to increase maximum speed in curves with a tilting train; higher tilting angle gives higher speed, to decrease power consumption by developing more sophisticated model that takes into account time margins and uses it for more energy efficient driving.

Cheng Gong, et al. studied a new integrated energy-efficient operation methodology (EOM) for metro system [1] is proposed and validated.in this research work they proposed timetable optimization (TO) and compensational driving strategy algorithm (CDSA).

The main idea is to synchronized the dwell time of each train at every station and make the braking and acceleration happen simultaneously so that the regenerative braking energy can used to the great extent. A genetic algorithms is used to modify the dwell time of each stop to obtain the most optimal energy-efficient timetable, then, in order to save additional energy when disturbance happen CDSA is formulated, to validate the correctness and effectiveness of energy-savings a real case of shanghai metro line one is studied.

David Fournier et.al proposed optimizing metro regenerative energy usage [2]. They showed that the accelerating and braking trains need by synchronized to fully benefit from the regenerative energy and a metro timetable is energetically optimized when all the train regenerative braking is utilized to power other trains. They presented a greedy heuristic to tackle the problem of minimizing global energy consumption of a metro train line by re-scheduling dwell times in stations. They showed their results by savings of the total energy consumption by 5.1%.

In mass transit system, there are two operating modes for two consecutive trains:

- ✓ The following train either systematically applies the same speed profile as the leading train, or
- ✓ The following train adjusts its speed to a different speed profile according to the position, speed and regeneration potential of the leading train.

Haichuan Tang et al. they presented that optimized train speed profile to improve regeneration efficiency of train transit operation [4]. This paper is to develop the optimal speed profile for following train in order to minimize pantograph voltage fluctuation and improve energy recovery efficiency. To solve this, dynamic programing is applied to this problem in order to optimize the speed profile, simulation result with Visual C++ demonstrate that the algorithm can provide an optimal operational strategy with better performance. This paper examines the prospects for recovering and reusing energy from regenerative brakes under transit system operational constraints. Simulation result show that, the optimal algorithm can successfully reduce total energy consumption and voltage fluctuation by increasing the use of regenerative braking energy produced by the leading train.

Kyung min Kim et al. suggested a mathematical approach for reducing the maximum traction energy [5].they described reduction in the peak traction energy of mass rapid transit (MRT) rail ways through timetabling. They develop a mixed integer programing (MIP) model that minimize the maximum traction energy that occurs when trains running simultaneously. They tried to two approaches the commercial MIP solver CPLEX and a heuristic algorithm .When multiple trains are operating in the same power supply system, the peak power energy is increased. This paper proposed a mathematical approach that can smooth the peak power demand in timetables. They determined a feasible solution that resulted in an improvement of approximately 32% over the current timetable.

To improve regenerative energy receptive and energy savings in a bi-directional metro transit network, Haichuan Tang et.al. Formulates a coordinated train control algorithm to improve regenerative energy receptivity in metro transit system [6] based on genetic algorithm techniques. They analyzed a mathematical energy consumption model of bi-directional trains running in the same power section had been established based on train operation and electrical theories. They applied genetic algorithms to generate an optimal speed profile for the second train to minimize energy consumption at the power substations improvements like dual search loops and adaptive probability are introduced to the GA formulation to ensure the efficiency and effectiveness of the algorithm. Finally, the energy saving from regenerative braking is estimated between 10% to 45%, it usually cannot be reached due to various factor. Based on current system regenerative receptive level, simulation result show that the coordinated train control algorithm can save up to 12.7%

Kim et.el proposed a mathematical model and approaches for synchronized energy saving in timetable [7]. The energy-efficient timetabling method, they maintains the planned traveling time between stations, but coordinated the train departure times at the starting station from current timetable. They formulated this problem as a multi-criteria mixed integer programing to minimize the peak energy and simultaneously to maximize the re-usage of regenerative energy. They show their experimental results by improvement of not only approximately 40% in peak energy, but also 5% in re-usage of regenerative energy.

In peak hours the first objective is to move as many people as possible increasing the train frequency, in off-peak hours other consideration can be taken into account. Andres Ramos et al. developed a mathematical programing approach to underground timetabling problem for maximizing time synchronization [8]. The model presented in their paper is a decision support tool that can be used for maximizing the overlapping time between the slow-down and speed –up processes of underground trains in order to achieve energy saving during off-peak hour. This problem has formulated as a MIP optimization problem with a combinatorial nature and very difficult to solve.

Gerben M. Scheepmarker et al. proposed running time supplements: energy-efficient train control versus robust timetables [10]. They describes the developed energy-efficient operation (EZR) model based on optimal control theory and algorithm that determines the joint optimal cruising speed and coasting point for individual train trips. An energy-efficient train control model has been developed in MATLAB and has been applied to a real case. This so-called EZR model determines the energy-efficient driving strategy by calculating the optimal cruising speed and coasting point based on the knowledge of the optimal energy-efficient driving regimes obtained from Pontryagin's Maximum Principle.

Shuvomoy Das Gupta et al. developed linear programing makes railway networks energy-efficient [12]. They proposed a novel two-stage linear optimization problem to calculate energy-efficient timetables in electric railway networks. The resultant timetable minimizes the total energy consumed by all trains and maximizes the utilization of regenerative energy produced by braking trains, subject to the constraints in the railway network.

- They proposed a novel two-stage linear optimization problem to calculate energy –efficient railway timetable. The first optimization model minimizes the total energy consumed by all trains subject to the constraints present in the railway network. The problem can be formulated as a linear program, with the optimal value attained by an integral vector.
- Based on the solution for the first problem, the final optimization model maximizes the transfer of regenerative braking energy between suitable train pairs, while keeping the total train energy consumption at the minimum.
- Optimization model is a linear program, hence is computationally the most efficient one.

They applied their model to eleven different instances of service PES2-SFM2 of line 8 of Shanghai Metro network. The timetables span full service period of one day (18 hours) with each instance having thousands of active trains. In comparison with the original timetables, the final timetable produced by their model reduces the total effective energy consumption significantly, even the worst case reduction being 19.27%.

Finally, energy consumption is an important topic nowadays, also in the railway sector. A lot of money can be saved by decreasing the energy consumption of the trains. All the above researchers are studied how to reduce the energy consumption of train by modifying the existing timetables.

CHAPTER THREE

3. Mathematical modeling and simulation for train energy analysis

3.1 Introduction

Railway operators are heavy users of electric energy. To implement energy saving programs and to study economical operation strategies, an energy estimating model is required.

On this chapter describe the physical properties of traction, coasting and braking train using dynamics. The movement of the train over a track between stations are deferent, it may be the train pass on three position such as level, uphill and downhill position, which has an acceleration, resistance to motion and the effect of gravity. The mass of the train, the magnitude and the angle of the track to gravity is used to determine the effect of gravity.

To estimate the energy consumption of the train balance of traction efforts applied on the train is the first approach found in the literature. During energy analysis the train with mass is consider as a point and Newton's second low is applied to determine the force.

In place of the use of a complete driving pattern with detailed sequential analysis of time, speed and /or distance is focused on the calculation of energy consumption. To analyze energy consumption of the train numerically, energy consumption is equals to the products of the driving resistance multiplied by the driven distance. For a given train the parameters used to calculate driving resistance are at most a function of speed. The train acceleration, rolling and gradient resistance are proportional to the train total mass.

Duration of operation between two stations, an ideal operation consists of a number of accelerations, operations at constant speed and then braking. This pattern will be similar between every stations.

The main objective of this research work is analyze the effects of train overloading on energy consumption compering with at normal and maximum loading conditions of AA LRT of Ayat to Torhiloch line during peak hour.

The numerical analysis presented in this chapter is used for comparing with simulation results.

3.2 Main parameters of Addis Ababa LRT East West Line

There are a lots of input parameters for simulation, including speed, train properties, operation parameters, railway alignment etc. the major input parameters of train is listed below in tables.

3.2.1 Technical data of LRT

The table below, all parameters are used to determine the traction force and train resistance to analyses the energy consumption of the train in different load condition.

Table 3.1Train specification parameters of AALRT

No	Input Data Parameters	value
1	Empty train Vehicle Weight	44000 Kg
2	Average Weight of passenger	60 kg
3	Motor efficiency	87%
4	input power per electric motor(four motor for one vehicle)	130 KW
5	Gravitational acceleration	9.81 m/s^2
6	Aerodynamic resistance coefficient (Ca)	1.8
7	Rolling resistance coefficient (Cr)	0.002
8	Mass factor (f_m)	1.05
9	Maximum operation speed	70 Km/hr
10	Train acceleration for maximum operation speed	$\geq$ 0.5 m/s^2
11	Service brake deceleration	1.1m/s^2
12	Air density	1.2 kg/m^3
13	Frontal area of vehicle (width X height)	2.65*3.70 = 9.805 m^2

3.2.2 Train weight

Table 3.2 Passenger loading of AALRT

No	Number of passengers	Seated	Standing	Total
1	Seats capacity (AW2) (standing 6 persons/m2)	65	189	254
2	Maximum train capacity (AW3)(Standing 8 persons/m2	65	252	317
3	Unacceptable overloading capacity(AW4)(Standing 10 person/m2)	101	319	420

3.3 Train Equation of motion

To solve the energy consumption of train operation, it is necessary to determine the dynamic behavior of the train at a specified route.

Using equation of motion evaluate accelerating and braking distance of the train

$$v_{max}^2 = v_o^2 + 2ax \dots\dots\dots\dots\dots\dots 3.1$$

Where

V_{max} Maximum operation speed in m/s

v_o Initial speed in m/s

a Acceleration or deceleration m/s

x Acceleration or deceleration distance in m

From table 3.1 train technical parameters of AA LRT, determine acceleration and braking distance in m.

$$x_a = \frac{v_{max}^2}{2 * a} = \frac{19.44^2}{2 * 0.8}$$

$$= 236.2m$$

$$x_b = \frac{v_{max}^2}{2 * a} = \frac{19.44^2}{2 * 1.1}$$

$$= 171.78m$$

Train speed between Ayat to Meri station at level distance of 170m is:

$$x_a = \frac{v_{max}^2}{2 * a}, \quad v_{max}^2 = 2x_a * a$$

$$v_{max}^2 = 2 * 0.8 * 170$$
$$= 16.49\ m/s$$

The model presented is based on the fact that the energy needed during a specific trip of a train is the energy needed to overcome all the resistances during the motion of the train. All the different driving resistances must be considered. These are presented as below.

3.4 Train driving resistances

The traction, braking and physical properties of a train determine its dynamics. The movement of the train over track is illustrated below, which has an acceleration, a resistance to motion, and the effect of gravity. The effect of gravity is determined by the mass of the train, the magnitude, and angle of the track to gravity.

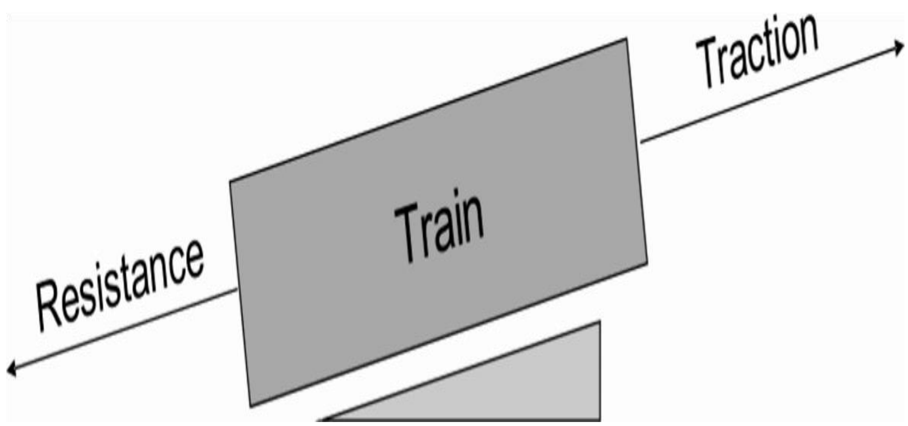

Figure 3-1The movement of a train over track

The above figure shows that motion of a train with forward force from traction, resistive force from resistance and effect of the track gradient due to the force from gravity.

Before analyzed energy consumption and regenerative energy of the train, first of all determine train acceleration force and driving resistance. Using train specification parameters of AALRT table 3.1, passenger loading table 3.2 and track profile table 3.3 calculate acceleration force, aerodynamic, rolling and gradient resistance of the train.

The energy consumption between Ayat to Meri stations are calculated analytically as bellow. The space between Ayat to Meri stations is 1260m. the track profile include 170m level, 250m downhill, 510m level, 224m uphill and 106m level.

Using Newton' 2nd low, determined the sum of forces with acceleration such as;

$$\sum F = m * a \dots\dots\dots\dots\dots\dots\dots 3.2$$

a is the acceleration that the train is experiencing when all the different forces F are applied to it. Thus, the connection between the driving resistances and motion is given as follows:

$$f_m * m * a = F_t - (F_r + F_a + F_g + F_c) = F_t - F_r - F_a - F_g - F_c \dots\dots\dots\dots\dots 3.3$$

Where

F_t: Traction force at the wheels

F_r: Rolling resistance

F_a: Aerodynamic resistance

F_g: Gradient resistance

F_c: Curve resistance

Table 3.3 Track profile and station length of Ayat to Torhiloch line

No.	Stations name	Track profile	Total Station length(m)
1	Ayat -Meri	$0 \le X_L \le 170$ $170 \le XD \le 419.995$ (38.5‰) $419.995 \le X_L \le 929.995$ $929.995 \le X_U \le 1153.995$ (50‰)	1260
2	Meri - CMC	$0 \le X_L \le 1092$	1092
3	CMC - St.Micael	$0 \le X_L \le 435.078$ $435.078 \le XD \le 711.078$ (37.5‰) $711.078 \le X_L \le 863$	863
4	St.Micael - Civel Service Collage	$0 \le X_L \le 860$	860
5	Civel Service Collage - Management institute	$0 \le X_L \le 724.821$	724.821
6	Management institute - Gurd Shola 1	$0 \le X_L \le 128.912$ $128.912 \le X_D \le 348.52$ (53.6‰) $348.52 \le X_L \le 970$	970
7	Gured Shola 1 - Gured Shola 2	$0 \le X_L \le 70.52$ $70.52 \le X_U \le 421.017$ (29‰) $421.017 \le X_L \le 1081.761$	1081.761
8	Gured Shola 2 - Megenagna	$0 \le X_L \le 509.156$ $509.156 \le X_D \le 714.156$ (43.5‰) $714.156 \le X_L \le 805$	805
9	Megenagna - Leme hotel	$0 \le X_L \le 426.156$ $426.156 \le X_D \le 581.156$ (35‰) $581.156 \le X_L \le 802$	802
10	Leme hotel - Hayahulet 1	$0 \le X_L \le 746$	746
11	Hayahulet 1 - Hayahulet 2	$0 \le X_L \le 164.087$ $164.087 \le X_U \le 489.087$ (55‰) $489.087 \le X_L \le 771$	771
12	Hayahulet 2 - St. Urael	$0 \le X_L \le 633.974$ $633.974 \le X_D \le 829.974$ (43.5‰)	950

		$829.974 \le X_L \le 950$	
13	St.Urael -Bambis	$0 \le X_L \le 675$	675
14	Bambis - St.Estifanos	$0 \le X_L \le 95.326$ $95.326 \le X_U \le 449.33$ (47.5‰) $449.33 \le X_L \le 583$	583
15	St.Estifanos - Stadium	$0 \le X_L \le 650$	650
16	Stadium - Legehar	$0 \le X_L \le 435$	435
17	Legehar -Mexico	$0 \le X_L \le 570$	570
18	Mexico - Tegebared	$0 \le X_L \le 688$	688
19	Tegebared - Lideta	$0 \le X_L \le 61.313$ $61.313 \le X_D \le 226.313$ (46‰) $226.313 \le X_L \le 386.313$ $386.313 \le X_U \le 664.313$ (55‰) $664.313 \le X_L \le 735$	735
20	Lideta - CocaCola	$0 \le X_L \le 229.313$ $229.313 \le X_D \le 666.462$ (55‰) $666.462 \le X_L \le 732$	732
21	CocaCola - Torhiloch	$0 \le X_L \le 342.462$ $342.462 \le X_U \le 484.462$ (55‰) $484.462 \le X_L \le 769$	769

$m * a$ is normally called the acceleration force F_A, or acceleration resistance.

$$m * a = F_t - F_r - F_a - F_g + F_c \dots \dots \dots \dots \dots \dots 3.4$$

The traction force of the train becomes;

$$F_t = F_r + F_a + F_g + F_c + F_A \dots \dots .. \dots \dots \dots \dots 3.5$$

Acceleration resistance force for normal condition, $f_m = 1.5$ is mass factor which is taken from the paper [26].

$$F_A = m * f_m * a \dots \dots \dots \dots \dots \dots \dots 3.6$$

$$\text{m} = \text{passenger weight} + \text{vehicel weight} \dots \dots \dots \dots 3.7$$

$$= 44000kg + (254 * 60)kg$$

$$= 59240kg$$

$$F_A = 59240 * 1.05 * 0.8$$

$$= 49761.6N$$

3.4.1 Curve resistance

When the train travels on a curve section of its travel ways, an external force acts on the vehicle. Different components of these forces tend to retard the forward motion of the vehicle. The sum of these component is the curve resistance.

In train motion this resistance depends on

- friction between wheel flange and rail,
- Wheel slippage on the rails, and the radius of curvature.

Curve resistance is also caused by increasing of tension (direction of tangent of the curvature, increase of pressure on the internal track or external one and possible bad maintenance on the line.

The formula that gives the curve resistance used is

$$F_c = \frac{c_{ro}}{R - c_{r1}} * m_{stat} \dots\dots\dots\dots\dots\dots\dots 3.8$$

Where

F_c: Total curve resistance

m_{stat}: Total train static mass (Kg),

Sum of train empty weight and passenger weight

C_{r0}, C_{r1}: Constant known values

R: Curve radius (m)

3.4.2 Aerodynamic resistance

The air in front of and around a vehicle in motion causes resistance to the movement of the vehicle, and the force required to overcome this resistance is known as air resistance.

The magnitude of this force depends on the square of the velocity at which the vehicle is traveling and the cross-sectional area of the vehicle.

Calculation of the air resistance in train motion is:

$$F_a = 0.5 * \rho * C_a * A_{fr}(v + v_{wind})^2 \ldots\ldots\ldots\ldots..3.9$$

Where

F_a: Total aerodynamic resistance (N)

v: Train's speed (m/s)

v_{wind}: The (head) wind speed (m/s)

ρ: Air density (kg/m3)

C_a: drag coefficient

A_{fr}: The frontal area (m2)

The value of train speed of AALRT is 0-19.44 m/s, for train traction phase its variable with time. For constant speed, the maximum speed 19.44 m/s is taken. The value of train speed is 16.49 m/s at level distance 170 m between Ayat to Meri. Take average speed to determine train energy consumption analytically. Aerodynamic resistance force becomes

$$F_a = 0.5 * \rho * C_a * A_{fr} * v_{tr}^2 \ldots\ldots\ldots\ldots..\ldots\ldots.3.10$$

$$F_{a170} = 0.5 * 1.2 * 1.8 * 9.805 * 8.25^2$$

$$= 720.74N$$

The velocity for aerodynamic condition we can take the average value of the level position, which is calculated before on station one.

At distance 66.20m

$$F_{a66.20} = 0.5 * 1.2 * 1.8 * 9.805 * 17.97^2$$

$$= 3419.54N$$

Aerodynamic resistance force for constant speed

$$F_a = 0.5 * 1.2 * 1.8 * 9.805 * 19.44^2 \, , at \; v_{max} = 19.44m/s$$

$$= 4001.88N$$

During coasting phase train running at maximum speed, the acceleration of the train is zero.

3.4.3 Gradient resistance

In a rail vehicle rolling along a straight level track, the force component perpendicular to the direction of gravity is zero.

when the plane of the track is inclined (e.g. when the train runs uphill or downhill), a force component F_2 develops parallel to the plane of the track and in the case of an uphill gradient this component is an additional resistance to vehicle motion.

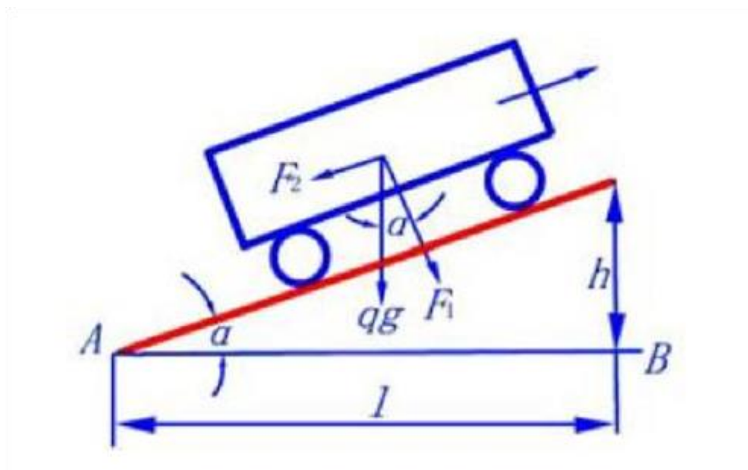

Figure 3-2 Derivation grade resistances

The equation that gives the gradient resistance is:

$$F_g = m_{tot} * g * \frac{\Delta h}{x} * 1000 \dots\dots\dots\dots\dots\dots\dots\dots 3.11$$

Where

F_g: Total gradient resistance (N)

m_{tot}: Train mass (kg)

g: Acceleration of gravity (9.81 m/s^2)

a: Angle of the gradient

Δh : Is the height difference (m) over the horizontal distance (m)

And the similar equation that Bombardier uses is:

$$F_g = m_{stat} * g * \frac{s}{1000} \dots \dots \dots \dots \dots \dots \dots \dots . . 3.12$$

Where

F_g: Total gradient resistance (N)

m_{stat}: Total train static mass (kg)

g: Acceleration of gravity (9.81 m/s^2)

S: Gradient (‰)

For downhill gradient, r_g(gradient between station Ayat to Meri) is 38.5‰

$$F_g = m * f_m * g * r_g/1000 \dots \dots \dots \dots \dots \dots \dots \dots \dots 3.13$$

$$= 59240 * 1.05 * 9.81 * {}^{38.5}/_{1000}$$

$$= 23492.76N$$

For uphill gradient, r_g(gradient between station Ayat to Meri) is 50 ‰

$$= 59240 * 1.05 * 9.81 * {}^{50}/_{1000}$$

$$= 30510.08N$$

3.4.4 Rolling resistance

Rolling resistance is the sum of the mechanical forces, exclusive of windage and braking, acting to impede the forward motion of a train traveling at constant speed on level track under operating conditions.

For the calculation of total rolling resistance (normal and abnormal) is:

$$F_c = C_r * m_{tot} * g \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . 3.14$$

Where

F_R: Total rolling resistance (N)

C_R: Rolling resistance coefficient

m_{tot}: Train mass (kg)

g: Acceleration of gravity (9.81 m/s^2)

Rolling force is becomes

$$F_r = C_r * f_m * m * g \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3.15$$

$$F_r = 0.002 * 59240 * 1.05 * 9.81$$

$$= 1220.4N$$

3.5 Train Energy Consumption

The total energy consumption can be calculated in several ways. Two main ways to calculate the energy consumption. The first one is based on distance while the second one is based on time. In this research work, energy consumption of the train in Mathlab/ Simulink analyzed based on power and time and for analytical analysis energy consumption formulated based on train resistance and distance.

In this paper work energy consumption of the train during traction and regenerative energy are studied.

Based on knowledge of driving resistance energy consumption calculated by integration of total force by the traveled distance

$$E = \int_{x_1}^{x_2} F_{tot}\, dx \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.16$$

$$= \int_{x_1}^{x_2} F_T(v) = m * f_m * a + (F_r(v) + F_a + F_{cv} \pm F_g)\, dx \ldots\ldots .. 3.17$$

Where, F_{tot} is the sum of driving resistances of the train as before mentioned.

On the other way energy consumption calculation based on power and time is mention below.

The total power P_e needed can be calculated as:

$$P_e = v * F_{tot} \dots \dots \dots \dots \dots \dots \dots .. 3.18$$

Where

P_e: Total power (W)

v: speed (m/s)

F_{tot}: Sum of the driving resistances (N)

Based on that the energy consumption is obtained by integrating the total power needed for the total trip time. This gives:

$$E = \int_0^t P_e \, dt \dots \dots \dots \dots \dots \dots \dots \dots . 3.19$$

Where

E: Total energy consumption (J)

P_e: Total power (W)

t: Elapsed time (s)

If P_e is constant, the energy consumption is:

$$E = P_e * t \dots \dots \dots \dots \dots \dots \dots \dots .. 3.20$$

The model that was preferred for this thesis was the one based on time.

Train model

The different modes that the train can be based on the output power of the motor and the motor torque. The output power (P) of the motor is given by:

$$P_{out} = T * \omega \dots \dots \dots \dots \dots \dots \dots . 3.21$$

Where:

P_{out}: The output power of the motor

T: The motor torque (tractive effort)

ω: The motor angular speed

3.5.1 Energy consumption for traction

To calculate energy consumption when the train accelerates to achieve maximum speed the following equation has been used

$$m * f_m * a = F_T(v) - \left(F_r(v) + F_a + F_{cv} \pm F_g\right) \ldots\ldots\ldots\ldots\ldots..3.22$$

Or

$$F_T(v) = m * f_m * a + \left(F_r(v) + F_a + F_{cv} \pm F_g\right) \ldots\ldots\ldots\ldots\ldots 3.23$$

Energy for level position

$$E_1 = (F_A + F_a + F_r)X_l \ldots\ldots\ldots\ldots\ldots\ldots 3.24$$

$$= (49761.6 + 720.74 + 1220.4) * 170$$

$$= 8789465.8J$$

For downhill acceleration

$$E_2 = (F_A + F_a + F_r - F_g)X_{down} \ldots\ldots\ldots\ldots\ldots\ldots 3.25$$

$$= (49761.6 + 3419.54 + 1220.4 - 23492.76)236.2 - 170$$

$$= 2046161.24J$$

Acceleration during powering mode is calculated by:

$$a_i = \frac{F(v) - \sum R(v)}{f_m * m} \ldots\ldots\ldots\ldots\ldots\ldots 3.26$$

3.5.2 Energy consumption for speed holding

When the train achieves the maximum speed, traction force must overcome running, grade, aerodynamic and curvature resistance for speed holding. Therefore, acceleration in these moments is zero and energy usage equals

$$0 = F_T(v) - \left(F_r(v) + F_a + F_{cv} \pm F_g\right) \ldots \ldots \ldots \ldots \ldots \ldots 3.27$$

$$F_T(v_{max}) = F_r(v_{max}) + F_a + F_{cv} \pm F_g) \ldots \ldots \ldots \ldots 3.28$$

$$E = \int F_T(v_{max})\, dv \ldots \ldots \ldots \ldots \ldots \ldots \ldots 3.29$$

For level constant speed

$$E_3 = (F_a + F_r)X_l \ldots \ldots \ldots \ldots \ldots ..3.30$$

$$= (4001.88 + 1220.4) * 510$$

$$= 2663362.8J$$

For downhill constant speed

$$E_4 = \left(F_a + F_r - F_g\right)X_{down} \ldots \ldots \ldots \ldots ..3.31$$

$$= (4001.88 + 1220.4 - 23492.76)(250 - 66.2)$$

$$= -3358114.2J$$

For uphill constant speed

$$E_5 = \left(F_a + F_r + F_g\right)X_{uphill} \ldots \ldots \ldots \ldots \ldots .3.32$$

$$= (4001.88 + 1220.4 + 30510.08) * 224(171.78 - 106)$$

$$= 5653574J$$

During costing mode:

$$a_i = \frac{-\sum R(v)}{f_m * m} \ldots \ldots \ldots \ldots \ldots \ldots .3.33$$

Model of constant speed becomes;

$$F_t - \sum R = 0 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..3.34$$

$$F_t - F_r - F_a - F_g - F_c = 0 \ldots \ldots \ldots \ldots .3.35$$

$$F_a = F_t - F_r - F_g - F_c \ldots \ldots \ldots .. \ldots \ldots .3.36$$

$$v_c^2 = \frac{P * \frac{\eta}{v} - F_r - F_g - F_c}{0.5 * \rho * C_a * A_{fr}} \ldots\ldots\ldots\ldots\ldots\ldots .3.37$$

Total energy consumption of train the sum of tractive and speed holding becomes

$$E_t = E_1 + E_2 + E_3 + E_4 + E_5 \ldots\ldots\ldots\ldots\ldots\ldots 3.38$$

$$= 8789465.8 + 2046161.24 + 2663362.8 - 3358114.2 + 5653574$$

$$= 15794449.64J$$

When we compare the simulation result with numerical analysis the difference is small

3.5.3 Regenerative Braking

During regenerative braking traction force is zero, energy generation can be calculated with the following formula

$$m * f_m * a = F_{reg}(v) + \left(F_r(v) + F_a + F_{cv} \pm F_g\right) \ldots\ldots\ldots\ldots\ldots .3.39$$

$$F_{reg}(v) = m * f_m * a - \left(F_r(v) + F_a + F_{cv} \pm F_g\right) \ldots\ldots\ldots\ldots 3.40$$

$$E_{reg} = \int F_{reg}\, dv \ldots\ldots\ldots\ldots 3.41$$

During braking mode acceleration calculated by:

$$a_i = \frac{F(v) + \sum R(v)}{f_m * m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots ..3.42$$

3.6 Train energy consumption simulation model

Simulink

The main goal of this thesis work is to determine the energy consumption of train at different load condition by using train driving resistance and equation of motion. The model is constructed using MATLAB/SIMULINK software.

Simulink is graphical extension to Mathlab for modeling and simulation systems. In Simulink, systems are drawn on screen as block diagrams, many elements of block diagrams are available, such as transfer function, summing junctions etc.., as well as virtual input and output devices such as function generators and oscilloscopes. Simulink is integrated with Mathlab and data can be easily transferred between the programs.

There are two major class of items in Simulink: blocks and lines. Blocks are used to generate, modify, combine, output and display signals. Lines are used to transfer signals from one block to another.

Blocks

There are several general classes of blocks:

- Sources: Used to generate various signals
- Sinke: Used to output or display signals
- Discrete: Linear, discrete-tie system elements (transfer functions, state-space models, etc.)
- Linear: Linear, continuous-time system element and connections (summing junctions, gains, etc.)
- Nonlinear: Nonlinear operators (arbitrary functions, saturation, delay, etc.)
- Connections: Multiplex, Demultiplex, System Macros, etc.

Lines

Lines transmit signals in the direction indicated by the arrow. Lines must always transmit signals from the output terminal of one block to the input terminal of another block. One exception to this is a line can tap off of another line, splitting the signal to each of two destination blocks. Lines can never inject a signal into another line; lines must be combined through the use of a block such as a summing junction.

3.6.1 Simulation

During train simulation programs energy consumption simulation is usually based on train movement module. Train dynamic model is required to obtain the parameters for calculating energy consumption at every time step.

The Simulink diagrams constructed based on mathematical model which previously analyzed. There are steps to model a Simulink diagrams such as

Identify the system

Before constructed a Simulink diagram, describe and represent a system. The system to be simulated in this research work is train traction, speed holding energy consumption and regenerative energy of Ayat to Torhiloch line AALRT train. This model define energy of a train at different load condition such as normal, maximum and train overloading.

The block diagram constructed at three track position such as:-

- ✓ Level position
- ✓ Downhill position and
- ✓ Uphill position

Identify all components

Parameters are represented by blocks and lines transmit signals (input and output values) that connected with blocks in Simulink diagrams. Three types of components defines a system such as:

Parameters a system values that remain constant unless they are changed. Gravitational acceleration, aerodynamic resistance coefficient, rolling resistance coefficient etc.

State these are variables in the system that change over time, such as train speed, acceleration, tractive force, aerodynamic force etc.

Signals input and output values that change dynamically during a simulation. Gradient, speed, acceleration are input values, energy consumption and regenerative energy are output values. These values are change when the input values are change.

Modeling the system equations

In this step, formulate a mathematical equation to describe the model. The model may include:

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

The model constructed based on train driving resistance such as

- ✓ Rolling resistance
- ✓ Aerodynamic resistance
- ✓ Gradient resistance

Additionally the model includes train total mass and mass factor.

All the above parameters include in to traction, speed holding energy consumption and regenerative energy analysis. During level position gradient resistance (uphill and downhill) are zero.

Simulink block diagram building

In this step develop schematic and networked Simulink block diagram after formulated a mathematical equation for traction, speed holding and regenerative energy.

Run the simulation

After all the above steps are preformed, input all the parameters and run analyze the system.

Validate the model

Compare the model’s result with numerical analysis.

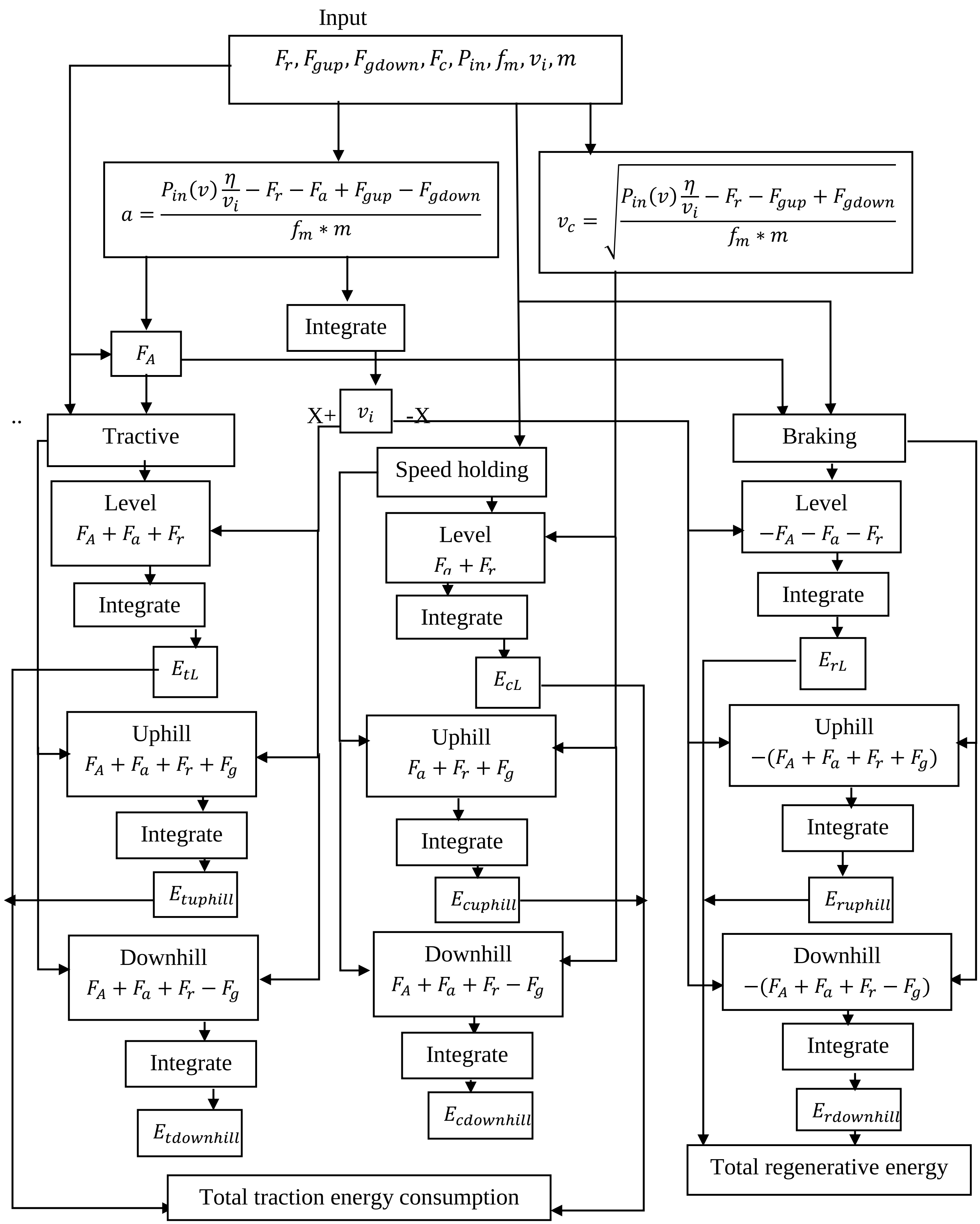

Figure 3-3 Energy analysis flow chart

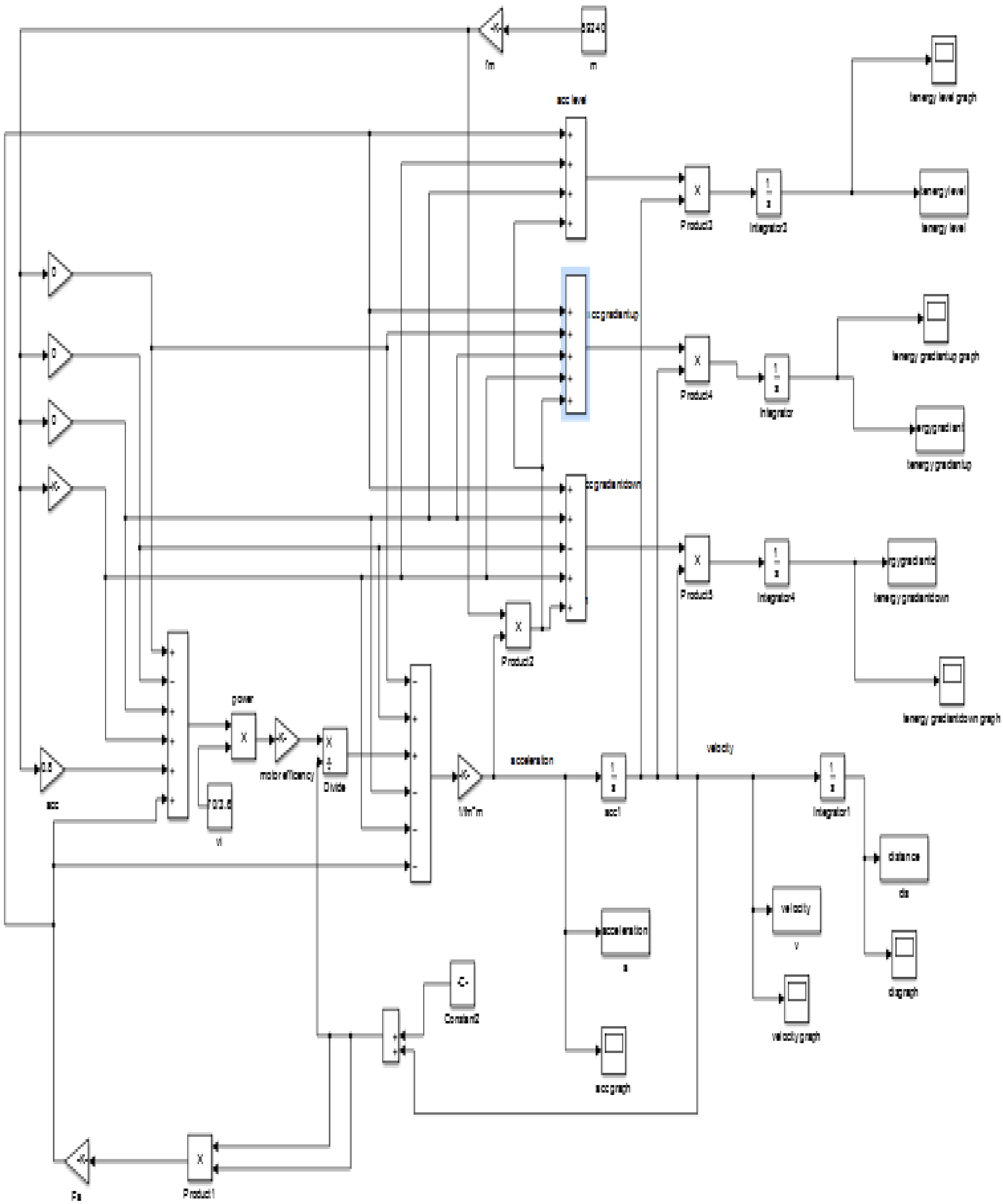

Figure 3-4 Simulink block diagram for train traction phase

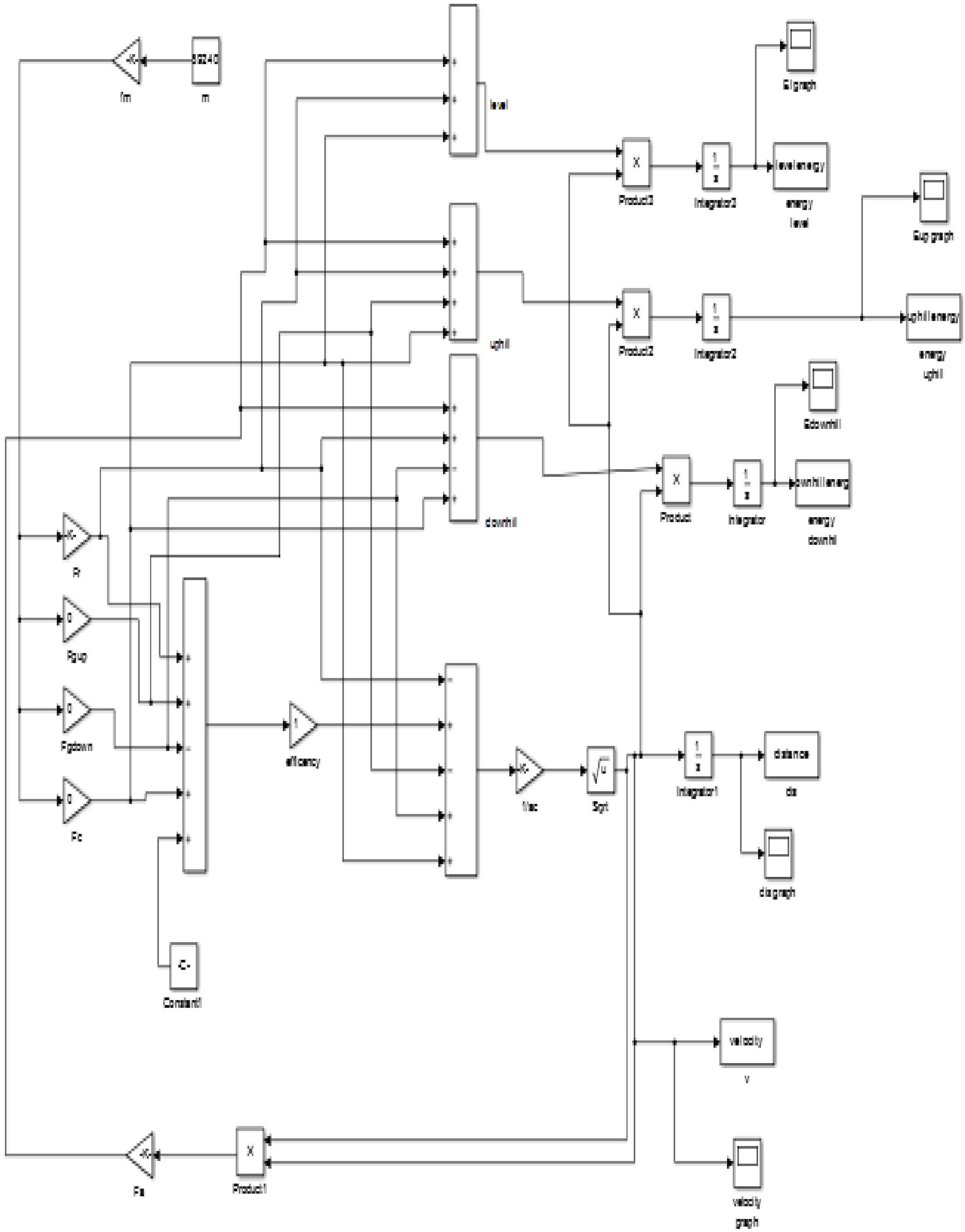

Figure 3-5 Simulink block diagram for train speed holding phase

CHAPTER FOUR

4. Result and Discussion

4.1 Result

This chapter gives result and brief discussion of energy simulation of the train that previously interpreted. The main objective of this thesis work is investigated total energy consumption during train acceleration and coasting phase and regenerative energy of trains during braking phase using Mathlab/Simulink at different load capacity. Three load conditions are considered here, such as train operation at normal load, maximum and overload.

Different inter stations runs with level, uphill and downhill tracks have been examined to obtain energy consumption of the train. With based on train simulate, the results are summarized in tables 4.1, 4.2 and 4.3.

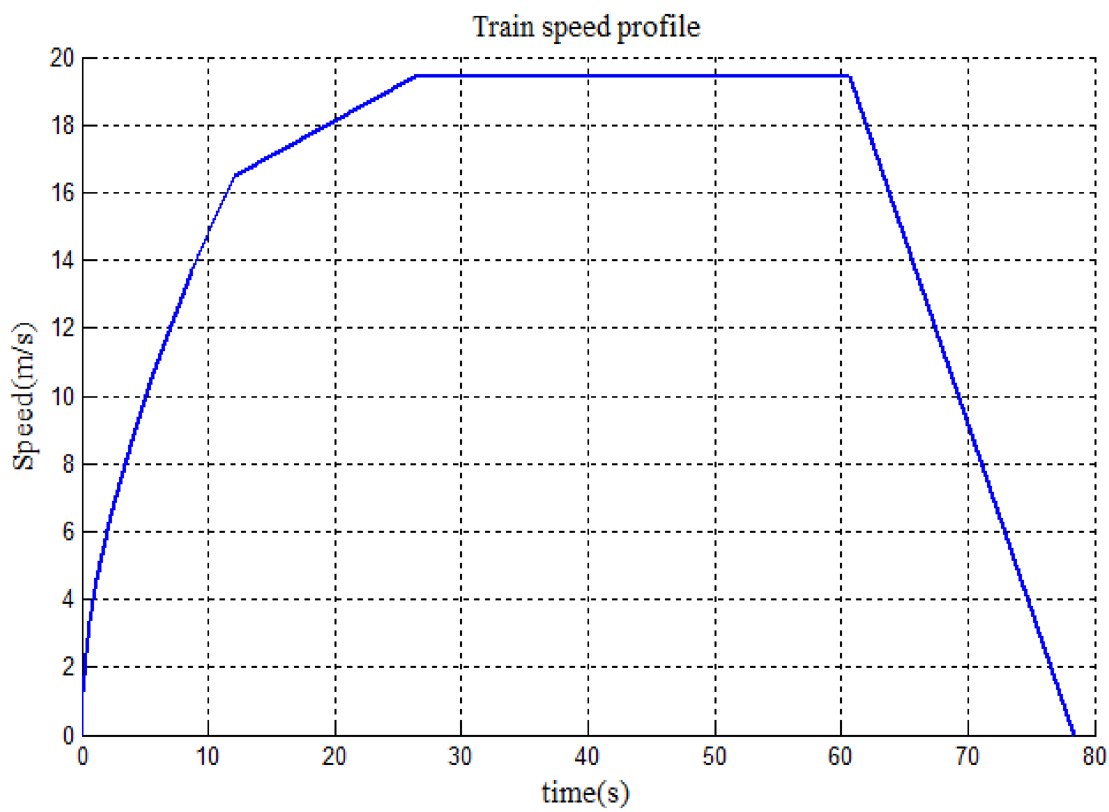

Figure 4-1 Train speed profile at station Ayat to Meri

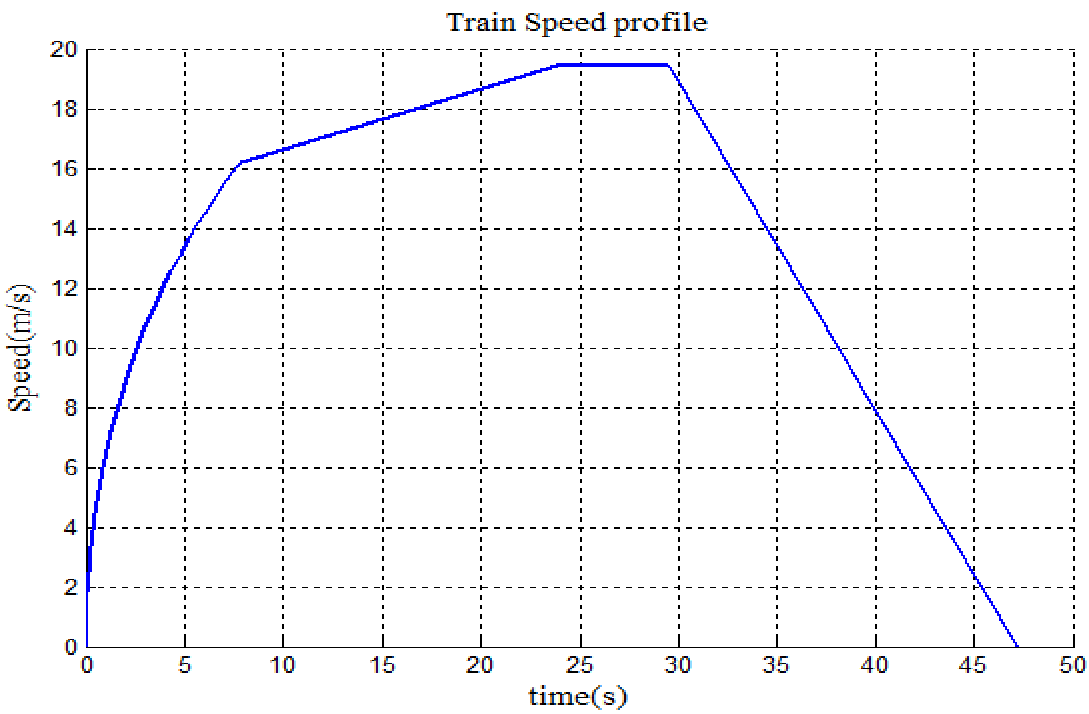

Figure 4-2 Train Speed profile at Hayahulet 1 to Hayahulet 2 stations

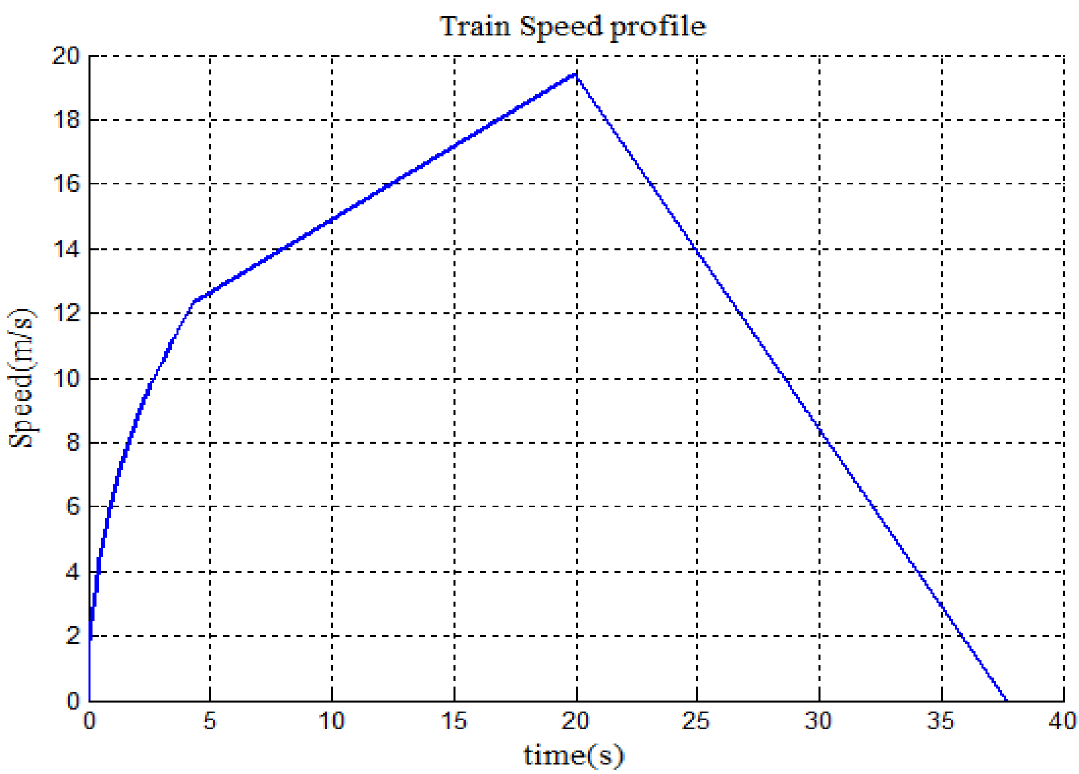

Figure 4-3 Train Speed profile at station Bambis to St.Estifanos

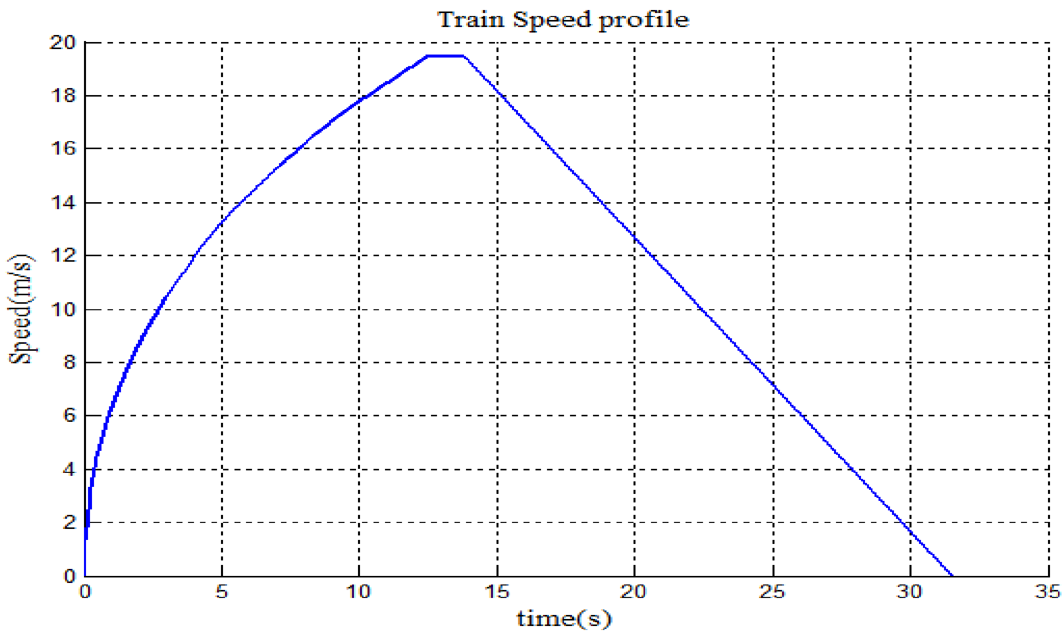

Figure 4-4 Train speed profile at Stadium to Legehar station

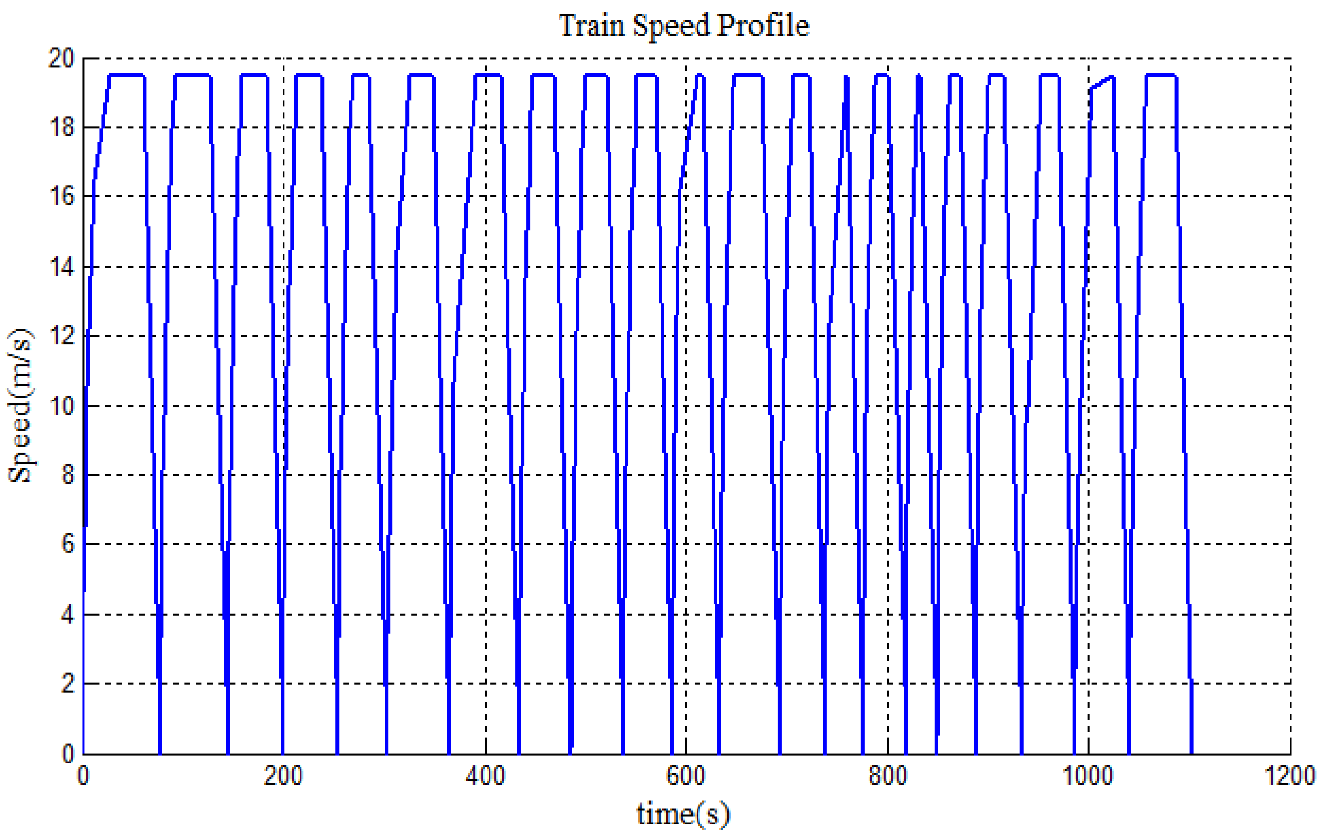

Figure 4-5 Train Speed profile from Ayat to Torhiloch stations

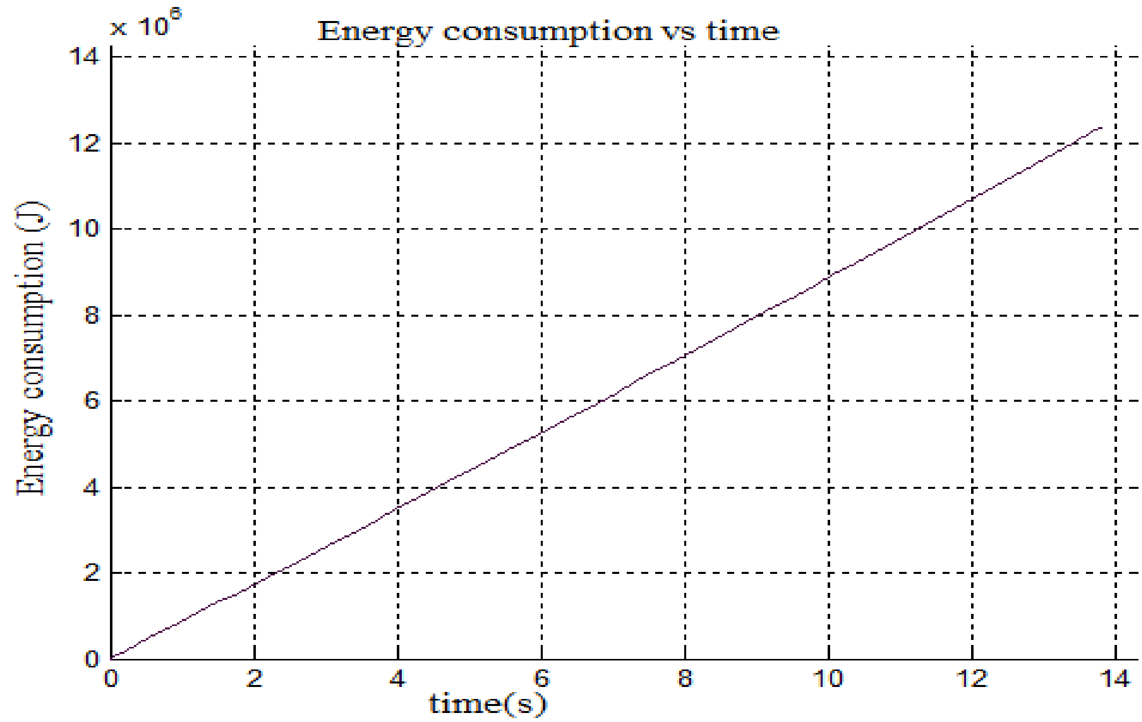

Figure 4-6 Traction energy consumption of train at normal condition

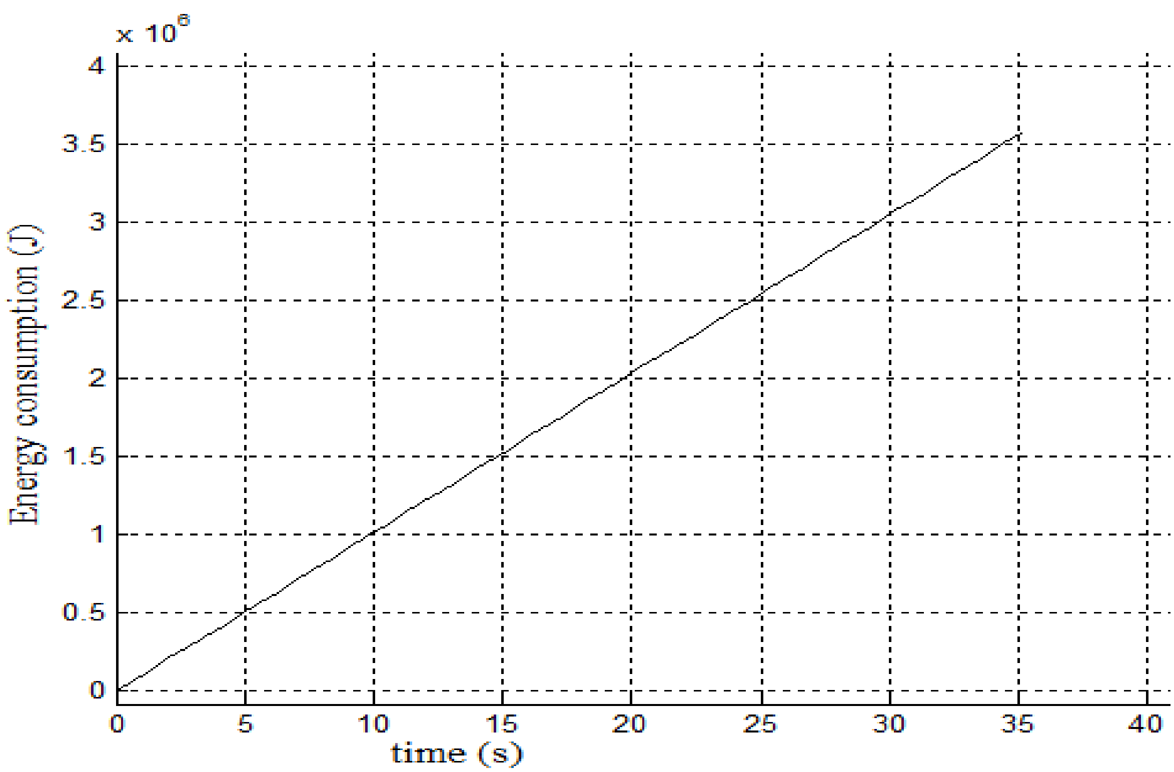

Figure 4-7 Train constant energy consumption at normal consumption

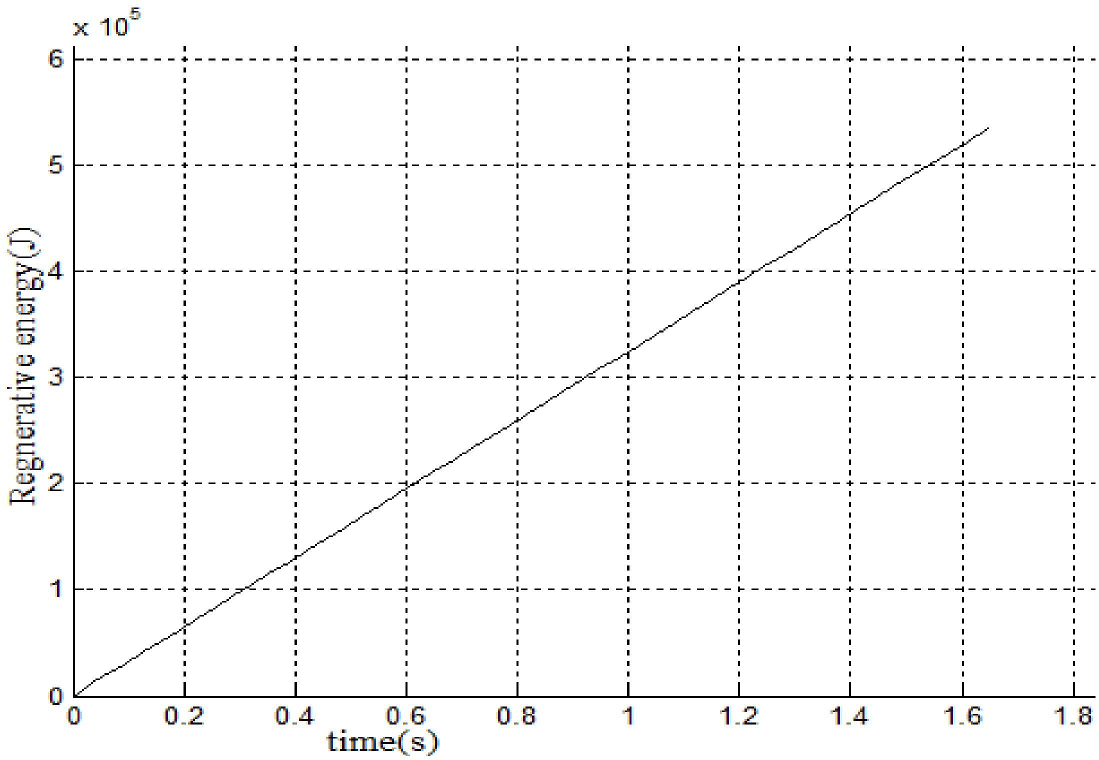

Figure 4-8 Regenerative energy at normal condition

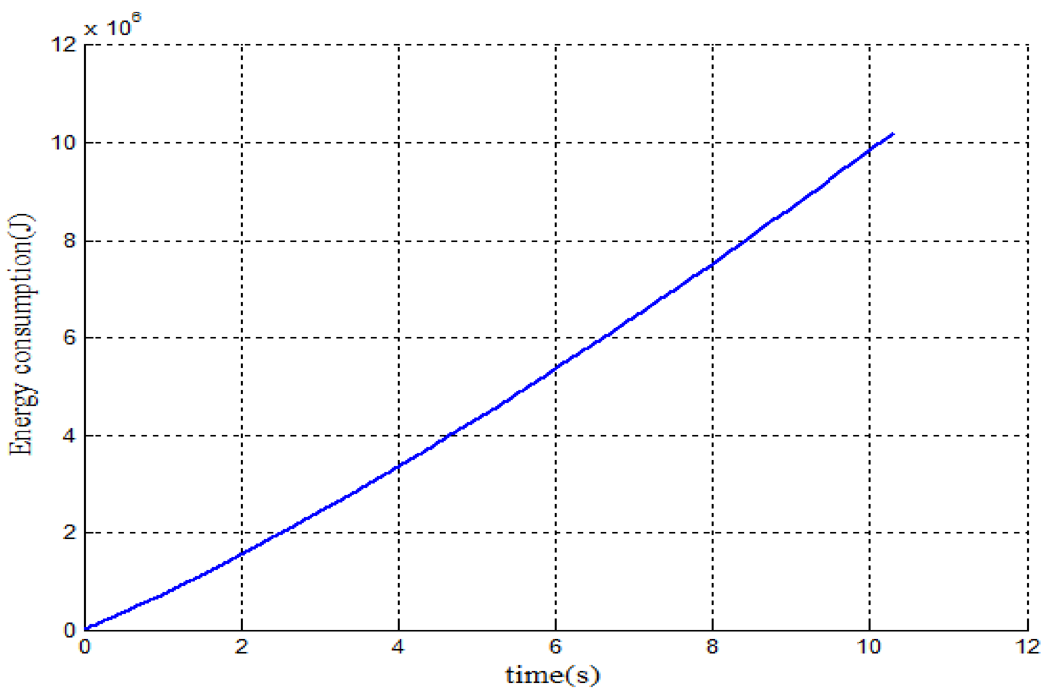

Figure 4-9 Level traction energy at 170m on overload condition

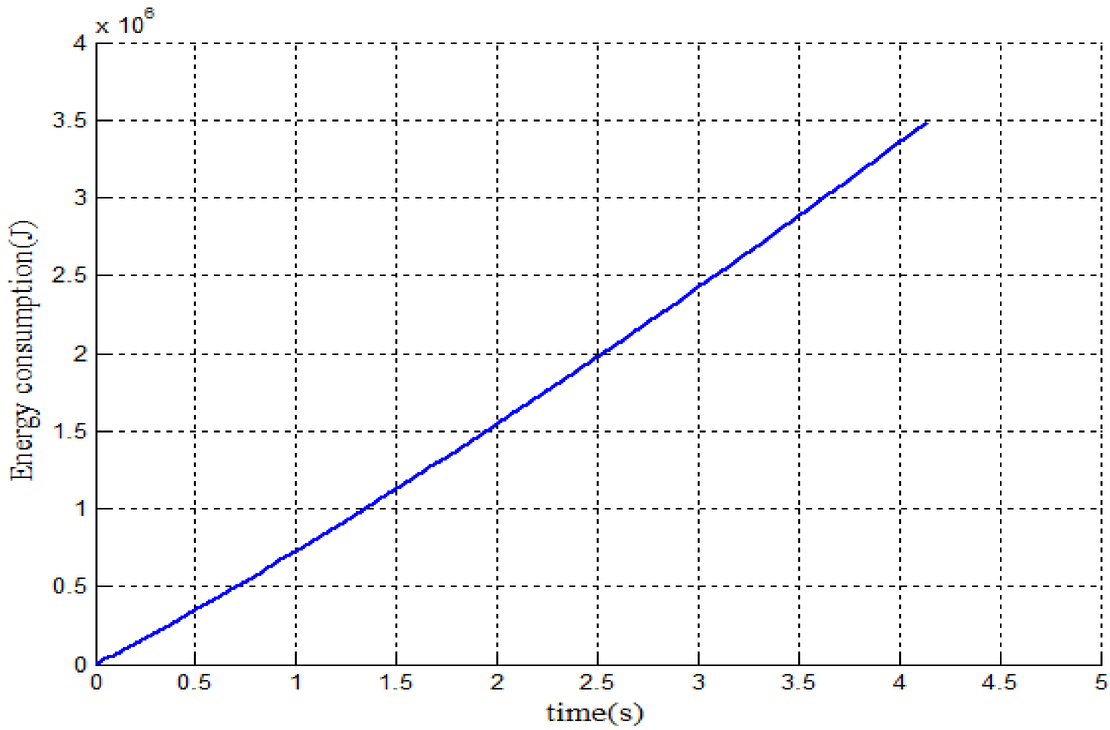

Figure 4-10 Downhill traction energy consumption 66.2m at overload

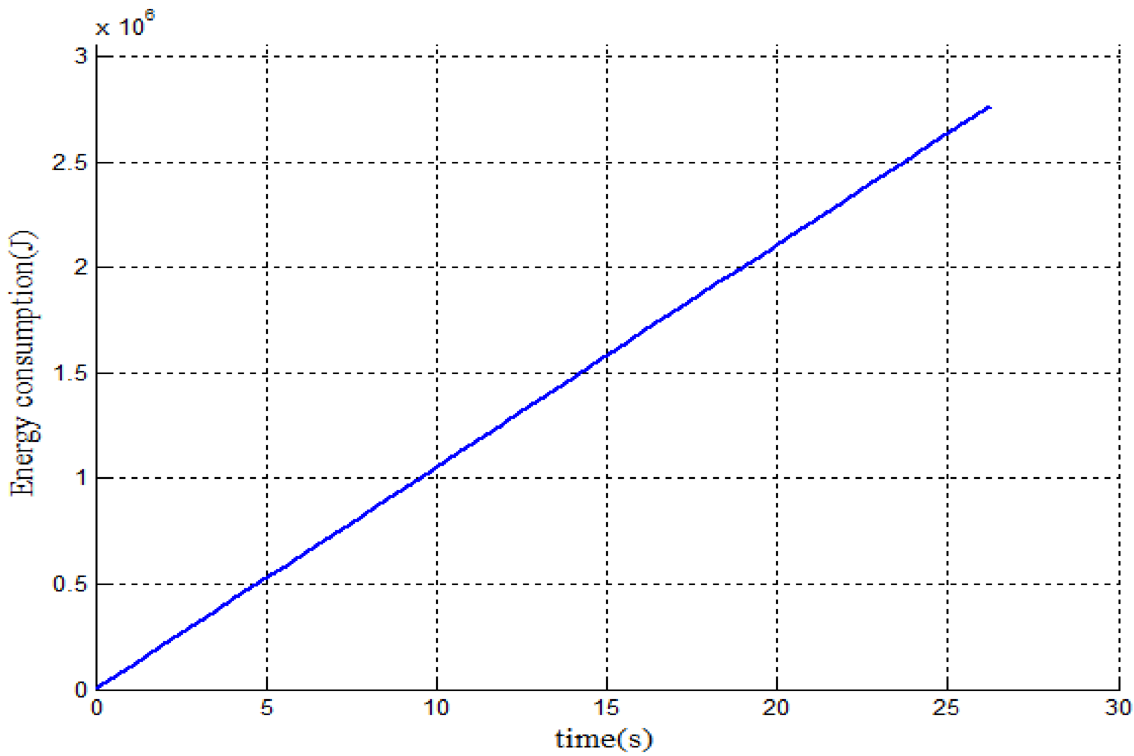

Figure 4-11 Level constant energy 510m at overload

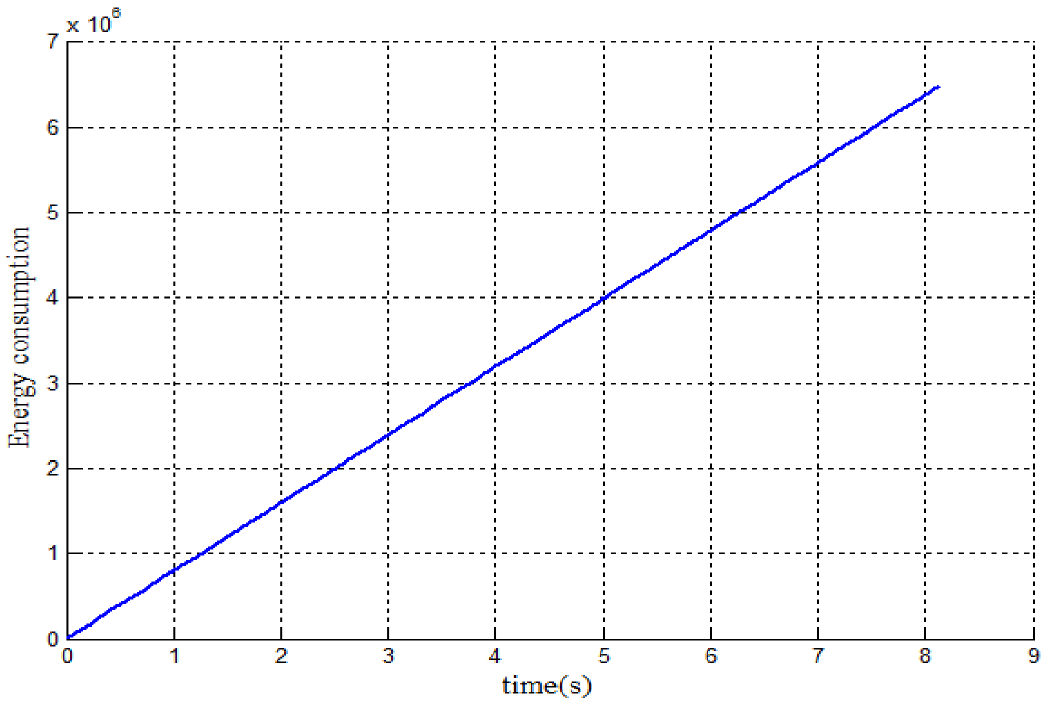

Figure 4-12 Uphill constant energy consumption 158.225m at overload

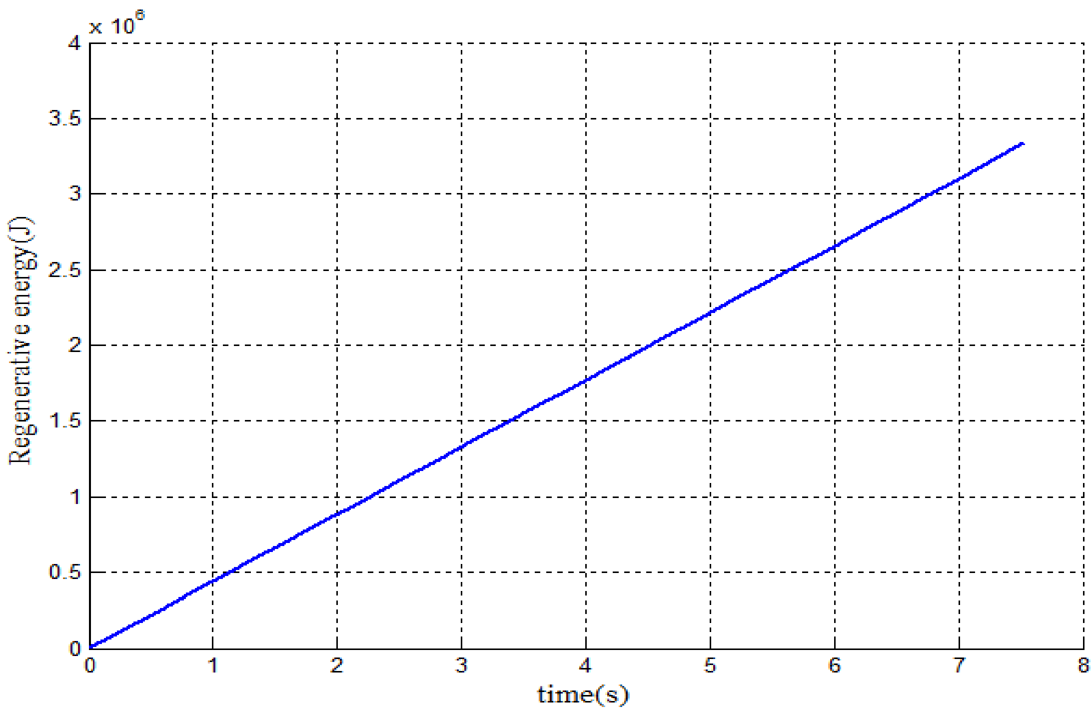

Figure 4-13 Regenerative energy at overload condition

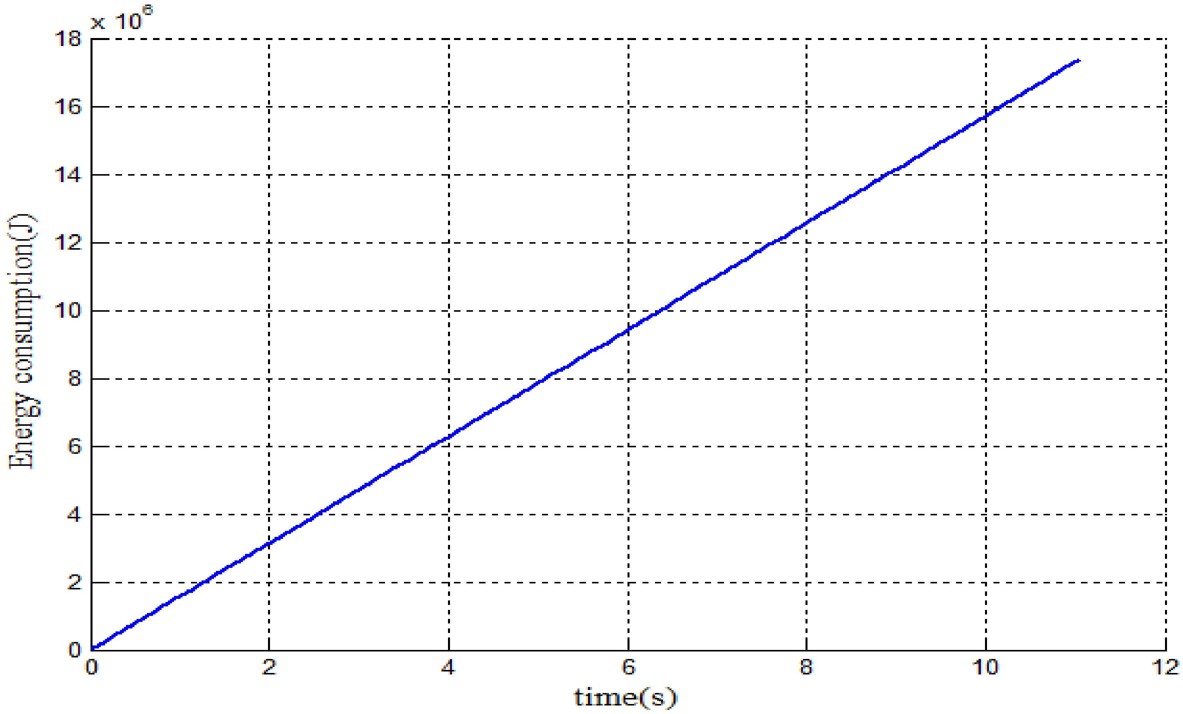

Figure 4-14 Maximum traction energy consumption at overload Gurdshola 1- Gurdshola 2 uphill

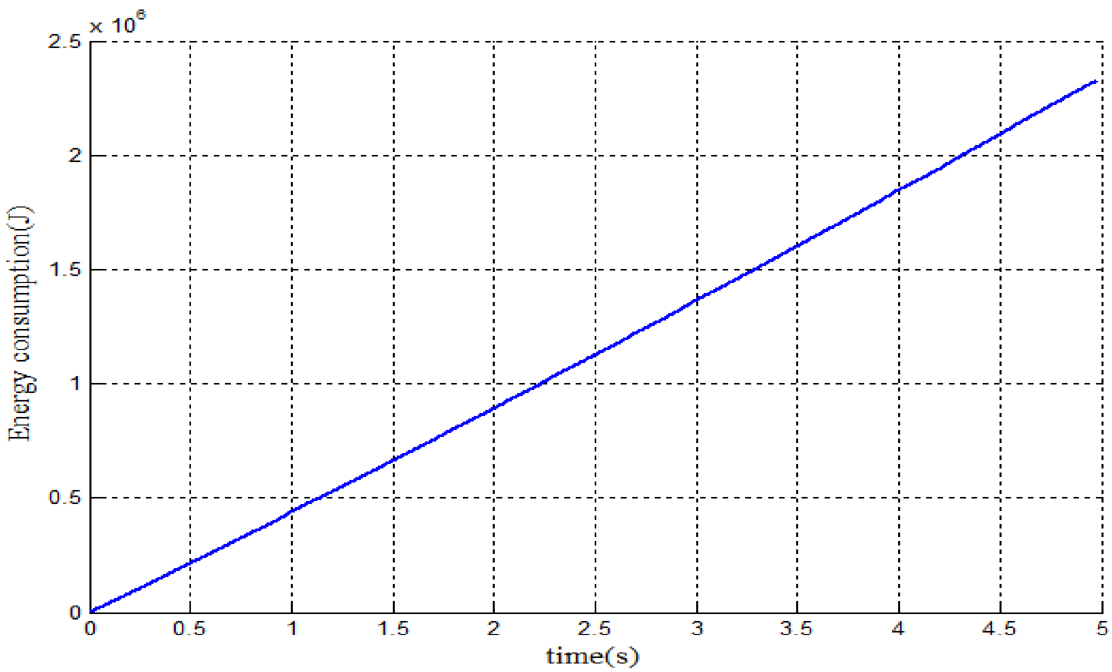

Figure 4-15 Minimum traction energy consumption at Management institute to Gurdshola 1 downhill overload condition

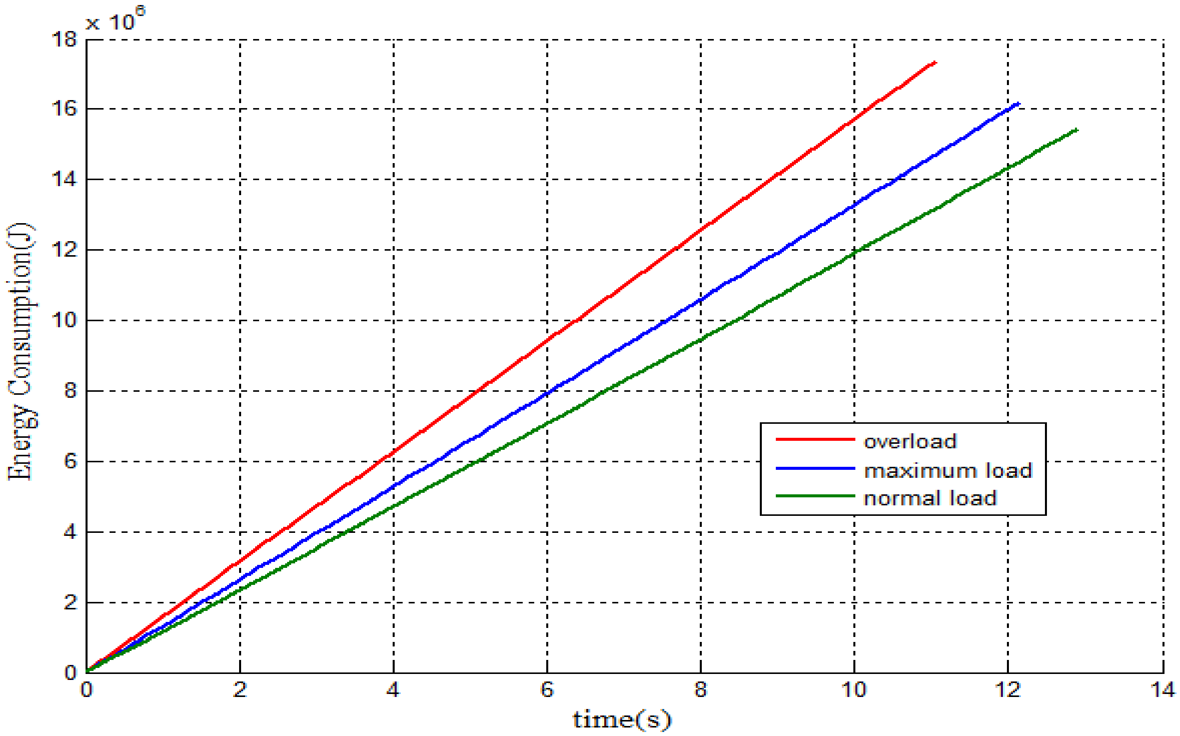

Figure 4-16 Uphill traction energy consumption at different load condition on Gurdshola 1 to Gurdshola 2

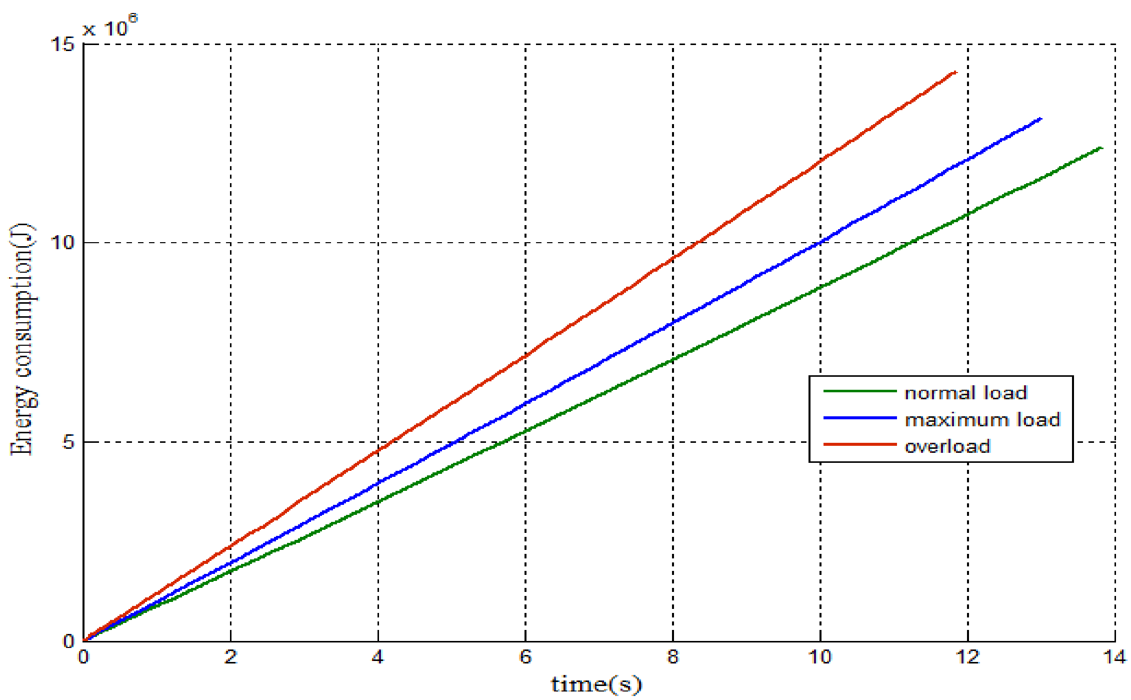

Figure 4-17 Level traction energy at different load conditions on station Meri to CMC

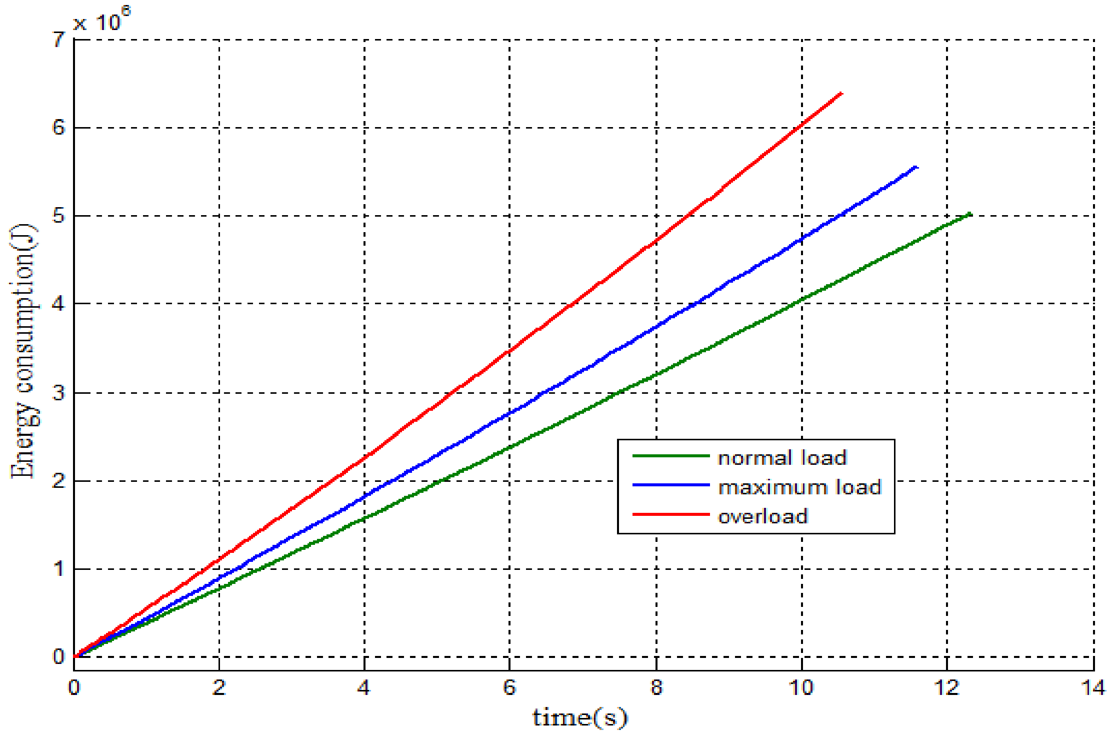

Figure 4-18 Downhill traction energy consumption at different load conditions on Tegebared to Lideta stations

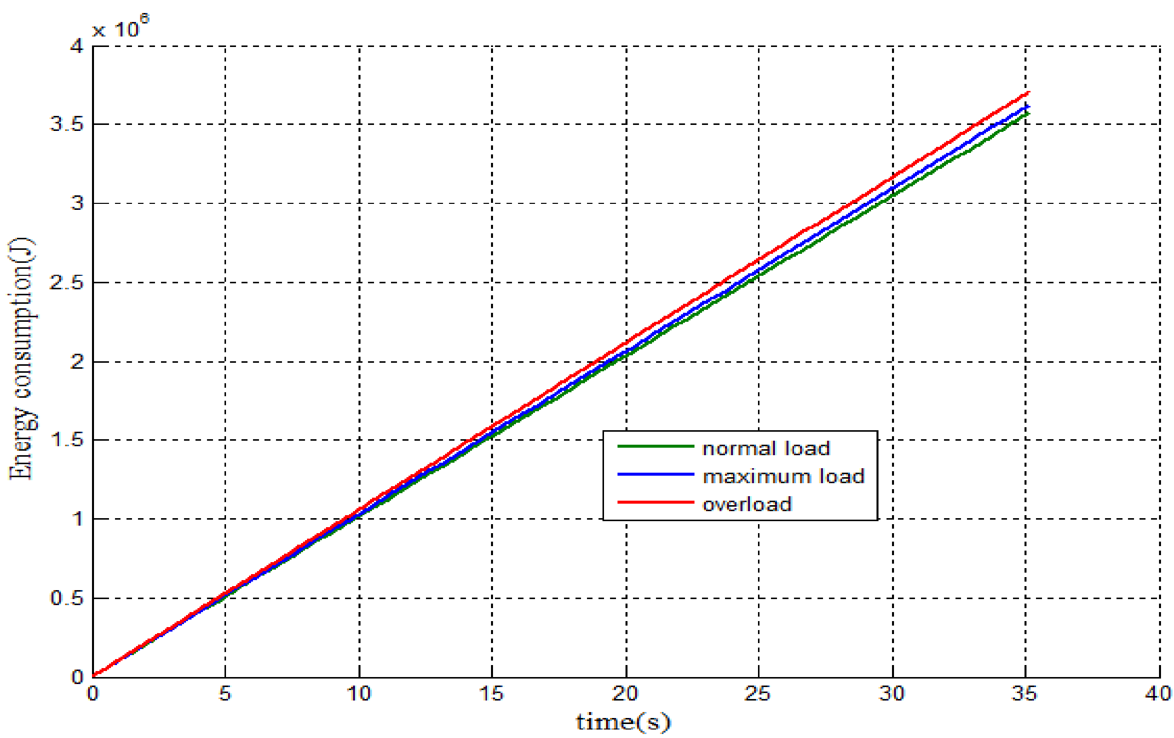

Figure 4-19 Level constant energy consumption at different load condition on station Meri to CMC

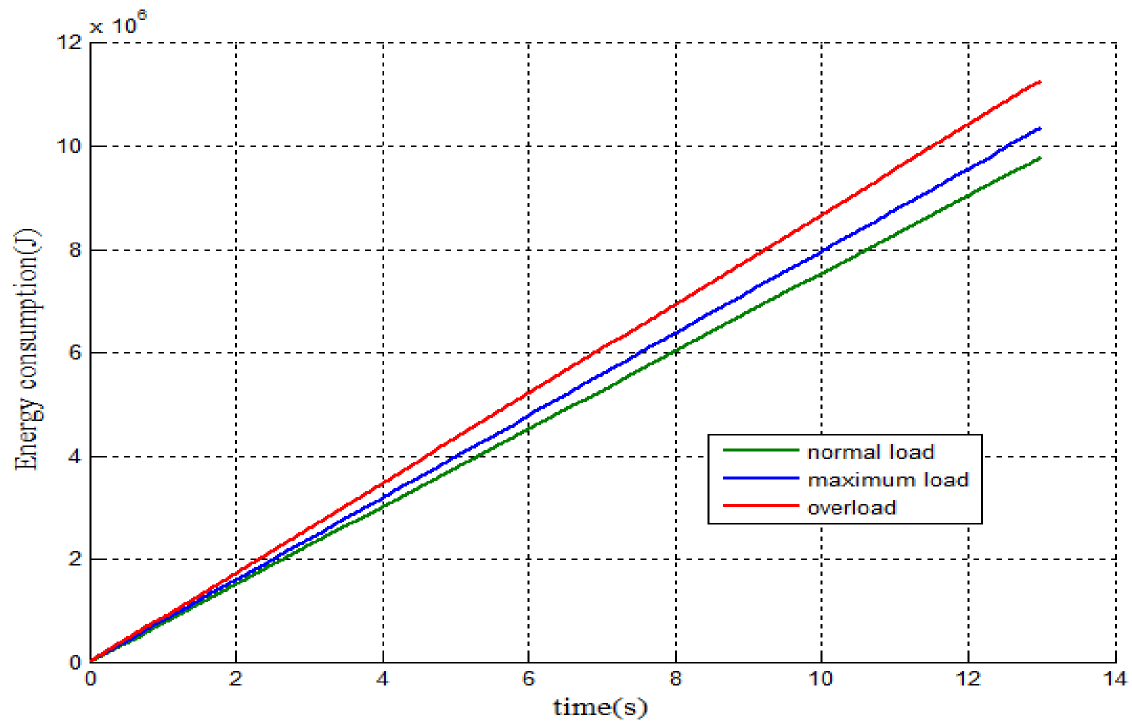

Figure 4-20 Uphill constant energy consumption at different load condition on Hayahult 1 to Hayahult 2 stations

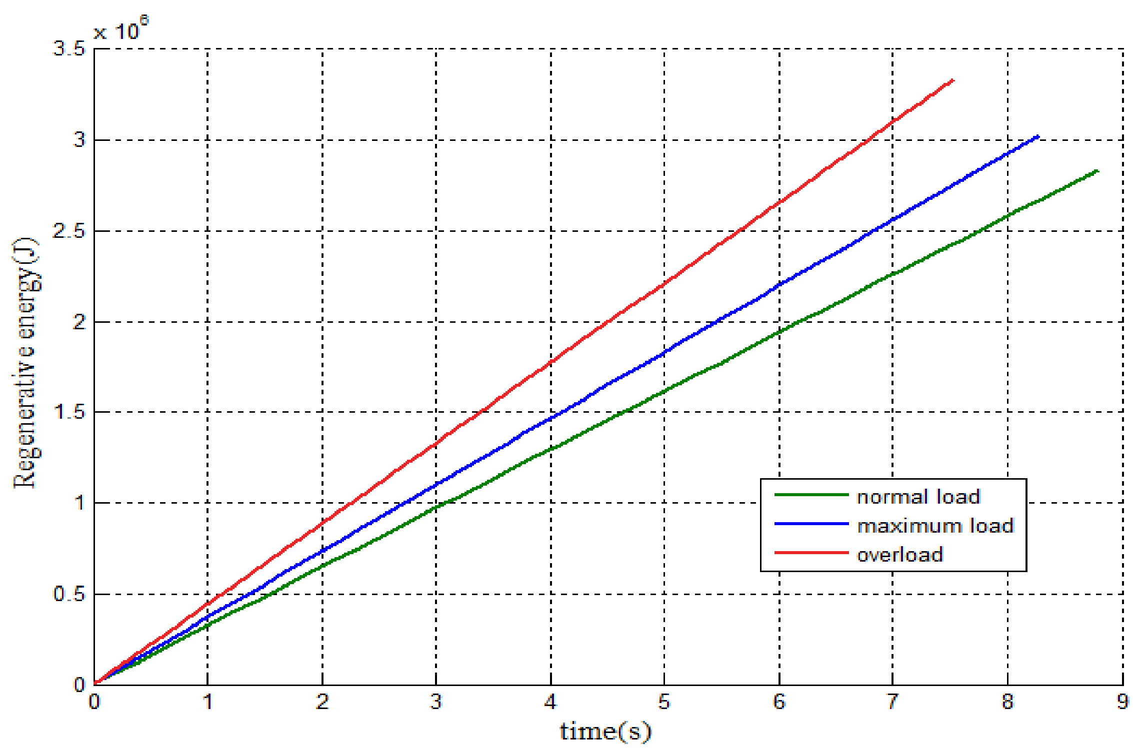

Figure 4-21Regenerative energy at different load condition on Meri to CMC stations

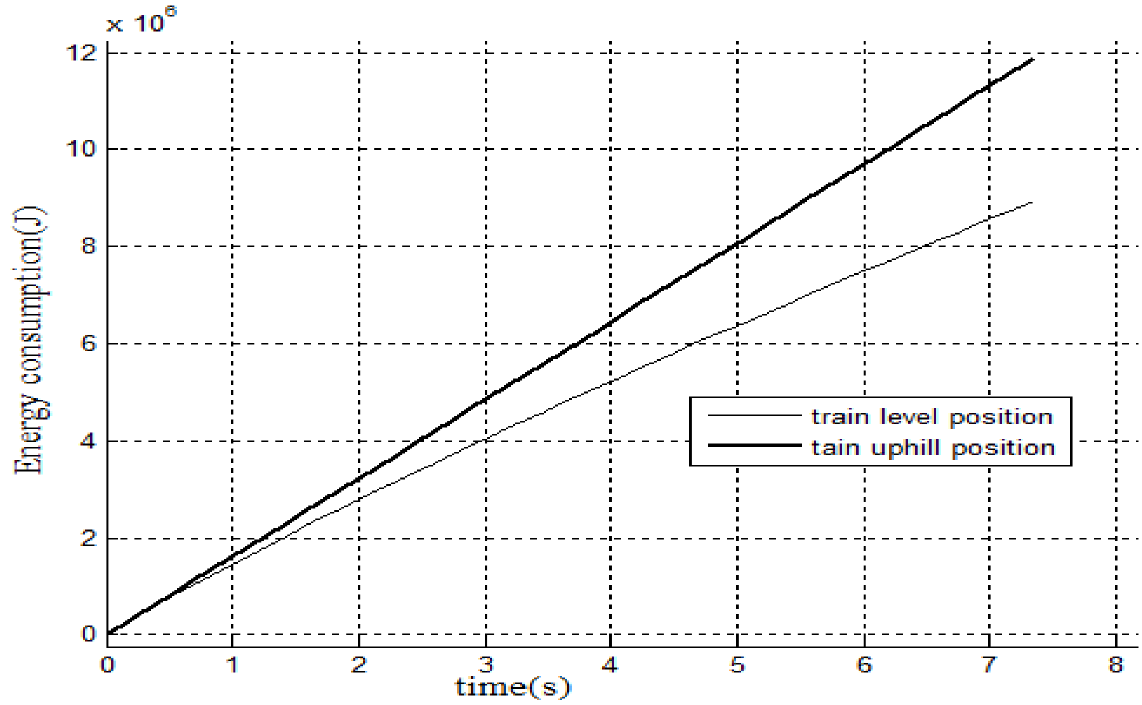

Figure 4-22 Level and uphill position train energy consumption

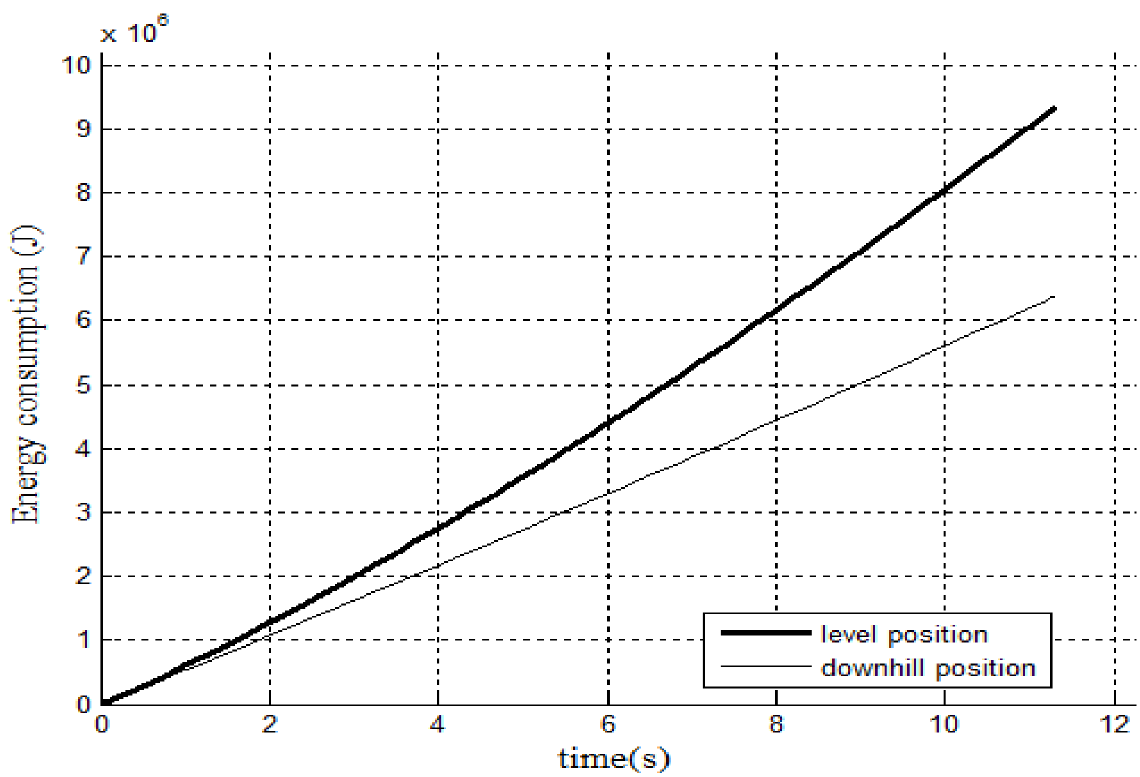

Figure 4-23 Level and downhill position train energy consumption

Table 4.1 Energy consumption of train at normal load

Energy consumption of normal load						
No	Station	Station distance	Traction energy	Constant	Total	Regenerative energy
1	Ayat-Meri	1260	11092359.83	4886715.965	15979075.8	833097.6657
2	Meri-CMC	1092	12413469.81	3573271.624	15986741.44	535504.5971
3	CMC-St.Micael	863	12413469.81	-3484193.019	8929276.793	576656.0377
4	St.Micael-Civil service	860	12413469.81	2361320.068	14774789.88	535504.5971
5	Civel service-Manegment instiuute	724.82	12413469.81	1655154.708	14068624.52	535504.5971
6	Manegment instistute-Gurd shola 1	970	8490703.746	-737730.2163	7752973.53	535504.5971
7	Gurd shola1-Gurd shola 2	1081.8	15459771.66	6790277.894	22250049.56	535504.5971
8	Gurd shola2-Megenagna	805	12413469.81	-1219121.608	11194348.2	722364.3522
9	Megenagna-Leme hotel	802	12413469.81	-1252011.899	11161457.91	535504.5971
10	Leme hotel-Hayahulet 1	746	12413469.81	1765792.554	14179262.37	535504.5971
11	Hayahulet 1-Hayahulet 2	771	12804443.17	10383555.53	23187998.7	535504.5971
12	Hayahulet 2-St.Urael	950	12413469.81	-997358.7115	11416111.1	832081.8475
13	St.Urael-Bambis	675	12413469.81	1394893.305	13808363.12	535504.5971
14	Bambis-St.Estifanos	583	14010787.82	5987171.603	19997959.43	650373.0316
15	St.Estifanos-Stadium	650	12413469.81	1264295.282	13677765.09	535504.5971
16	Stadium-Legehar	435	12413469.81	141150.3798	12554620.19	535504.5971
17	Leghar-Mexico	570	12413469.81	846380.9533	13259850.77	535504.5971
18	Mexico-Tegebared	688	12413469.81	1462804.609	13876274.42	535504.5971
19	Tegebared-Lideta	735	8156722.884	7645522.106	15802244.99	359932.5337
20	Lideta-Coca	732	12346757.81	-10335242.4	2011515.407	354343.4303
21	Coca-Torhiloch	769	12413469.81	7548983.159	19962452.97	535504.5971
					295831756.2	**11825913.26**
						4.00%

Table 4.2 Energy consumption of train at maximum load

Energy consumption for maximum load						
No	**Station**	**Station distance**	**Traction energy**	**Constant**	**Total**	**Regenerative energy**
1	Ayat-Meri	1260	11815183.12	5059360.942	16874544.06	894873.1603
2	Meri-CMC	1092	13137630.02	3626537.256	16764167.28	570094.2423
3	CMC-St.Micael	863	13137630.02	-3822751.651	9314878.374	613729.6132
4	St.Micael-Civil service	860	13137630.02	2396519.693	15534149.72	570071.4836
5	Civel service-Manegment instiuute	724.821	13137630.02	1679827.499	14817457.52	570071.4836
6	Manegment instistute-Gurd shola 1	970	9078886.158	-928319.6491	8150566.509	570071.4836
7	Gurd shola1-Gurd shola 2	1081.761	16184516.74	7051429.756	23235946.49	570071.4836
8	Gurd shola2-Megenagna	805	13137699.61	-1398334.132	11739365.48	766279.75
9	Megenagna-Leme hotel	802	13137699.61	-1432555.387	11705144.22	570094.2423
10	Leme hotel-Hayahulet 1	746	13137699.61	1792114.595	14929814.2	570094.2423
11	Hayahulet 1-Hayahulet 2	771	13544287.91	10953374.32	24497662.23	570094.2423
12	Hayahulet 2-St.Urael	950	13137679.63	-1199461.07	11938218.56	883481.6252
13	St.Urael-Bambis	675	13137679.63	1415686.858	14553366.49	570094.2423
14	Bambis-St.Estifanos	583	14752295.59	6324492.86	21076788.45	694053.8476
15	St.Estifanos-Stadium	650	13137604.71	1283141.713	14420746.42	570094.2423
16	Stadium-Legehar	435	13137604.71	143254.7037	13280859.42	570094.2423
17	Leghar-Mexico	570	13137604.71	858997.7645	13996602.48	570094.2423
18	Mexico-Tegebared	688	13137604.71	1484610.292	14622215	570094.2423
19	Tegebared-Lideta	735	9388533.734	8049829.743	17438363.48	385501.7254
20	Lideta-Coca	732	13071039.91	-11087887.96	1983151.95	376142.5693
21	Coca-Torhiloch	769	13137604.75	7894564.619	21032169.37	570094.2423
					311906177.7	**12595290.65**
						4.04%

Table 4.3 Energy consumption of train at overload

Energy consumption for over load						
No	**Station**	**Station distance**	**Traction energy**	**Constant**	**Total**	**Regenerative energy**
1	Ayat-Meri	1260	12984983.93	5220998.93	18205982.86	995889.4248
2	Meri-CMC	1092	14327974.93	3713623.01	18041597.94	626624.9162
3	CMC-St.Micael	863	14327974.93	-4376267.48	9951707.449	674344.028
4	St.Micael-Civil service	860	14327974.93	2454068.55	16782043.47	626624.9162
5	Civel service-Manegment instiuute	724.82	14327974.93	1720166.08	16048141.01	626624.9162
6	Manegment instistute-Gurd shola 1	970	10042601.44	-1240004.3	8802597.142	626624.9162
7	Gurd shola1-Gurd shola 2	1081.8	17375336.08	7478395.04	24853731.12	626624.9162
8	Gurd shola2-Megenagna	805	14327974.93	-1691331.05	12636643.88	838065.9149
9	Megenagna-Leme hotel	802	14327974.93	-1727730.4	12600244.53	626624.9162
10	Leme hotel-Hayahulet 1	746	14327974.93	1835149.34	16163124.27	626624.9162
11	Hayahulet 1-Hayahulet 2	771	14756418.05	11884985.1	26641403.11	626624.9162
12	Hayahulet 2-St.Urael	950	14327974.93	-1529885.17	12798089.76	967488.8068
13	St.Urael-Bambis	675	14327974.93	1449682.07	15777656.99	626624.9162
14	Bambis-St.Estifanos	583	11196304.32	6875986.1	18072290.42	765453.4344
15	St.Estifanos-Stadium	650	14327974.93	1313954.08	15641929.01	626624.9162
16	Stadium-Legehar	435	14327974.93	146694.507	14474669.44	626624.9162
17	Leghar-Mexico	570	14327974.93	879624.983	15207599.91	626624.9162
18	Mexico-Tegebared	688	14327974.93	1520260.8	15848235.72	626624.9162
19	Tegebared-Lideta	735	10594443.25	8710839.47	19305282.72	427311.4186
20	Lideta-Coca	732	14261238.59	-12318404.5	1942834.093	411781.0175
21	Coca-Torhiloch	769	14327974.93	8459555.64	22787530.57	626624.9162
					332583335.4	**13853082.87**
						4.17%

4.2 Discussion

From the Mathlab/Simulink results of Ayat to Torhiloch line of Addis Ababa LRT describes as below.

Figure 4.1 shows that train speed verses time graph of Ayat to Meri stations, which contains a set of motion regimes such as acceleration, coasting, cruising and braking. From Ayat to Meri station there are level, downhill and uphill track profile. In these stations the train accelerate 170m level track profile, after 170m a station have downhill gradient. The train is accelerate during downhill gradient the drivers decrease the power to reach the required driving speed. On downhill train motion energy consumption of traction phase decreases it's because of gravitational force of train movement. The train accelerate until the velocity reached at maximum, and then maximum velocity is maintained until a brake must be applied to stop at next station (Meri). Ayat to Meri stations are longest distance of East West line (Ayat to Torhiloch) and from the simulation result it takes 78.343 seconds.

Figure 4.2 shows speed profile between Hayahulet 1 to Hayahulte 2 , speed profiles of these stations are the same as that of Ayat to Meri stations but, there coasting distance and cruising distances are large and small respectively that of first stations.

Figure 4.3 show that speed profile between Bambis to St. Estifanos. This figure contain train accelerating, coasting and braking. Between these stations the train accelerated level and uphill track position, the travelling time is 37.66 second its minimum compare to Ayat to Torhiloch stations. When the train accelerated on uphill track the drivers increase the power of train to reached required velocity. Because of gravitational force against train movement uphill gradient needs high energy consumption.

Figure 4.4 shows train speed profile between Stadium to Legehar stations, the distance of these stations are 435m and the least space with only level track profil of Ayat to Torhiloch line. These station contain 236.2m accelerated distance, 27.02m cruising and 171.78m braking distance with 31.52 second traveling time.

Figure 4.5 describes all 22 stations of Ayat to Torhiloch line speed profile which have train acceleration, coasting, cruising and braking modes.

Figure 4.6 and 4.7 shows energy consumption of the train at normal load condition. During traction condition the train consume more energy to reach at maximum speed. When the train reached its cruising phase the energy consumption less than that of traction phase. Both figures shows train moves at level position.

Figure 4.8 shows regenerative energy at normal load condition, during braking mode, the traction motor connections are altered to turn them in to 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). This energy feedback in to the main line and used by other trains which is accelerated in the same line but the accelerated train is not used the power dissipated the form of heat.

Figure 4.9 and 4.10 shows that train energy at level and downhill track between Ayat to Meri stations at overload traction mode. During train running downhill track it consume less energy. Figure 4.10, 4.11, 1.2 and 4.13 are describe train energy consumption and regenerative energy of Ayat to Meri station at overload condition. Maximum uphill traction energy consumption between Gurdshola one to Gurdshola two at overload condition is describe in figure 4.14 and minimum downhill traction energy consumption between Management institute to Gurdshola one presented in figure 4.15.

Figure 4.16, 4.17, and 4.18 describes train energy consumption at level, uphill and level track profiles at different load condition such as normal, maximum and overload. At the same Simulink input driving resistance parameters, speed and different load conditions train energy simulation results are different. From Simulink result, energy consumption of the train at traction and coasting phase are increase when train load capacity is increases especially on uphill tack profile it's because of gravitational force against the movement of train. Figure 4.19 and 4.20 describe train level and uphill constant energy consumption at different load condition and figure 4.21 show regenerative energy.

Train running on uphill position consume more energy during traction phase compare with level train movement. Figure 4.22 shows that energy consumption of train at normal load condition between Ayat to Meri stations. From the figure, the uphill position graph is above the level position. On figure 4.23, during train moves on downhill position, it consume less energy that of level position.

Tables 4.1, 4.2 and 4.3 result shows train accelerating, coasting and braking energy analysis of the train. Between two stations the train moves at level, uphill and level position. During downhill position train consume less energy it’s because of gravitational (gradient) force. On uphill movement train need more energy to reach on maximum gravitational speed.

From Simulink results, Gurdshola 1-Gurdshola 2, Hayahult 1- Hayahult 2, Bambis - St.Estifanos, St.Lideta – Cocacola, Cocacola – Torhiloch stations more energy consumed than other station, it’s because of gradient. Train consume high energy uphill that of level and downhill motion.

As we see the tables train consume 295831756.2 J at traction and constant of total energy. And regenerate 11825913.26 J energy during braking phase of normal load condition.

The result simulation of energy 311906177.7J traction and 12595290.65J regenerate for maximum load, 332583335.4 traction and 13853082.87 regenerate for overload conditions are analyze.

The Simulink result shows that, there is 11.05 % additional energy consumption is used during overloading compare to normal train loading, 6.22 % used compare to maximum train loading condition. The result shows that during overloading the train needs high amount of energy consumption to accelerate.

CHAPTER FIVE

5. Conclusion, Recommendation and Future Works

5.1 Conclusion

The main objective of this thesis work is to find the energy consumption of Addis Ababa Light Rail Transit (AALRT) particularly from Ayate to Torhiloch line at different load conditions. The development of the model that can be used to calculate energy consumption in train based on the dynamics of train operation represented by equation of motion, traction force and driving resistances such aerodynamic, rolling and gradient resistance that act on the train.

The simulation result preformed using Mathlab/Simulink software, varies settings are made on the built in simulation. The block diagram that constructed on Simulink used to evaluate energy consumption. After build the block diagrams and input all the required parameters, train speed profile, energy consumption during traction, speed holding and braking phase at different track position such as level, uphill and downhill position are determined.

The simulation result show that the energy consumption of train at different load capacity. Total energy consumption at normal load, maximum load and overload capacity are 295831756.2J, 311906177.7J and 332583335.4J respectively. And regenerative energy at normal load 11825913.26J, at maximum load 12595290.65J and at overloading condition 13853082.87J. The results of this thesis work clearly indicate that the energy consumption of train during overloading condition is high compare with normal load by 11.05 % and 6.22% by maximum load.

Table 4.4 summarized three load conditions

No	Number of passenger	Train empty weight	Passenger weight	Total weight	Total traction energy	Regenerative energy
1	254	44000	60	59240	295831756.2	11825913.26
2	317	44000	60	63020	311906177.7	12595290.65
3	420	44000	60	69200	332583335.4	13853082.87

5.2 Recommendation

Energy consumption is a critical issue in rail transportation sector, from the simulation results of AALRT Ayat to Torhiloch line as shown the above appendix tables the energy consumption of train increase during train overloading capacity.

Therefore, it must be recommended that Ethiopian Railway Corporation should give attention to overloading condition of the train which is important power saving and cost reduction of company.

5.3 Future works

- Analysis of effect of train over loading on the catenary systems of AALRT
- Compare the simulation result with the actual energy consumption of AALRT Trains
- Study cost analysis of the train energy consumption during overloading condition compare with normal load condition.
- Make timetable for train to use the regenerative energy effectively

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