Introducing regenerative braking to Metrorail trains and use of the energy generated to reduce the traction energy bill

Mothobi Jacob Khoaele

207521892

A thesis submitted to
the University of KwaZulu-Natal,
College of Agriculture, Engineering and Science,
in partial fulfillment of the requirements for the degree of

Master of Science in Power and Energy Systems

Supervisor: Professor David Dorrell

School of Engineering

University of KwaZulu-Natal

March 2020

I, Mothobi Jacob Khoaele , declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original research.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

   a) their words have been re-written but the general information attributed to them has been referenced:

   b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.

(v) This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation/thesis and in the References sections.

Candidate: Mothobi Jacob Khoaele

Signature: ______________

As the candidate's supervisor I agree to the submission of this thesis for examination.

Supervisor: Professor David Dorrell

Signature: D Dorrell

ABSTRACT

Introducing regenerative braking to Metrorail trains and use of the energy generated to reduce the traction energy bill

Mothobi Jacob Khoaele
School of Engineering
Master of Science in Power and Energy Systems

Metrorail trains in Kwazulu-Natal are more than forty years old and use a vacuum type braking system. In this system, there are two vacuum cylinders per coach. When the driver applies brakes, the vacuum (-64 kPA) created by the exhausters (one on each motor coach) is destroyed. This is achieved by energising the Quick Service Application (QSA) valves connected to the train pipes. The QSA valves then open and allow atmospheric pressure to destroy the vacuum and create the braking effect. This causes the brake rigging and brake blocks to grip the wheel tyres. This type of braking is called mechanical or friction braking. The excess kinetic energy is converted to heat by friction and therefore wasted. As a result of this energy loss in the braking system, there is a need to investigate the possibility of using technology, readily available in the market, that can be retrofitted to current trains in order for them to have regenerative braking capability. The energy obtained through regenerative braking will be released into the network and used by other trains. Releasing this energy into the network will lead to a reduction in the energy bill and therefore financial savings since it will be used by other trains.

In this study, the energy recuperated through regenerative braking is quantified in terms of kWh and Rand value savings. The research shows that introducing regenerative braking could save Metrorail 20.3 % on the traction energy consumption. It shows that introducing regenerative braking could also reduce maintenance costs by 22.2 % by reduced braking wear.

The recommendation is to retrofit regenerative braking technology as it has positive financial benefits. It is further recommended that in order to maximise savings, local service providers should utilised.

Keywords: Trains, regenerative braking

ACKNOWLEDGMENTS

Firstly, I would like to thank God for giving me strength throughout my studies and career.

Secondly, I would like to thank my thesis supervisor, Prof. David Dorrell, who was always available to advice whenever I ran into trouble.

I would also like to thank my sponsor, PRASA for giving me time and financial resources to complete my studies.

A special thanks to my parents Mr and Mrs Khoaele for encouraging me to pursue a career in Engineering.

Lastly, I would like to thank Mr Provagan Govender from ABB and Mr Letsane Rathaba from PRASA for their encouragement support during my studies.

Mothobi Jacob Khoaele

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Electrified systems for urban transport such as subway lines involve noticeable power demand levels. This means that electricity is one of the biggest cost drivers. The daily load shape of a system is due fundamentally to train traffic and often the presence of a high load factor. As a result of this, any provision aimed at energy conservation in a system is therefore likely to be recommended since it can provide a significant positive economic impact [1].

1.1 Traction Substation Feeding Arrangement

DC traction substations are widely used in urban railway transport systems. The voltages commonly used are 600 V, 650 V, 750 V, 1500 V and 3000 V [2]. In KwaZulu-Natal, the electricity required to run trains is supplied by Eskom and the Municipality at 11 kV, 33 kV and 88 kV AC. It is then stepped down and converted to 3000 V DC using traction substations. The 3000 V side of these substations are all connected to the overhead track equipment in a parallel feeding arrangement. Fig. 1.1 shows the schematic diagram of a traction substation power supply system [2].

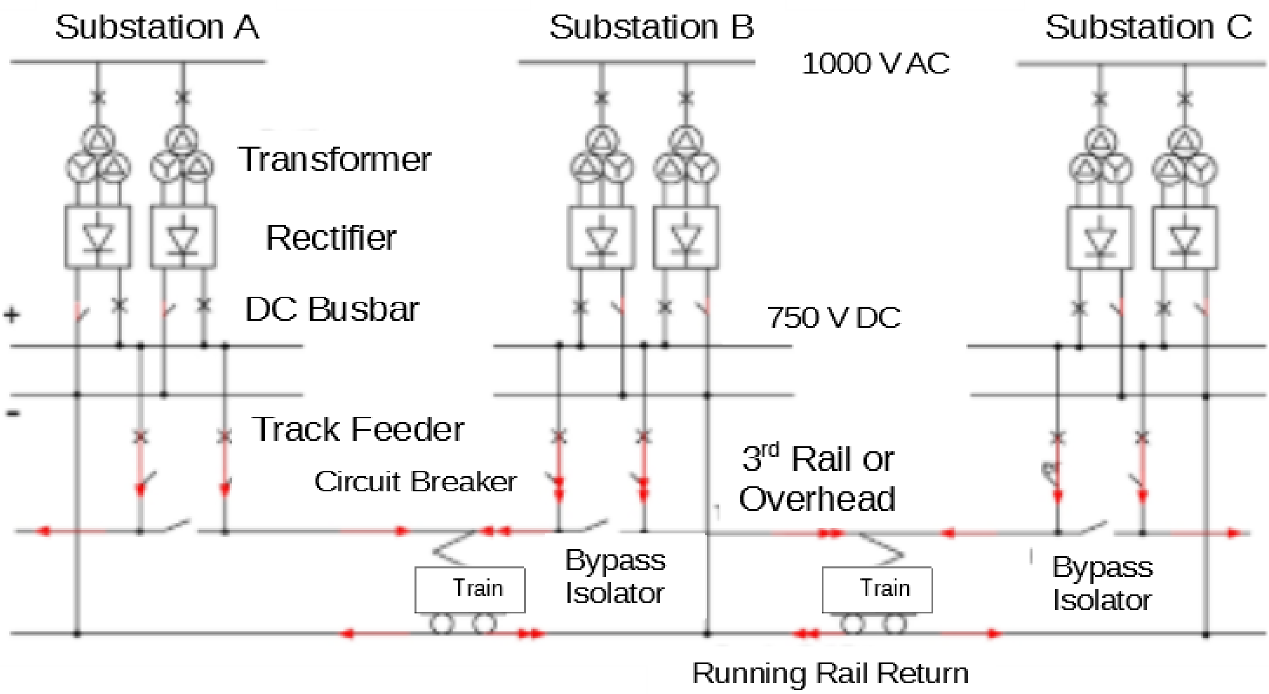

Figure 1.1 Schematic diagram of a traction substation power supply system [2].

1.2 Problem Statement

Metrorail trains in Kwazulu-Natal are older than forty years and use a vacuum type braking system. In this system, there are two vacuum cylinders per coach. When the driver applies brakes, the vacuum (-64 kPA) created by the exhausters (one on each motor coach) is destroyed. This is achieved by energising the Quick Service Application (QSA) valves connected to the train pipes. The QSA valves then open and allow atmospheric pressure to destroy the vacuum and create the braking effect. This causes brake rigging and brake blocks to grip wheel tyre. This type of braking is called mechanical or friction braking. The excess kinetic energy is then converted to heat by friction and therefore wasted.

Due to the terrain, trains have to accelerate and decelerate. This leads to faster wear on wheels and brake blocks. This also leads to high energy consumption. As a result of this energy inefficiency in the braking system, there is a need to investigate the possibility of using technology, which readily available in the market, that can be retrofitted to current trains in order for them to have regenerative braking capability. The energy obtained through regenerative braking will then be released into the network and used by other trains [3]. Releasing this energy into the network will lead to a reduction in the energy bill and therefore financial savings as it will be used by other trains [4]. Metrorail's total traction energy consumption is 12,949,418.72 kWh per month.

1.3 Research Objectives

- Investigate the feasibility of using readily available technology as a retrofit for regenerative braking. Retrofit means modifying equipment that is already in service using parts developed or made after the time of original manufacture.
- Estimate the cost of this technology.
- Determine the quantity of electric energy generated.
- Estimate the savings on the energy bill with regenerative braking.
- Determine whether the project has financial benefits or not.

1.4 Research Methodology

The research methodology undertook during this study was in the following order:

- A literature review was conducted in the initial stages of the research. Firstly, the literature review gave a theoretical background of mechanical and regenerative braking systems. As already stated, a mechanical braking system is currently used on Metrorail trains.
- Secondly, ways in which the usage of energy recuperated during regenerative braking can be maximised were investigated. As the aim of research is to send the energy recuperated to the

network so that it can be used by other trains, it is important that most of it gets utilised by other trains.

- Thirdly, simulation technologies that are available in the market that can be used to quantify energy recuperated during regenerative braking were investigated.
- Subsequent to that, previous work done on quantifying energy recuperated in kilowatt-hour from regenerative braking was investigated.
- Previous work done on quantifying the Rand value of savings from energy recuperated from regenerative braking was also investigated.
- The next step was to investigate technologies available in the market that can be retrofitted to current Metrorail trains for regenerative braking.
- Subsequent to that, relevant data on the locomotive, plain trailer and network was obtained. This included the mass of the locomotive and plain trailer, size of gradients, position of stations and curves.
- With certain assumptions, the above information was used to determine the mass of trains running per month with passengers.
- The next step was to determine the total energy recuperated in kilowatt-hour per month during regenerative braking. Due to affordability of relevant software, the energy recuperated was determined using calculations as there was no simulations software available during the time of the investigation.
- The cost of energy recuperated was determined.
- A feasibility study was then done to determine whether this research has financial benefits.
- Finally conclusions were drawn and recommendations made.

Chapter 2

Literature Review

Regenerative braking is an area that has been covered extensively in the past. However, the introduction of regenerative braking by retrofitting technology has not received sufficient attention. This chapter identifies the knowledge relating to the technology that is currently available in the market and can be retrofitted to current Metrorail trains so that they can have regenerative braking capability.

This chapter is divided into six sections. The first section deals with types of braking systems used in trains. The second section identifies ways in which the usage of energy recuperated from regenerative braking can be maximised. The third section covers simulation technologies available in the market that can be used to determine the energy recuperated from regenerative braking. The fourth section identifies ways of determining the energy recuperated from regenerative braking in kilowatt-hours. The fifth section presents a way of determine the rand value of savings due to regenerative braking. The last section covers the available technologies that can be retrofitted to Metrorail trains so that they can have regenerative braking capability.

2.1 Types of Braking Mechanisms in Trains

2.1.1 Mechanical Braking Mechanisms

The first type of braking is the mechanical system [3]. This is an old type system. With this type of braking, the kinetic energy of a moving train is lost as heat and also leads to wearing of wheels and brake blocks [3]. Metrorail trains use mechanical braking mechanisms.

Advantages of mechanical braking systems

This was described by [5]

- Can be used for emergency braking.
- Unlike regenerative braking, it can be used at speeds below 19 km/h.

Disadvantages of mechanical braking systems

- Slow responsiveness. It takes few several hundred milliseconds from the time the braking signal is activated to the time the pressure is exerted on the wheel.
- High maintenance cost. The friction needed for braking causes wear on brake discs and wheels.
- Environmental pollution. The heat, noise and particles released during braking cause harm to the environment.
- Brake force is uncertain. The friction coefficient depends on the brake shoe's temperature. It gets smaller with high temperatures. High temperatures are caused by long braking distances as a result of high speeds. Table 2.1 below shows the impact of speed on braking coefficient using Galton's formula.

Table 2.1 Impact of speed on braking coefficient [5].

Velocity (km/h)	**0 s**	**5 s**	**10 s**
21.94	0.213	0.193	-
27.43	0.205	0.157	-
38.40	0.182	0.152	0.133
43.88	0.171	0.130	0.119
49.37	0.163	0.107	0.099
54.85	0.153	-	-
60.34	0.152	0.096	0.083
65.92	0.144	0.093	-
76.79	0.132	0.080	0.070
87.76	0.106	-	-
96.54	0.072	0.063	0.058

2.1.2 Regenerative Braking

The second type of braking mechanism uses regenerative braking as part of electrical braking [3]. Whenever a railway line with a gradient more than of 0.6 is to be built, regenerative braking is recommended. But regenerative braking does not replace mechanical braking, it supplements mechanical braking. Regenerative braking is only there to reduce speed or maintain constant speeds [6]. During regenerative braking, the motor is not disconnected from the supply but acts as a generator [7][3] - or in modern systems it may well regenerate into the grid. The magnetic drag produced when the motor acts a generator then offers a braking torque [8]. The kinetic energy of a moving train is being converted to electrical energy [4]. The energy recuperated from regenerative braking can either be converted to heat by using braking resistors or it can fed back to the catenary. This method of braking, unlike the mechanical braking system, leads to reduced wear on brake blocks and wheels. Feeding energy back to the catenary can also lead to energy savings as the energy recuperated will be used by other trains [7]. If the traction substations are fitted with thyristor inverters, excess recuperated energy can be fed to the grid to supply homes and businesses [3]. This will assist the country. Introducing locomotives with regenerative braking technology yielded significant energy savings of about 13 % in New Zealand Railway's North Island main trunk [9]. In case of a shunt motor, whenever the back-EMF exceeds the supply voltage, it will run as a generator. The back EMF can exceed the supply voltage in two ways [8]:

- Increasing field excitation.
- Increasing motor speed beyond its normal value and keeping the field current constant.

In case of a DC series motor, reversal of current to produce generation would cause reversal of the field and hence the back EMF [8][6]. Modification is therefore necessary if this type of motor is used for regenerative braking [8]. Conditions under which regenerative braking cannot be introduced [10] where:

- On a section where the supply has been cancelled.
- When traction motors are cut out.
- When a motor alternator set is isolated.
- If the line voltage is already dangerously high.
- In the weak field notches.
- On sections where fast passenger trains can be delayed by the application of regenerative braking.
- When the resistance blower fails.

Advantages of regenerative braking

The benefits of regenerative braking are not only on energy savings. It improves safety, reduces outage time of locomotives as it reduces wear on brakes and finally improves running times as higher average speeds on descending gradients can be maintained. Below are regenerative braking advantages [6][11]:

- Reduced maintenance costs of wheels and brake shoes. In a train service at Birmingham and Manchester in the United Kingdom, with regenerative braking enabled, the lifespan of disk brakes is eighteen months and with regenerative braking disabled, the lifespan is reduced to eight days.
- Increased safety due to reduced tyre and brake shoe heating.
- Increased safety due to the fact that duplicate braking systems are provided.
- Higher average speed on descending gradients since a very uniform speed can be maintained.
- Elimination of delays due to inspections or worn out brake shoes.
- Increased comfort to commuters as a result of the uniform speed and elimination of noise and shocks caused by the air brake system.
- Saving of energy if recuperated energy is fed to the line.

Disadvantages of regenerative braking

- Dynamic braking effect diminishes below a speed of 16 – 19 km/h [11]. So, mechanical breaking is used below this speed [3].
- Failure to brake due to regeneration failure [12].

Ways to eliminate regeneration failure

Regeneration failure is caused by the lack of using the energy recuperated during regenerative braking [5]. This normally happens when there is no simultaneous acceleration and deceleration of trains in the same section. Trains are normally fitted with braking resistors that would convert regenerative braking energy to heat should it not be absorbed by other trains [5]. Ways to maximise usage of regenerative braking energy are discussed in Section 2.4 can also eliminate regeneration failure.

2.2 Maximizing the Usage of Regenerative Braking Energy

The usage of energy obtained from regenerative braking must be maximised in order to maximise the savings in the traction energy bill. If the energy regenerated is not fully utilised, it will force line voltages to increase to dangerously high levels or lead to regenerative braking failure [13]. But because trains have a built-in protection, this energy will be dissipated as heat through braking resistors instead of causing damage [13]. Therefore it is important that most of the energy regenerated is used by other trains. Below are the methods that can be used to maximise the usage of regenerative braking.

2.2.1 Timetable Optimisation

To maximise the energy usage from regenerative braking, a timetable should be made in such a way that the running frequency of trains is high. High frequency means the time interval between successive trains is short. This means that when the trains decelerating regenerates, trains accelerating will use that energy [3].

In this section, timetable optimisation is discussed as another way of optimising the use of regenerative braking energy. A genetic algorithm is used as an optimisation method [14].

According to surveys, railway systems are one of the biggest consumers of electricity in most countries. Power loss due to a non-optimal timetable is one of biggest contributors to this high electricity consumption in railway systems. So, the timetable must be designed in such a way that in any section, when trains decelerate, other trains should be accelerating in order to maximise energy recuperation. Studies showed that a correct timetable can save up to 20 % in electrical energy consumption. Factors that must be taken into consideration when preparing a timetable are headways and reserve times. Firstly, the impact of headways on the utilization of regenerative braking energy is discussed, followed by the impact of reserve times [14].

Impact of headways on regenerative braking energy utilisation

A pilot railway system with the information shown in Table 2.2 shows the information used for simulation of the impact of headways on regenerative braking energy utilisation [14].

Table 2.2 Information used in simulating the impact of headways

Number of traction substations	3
Number of trains	4
Number of stations	5
Headways (mins)	2
Reserve time (s)	5
Supply voltage (V)	750
Maximum tolerable voltage (V)	900
Maximum acceleration (m/s^2)	1
Maximum deceleration (m/s^2)	-1

The other technical information such as rails, train data and electrical specifications were obtained from Tehran in Iran. Using information on Table 2.2, simulation results showed that voltages remained at 750 V. This is because the energy released by decelerating trains during regenerative braking was absorbed by other trains accelerating. The simultaneous acceleration and deceleration leads to energy saving [14].

Another simulation was done with the same information as shown in Table 2.2, but with headways no longer two minutes but increased to four minutes. In this case, acceleration and deceleration do not happen at the same time. So, some of the energy released by decelerating trains is not absorbed by accelerating trains. If regenerative braking energy is not properly utilised, it can lead to high and intolerable voltages. In this simulation, the voltage went to as high as 900 V, which cannot be tolerated by the system. But it will not exceed 900 V as it will be dissipated through braking resistors. Table 2.3 shows the impact of headways on regenerative braking energy utilisation [14].

Table 2.3 Impact of headways on regenerative braking energy utilisation [14].

Headway time (mins)	Consumed energy (kWh)	Saved energy (kWh)
4	820.75	0
2	849.92	29.17

From Table 2.3, it can be deduced that the shorter the headway, the more the energy that can be used from regenerative braking and the more the energy saving.

Impact of reserve time on regenerative braking energy utilisation

On Tehran railways, stop times vary between 20 and 40 s. A genetic algorithm was used to determine the optimised stop time. The stop time obtained by the genetic algorithm, the 20 s stop time and the 40 s stop time were compared to find which leads to the highest utilisation of regenerative braking energy. Table 2.4 shows the comparison of these times on the energy consumed [14]. Small energy consumption means better utilisation of regenerative braking energy.

Table 2.4 Impact of reserve time on regenerative braking energy utilisation [14].

Consumed energy	Headway time = 2 min	Headway time = 4 min
Optimised stop time	772 kWh	766.6 kWh
Stop time = 40 s	883.3 kWh	850 kWh
Stop time = 20 s	819.4 kWh	850 kWh
Percentage energy saving	14 %	10 %

From Table 2.4, it can be deduced that the shorter the reserve time, the more the energy that can be utilised from regenerative braking. But this is only true were headways are shorter. But the optimised stop time is the one were regenerative braking energy is best utilised.

2.2.2 Storing Excess Energy from Regenerative Braking

The excess energy that cannot be absorbed by other trains in the network can be substantial. So, it is important that it can be stored and used at a later stage when required. This can be achieved by installing stationery and on-board storage systems during construction and therefore increasing energy savings [3].

2.2.3 Adjustment of the Train Operation Curve

"Adjustment of the train operation" means changing the operating condition of a train so that it uses regenerative braking [13]. With substations fitted with diodes for rectification, regenerative braking can lead to excessive over-voltage if it is not absorbed by other trains. Adjustment of the train operation curve method ensures that maximum energy released by trains during regenerative braking is absorbed by other trains requiring that energy. This means that the headways, stop time, acceleration and deceleration time must be coordinated. With today's advanced communication technologies, it is possible to have multiple trains communicating between themselves and stations in order to achieve coordination. So, the decision to accelerate or decelerate is not under the driver's control, it depends on the need and controlled automatically by a sophisticated system. In this method, the priority to use available regenerative braking energy is given to trains with low speed, and trains closer to a braking train as there are less technical losses due to the short distance and finally to short distance trains as a few minutes delay will have little impact on long distance trains as they are already travelling for long duration. These are the trains that will be given an opportunity to accelerate. Fig. 2.1 shows two trains in the same section, one train decelerates and the other train uses the energy regenerated by that train to accelerate [13]. The actual data was sim-

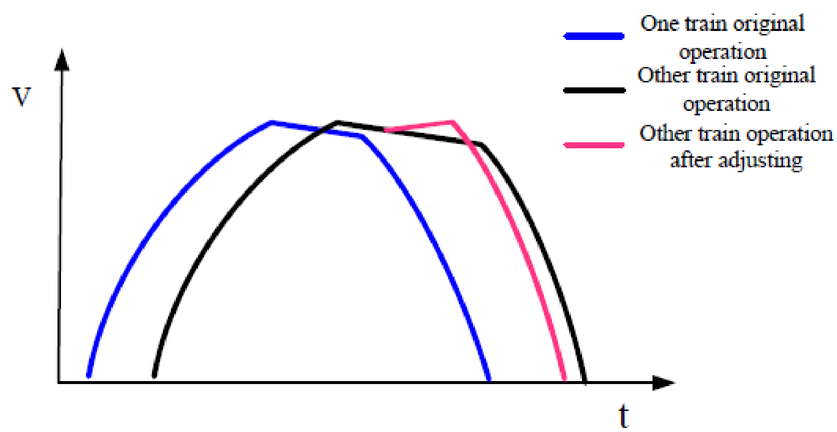

Figure 2.1 Adjustment of train curve [13]

ulated in four Beijing Metro stations to determine the impact of adjusting the train operation curve. 9.07 % more energy was recovered with the introduction of the train operation curve adjustment [13]. This is significant.

2.2.4 High Deceleration

High train deceleration means more energy will be recovered from regenerative braking. Trains arriving at the station should have maximum deceleration and trains leaving the same station must have maximum acceleration and in order to fully utilise regenerative braking energy. [8].

2.2.5 Efficiency of the System

Higher efficiency of the system will lead to lower technical losses and therefore more energy recovered from regenerative braking [8].

2.2.6 Train Resistance

Train resistance is the impact of all the forces opposing the movement of train. It is the product of the train specific resistance and the mass of the train. The higher the train resistance, the lesser the energy recuperated from regenerative braking. So, the smaller the train resistance, the more the energy is recuperated [8].

According to the Davies formula, resistance to motion can be calculated from [15]:

$$\text{Basic resistance force} = \frac{A + Bv(x) + Cv^2(x)}{1000000} Mg \tag{2.1}$$

where A = 1.08; B = 0.008; C = 0.00096; M = mass of train; and g = gravitational acceleration.

Or, according to the Davies formula [16]:

$$\text{Basic resistance force} = A + B \times V + C \times (V + V_w)^2 \tag{2.2}$$

$$A = 6.4M + 130N_e$$

$$B = 0.14M$$

$$C = (0.046 + 0.0065(N_v - 1)) \times S$$

where M is the train static weight in tons; N_e is the number of axle per train; N_v is the number of cars per train; S is the frontal area in m^2; V is the train speed in km/h; and V_w is the head wind speed in km/h (positive if wind direction is opposite to the train direction, negative otherwise.

2.3 Simulation Packages to Determine the Quantity of Energy Recuperated

Simulation technology is an important method in determining the train performance under specified conditions. They are also important for investment purposes as one would like to do financial evaluation before committing resources to a project. But only a few simulation packages in the market take regenerative braking into consideration. When using some of these packages, an experience coefficient of regenerative braking is introduced [17]. As this coefficient depends on the experience and judgement of an individual, it becomes difficult to determine accurate quantity of energy recuperated from regenerative braking.

Below are technologies that can be used to simulate regenerative braking of multi-trains.

2.3.1 Simulation Platform

The simulation platform should be capable of simulating multi-train operation, energy consumption, regenerated energy and auxiliary energy consumption. This makes it appropriate for the design and reasonable operation plans of new railway lines. In July 2011, the simulation platform showed that the energy consumption in Haidong line varied between 635.9 and 985.7 million kWh. The real energy consumption was also found to be varying between the two figures. This is proof that the simulation platform is an accurate tool. Table 2.5 shows the composition of the simulation platform [17].

Table 2.5 Simulation platform composition [17].

Basic data module	Includes railway line data, calculation parameters, train data and timetable.
Multi-train operation and energy consumption calculation simulation module.	Includes running times, train over speed protection and manual driving where necessary.
Results data processing module	Includes calculated results with two displays modes, diagram and table.

2.3.2 RAILSIM Simulation Software

RAILSIM simulation software can be used and it has a user-friendly interface for simulating complex rail systems, light lines, underground trolleys etc. [3].

2.3.3 MATLAB/Simulink Simulation Models

MATLAB/Simulink is a dynamic system simulation software package. It offers the potential to simulate mixed electrical, mechanical and control systems in a single environment. Its powerful graphical interface makes the modelling of complex railway traction drives possible. It was used in the in the Queensland Rail coal transport study of retrofitting converters [9]. It was also used in the simulation studies conducted on the Beijing No. 5 line subway and the results proved it to the accurate and reliable [18].

2.3.4 The Train Operations Model

The train operation model contains all the computer tools to simulate the operation of a rail in transit system. This is achieved by producing outputs which characterise train motion and energy consumption as time-function given inputs specific to a railway line. It can be used to determine the energy consumption, losses and savings due to regenerative braking technology. It was developed in 1985 and has been used continuously since that time. There are over eighty licensees of the Train Operations Model and its accuracy has been verified over fifteen rail systems. It has been used over main line railways, heavy and light rail systems, trolleybus systems, high speed rail, MAGLEV systems and people movers [19].

2.3.5 Use of Excel Spreadsheet Calculation

Commercial software is expensive and not possible for this project. The programming could have been done in MATLAB for this project which is available through the university. However, for convenience, since the project is mostly data processing rather than complex programming it was decided to use Excel as the processing environment.

2.4 Determining the Energy Recuperated from Regenerative Braking in kWh

Knowing the quantity of energy recuperated from regenerated braking is very important for one to know in order to decide whether to invest in the regenerative braking technology or not. If the savings from energy recuperated from regenerative braking exceed the capital investment of technology to be retrofitted, then the investment can go ahead, otherwise it is not advisable. So, having accurate methods of determining the quantity of energy recuperated is very important. Below are the methods that can be used to determine the energy recuperated.

2.4.1 Determining the Energy Recuperated from Regenerative Braking with Trains Already Fitted with Regenerative Braking Technology

In the city of Rome, trains running in line B had regenerative braking capability but the impact of regenerative braking was not known. For investigation, two conditions were set. Condition A was with all trains running with regenerative braking enabled and condition B was with regenerative braking disabled and trains using pneumatic braking. But to minimise customer discomfort, condition B was limited to peak hours on two consecutive days. Statistics were used to determine the full day's energy consumption. Stations and other loads were disconnected to ensure that only trains use electricity during this investigation. This study showed a significant energy savings of 19 % to 21 % with regenerative braking enabled. A comparison was done with the results of the simulation model. Simulation model shows the savings to be 15 % [1].

2.4.2 Determining the Energy Recuperated from Regenerative Braking by Calculation

Simulation technologies can be used to determine the energy recuperated during regenerative braking. These technologies are sometimes not affordable and the only available option is to do calculations with the aid of spreadsheets specifically developed for the project. This work illustrates this. This section discusses a way in which the energy recuperated on a level track, gradient and energy recuperated while maintaining constant speed on a downward slope can be determined by calculation. Clearly this method requires a knowledge of the civil data as accurate as possible for the results to be accurate.

Determining the energy recuperated on a level track by calculation

According to Sections 2.2.4, 2.2.5 and 2.2.6, the energy recuperated from regenerative braking depends on the magnitude of deceleration (V_1 and V_2), efficiency of the system and train resistance [8].

The net energy returned to the line

$$W = \eta \left[0.01072 \frac{M_e}{M} (V_1^2 - V_2^2) - 0.2778 r d \right] \text{Wh/tonne} \tag{2.3}$$

where:

M is the stationery or dead mass of the train.

M_e, the effective mass, is the mass of the train in motion. Since a train has rotating parts like wheels, axles, motor and gears, the effective mass is 8 to 15 % more than its stationery mass.

r N/tonne is the specific resistance of the train, the total resistance = rM N.

d is the total distance travelled during braking.

η is the efficiency of the system.

Determining the energy recuperated on the gradient by calculation

As all ready stated, according to Sections 2.2.4, 2.2.5 and 2.2.6, the energy recuperated from regenerative braking depends on the magnitude of deceleration (V_1 and V_2), efficiency of the system and train resistance [8]. And this applies on gradients. The net energy returned to the line

$$W = \eta \left[0.01072 \frac{M_e}{M} (V_1^2 - V_2^2) + d\,(27.25G - 0.2778r) \right] \text{Wh/tonne} \tag{2.4}$$

where additionally:

G is the gradient in percentage.

Determining energy recuperated on the down gradient while maintaining constant speed

If regenerative braking is only used to keep the train speed constant in a down gradient [8], then

$$F_t = (98MG - Mr) = M\,(98G - r)\,\text{N} \tag{2.5}$$

$$F_t = (98G - r)\,\text{N/tonne} \tag{2.6}$$

Then net energy returned to the line

$$= \eta F_t \left(\frac{1000}{3600} \right) vt \tag{2.7}$$

where:

F_t is the tractive force, is the force used for train propulsion.

v is the velocity of the train in km/h.

t is the duration of regenerative braking in seconds.

2.4.3 Determining the Energy Recuperated from ShengXian Lake Station to North Railway Station by Simulation on Chengdu Line I

A simulation was done on the Chengdu line I from ShengXian lake station to North railway station to determine the energy recuperated during regenerative braking. The civil data for simulation is shown on Table 2.6 [15].

Table 2.6 Civil data for simulation on Chengdu Line I [15].

Location (m)	**Speed (km/h)**	**Gradient (%)**
2821	60	2
2847	70	2
2860	70	-22
3060	70	-8
3532	80	-8
3639	70	-8
4002	70	21
4261	80	21
4321	60	-2
4414	60	-2

Summarising information in Table 2.6 is given below. From ShengXian lake station, the train leaves location 2821 travelling at a speed of 60 km/h on an up gradient of 2 %. It continues at this speed for 26m until it reaches location 2847. From location 2847 it travels at 70 km/h on an up gradient of 2 % for 13 m until it reaches kilometre location 2860. It then leaves location 2860 travelling at 70 km/h on a down gradient of 22 % for 200 m until it reaches location 3060. From location 3060 it travels at 70 km/h on a down gradient of 8 % for 472 m until it reaches location 3532. It again leaves location 3532 travelling at 80 km/h on a down gradient of 8 % for 107 m until it reaches location 3639. From location 3639 it travels at 70 km/h on a down gradient of 8 % for 363m until it reaches location 4002. It then leaves location 4002 travelling at 70 km/h on an up gradient of 21 % for 259 m until it reaches location 4261. From location 4261 it travels at 80 km/h on an up gradient of 21 % for 60 m until it reaches location 4321. Finally, from location 4321 it travels at 60 km/h on a down gradient of 2 % for 93 m until it reaches location 4414 towards North railway station.

By calculation, regenerative braking energy was found to be 48.2 kN $\times$ distance from ShengXian lake station to Northway railway station [15].

Below are some of the important formulae that were used [15]:

- Braking force = Total force – force due to resistance – force due to grade.
- Regenerative braking energy = dynamic braking force $\times$ distance.
- Distance = train velocity $\times$ time.

2.5 Determining the Rand Value of Savings from Regenerative Braking

In China, 137 high speed trains run daily between Beijing South station and Tianjin West station. The energy recuperated due to regenerative braking per train is 243 kWh. Using this information, a daily, a monthly and a yearly figure of energy recuperated per train was determined. Multiplying this by the number of trains that run per year, the total energy recuperated per annum from regenerative braking was determined. The energy recuperated per annum was found to be 1.2×10^7 kWh. An electricity tariff of 0.1 US $ in Beijing was used. The energy savings from regenerative braking were found to be US$ 1.2 million per annum. The savings can also be determined for multiple stations, if the time table and number of trains run are known. This includes weekend services [11].

From above, it can be deduced that if the total energy recuperated from regenerative braking in kWh is known, multiplying that by the electricity tariff will give the rand value of savings from regenerative braking.

2.6 Technologies Available in the Market as Retrofit for Regenerative Braking

In this section, previous work that has been done on locomotives that were not manufactured with regenerative braking capability but later modified will be discussed.

It is important to note that retrofitting the entire fleet of locomotives is not economically feasible. But once locomotives reach a major overhaul age, retrofitting becomes economical. Locomotive re-manufacture is more favoured today compared to standard overhaul as it allows introduction of new technology [9].

The sections below describes the previous work done on retrofitting locomotives with regenerative braking technology.

2.6.1 Retrofitting by Queensland Rail, Retrofit Converters

Queensland Rail coal transport network is fed from 25 kV A.C. supply is shown in Fig. 2.2 [9]. This section of the report explains the research done by Queensland Rail coal transport on the feasibility of retrofitting existing phase controlled DC motor drives with pulse width modulation (PWM) rectifier technology. Even though phase controlled rectifier systems have regenerative braking capability, the disadvantage is that the energy recuperated is not returned to the line and used by other trains, but wasted as heat through switching resistors. Regenerative braking is achieved by switching resistor banks across armature and controlling the field current. This technology is unreliable due to limitations in old control systems technology and also have poor power factor. The aim this research is to replace this technology with reliable regenerative braking system and unity power factor. The research was for 3100/3200 HITACHI and 3500/3600 ASEA electric locomotives. Even though the research was only at early stage, retrofitting at full scale demonstrated that the project will be technically and economically feasible. Fig. 2.2 shows the schematic diagram of

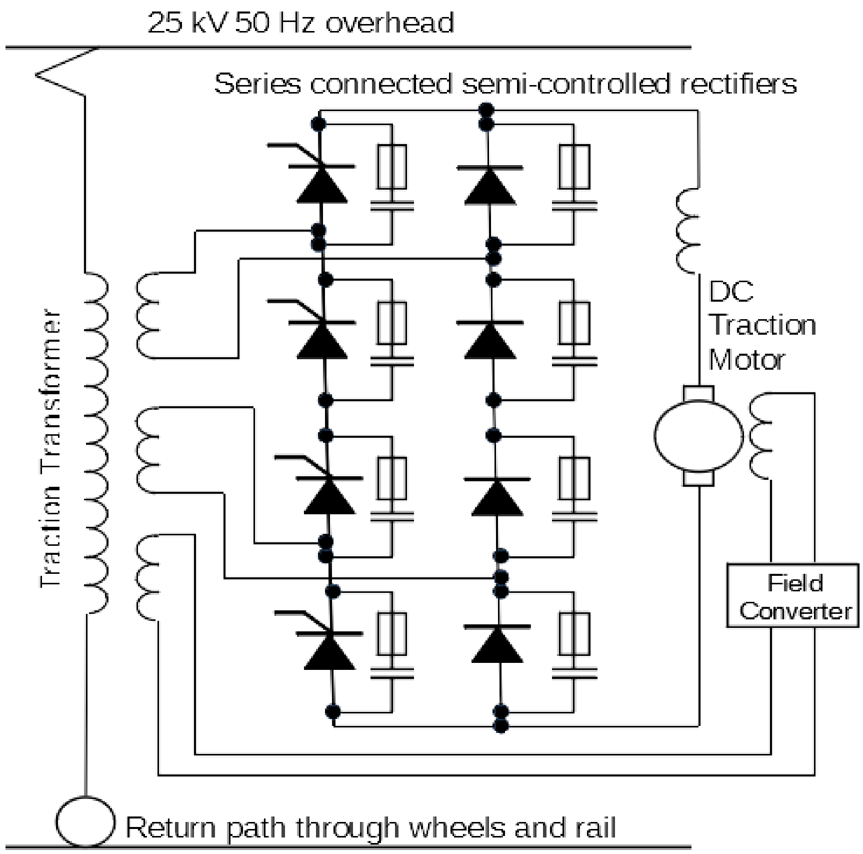

Figure 2.2 Queensland Rail's traction package [9]

a Queensland rail motor coach before modification [9].

Below is a list of components used by Queensland Rail coal and minerals to modify their current trains so that they can have regenerative braking capabilities [9]:

- Drive units
- Converters
- Transformers
- Cooling systems
- Driver cab electronics and controls.

There are two types of converter configurations that can be used for retrofitting [9]:

- Voltage sourced PWM
- Current sourced PWM

2.6.2 Retrofit by Amtrak, Integration of AC Drive Technology Retrofit Converters

In 1983, Amtrak experienced an abnormally high usage of DC motors on both diesel-electric and electric locomotives. Amtrak then decided to experiment with AC traction as it was highly recommended as the answer to many traction motor problems [20].

In 1984, Amtrak decided to purchase three phase drive systems from a company known as Brown Boveri Corporation (known as ABB today) in order to evaluate the new AC drive technology. The equipment was delivered and installation was mainly done by the locomotive shop mechanics. The locomotive frame was extended by one foot in order to fit all the equipment. On 7 April 1988, the modified motor coaches were put into passenger service after the final tests [20].

The thyrister technology was later replaced with the Gate Turn Off devices (GTOs). The GTO inverter to supply the three phase induction motor drive system was designed by EMD and the head-end power inverter was manufactured by Siemens. The head-end power inverter supplies, lighting, heating, cooling and refrigeration equipment. On October 1990, the locomotive was put into service [20].

Maintenance advantages of AC drive technology retrofit converters [20]

- DC control switchgear components, its wiring, and control interlocking relays are eliminated. All these are the reasons for poor reliability and high maintenance costs.
- AC motors are more reliable and require less maintenance that DC motors.

- High tractive effort.
- AC requires lesser number of traction motors than DC.
- Reduction in capital costs due to lower number of locomotives required.

Maintenance disadvantages of (AC) drive technology retrofit converters [20]

- Complicated inverter drives system.
- Electricians and mechanics will have to be trained on the new technology.
- Capital investment required in the new tools required to repair the AC equipment.

2.7 Retrofitting Estimated Cost

Now that the technology that can be retrofitted for regenerative braking is available in the market, the next step was to get estimated costs of retrofitting this technology per motor coach. With regards to this costs, Prabargan Govender of ABB [21] said:

"ABB Ltd (ABB) has the capacity to retrofit AC drive converters on current Metrorail trains so that they can have regenerative braking capability. This technology is reliable available and has a lifespan of fifteen years. The estimated cost for retrofitting one motor coach is one million euro including labour, material and commissioning. With one euro equals to sixteen rand and twenty cents, the cost per motor coach is sixteen million and two hundred thousand rand. For one hundred and forty motor coaches, the estimated cost is R 2,268 million."

2.8 Summary

The literature survey has highlighted critical issues that need to be taken into consideration when introducing regenerative braking technology to Metrorail trains. This chapter identified AC drive retrofit converters as cheaper in capital cost, cheaper to maintain and very reliable. This makes them ideal for commuter service. There have been other studies into using regenerative train braking [22] [23] [24] [24] and these will help in developing regenerative train systems.

Below are the key issues that were raised from literature review:

- Regenerative braking is recommended for railway lines with a gradient more than 0.6.
- Regenerative braking does not replace mechanical braking, it supplements mechanical braking. Regenerative braking is only there to reduce speed or maintain constant speeds. Mechanical braking is required for emergency braking and to bring a train to a complete stop at the station.
- The energy recuperated from regenerative braking can either be converted to heat by using braking resistors or it can fed back to the catenary. Feeding energy back to the catenary can also lead to energy savings as the energy recuperated will be used by other trains.
- If the traction substations are fitted with thyristor inverters, excess recuperated energy can be fed to the grid to supply homes and businesses. This will assist the country especially now that Eskom has serious capacity constraints leading to load shedding.
- The benefits of regenerative braking are not only on energy savings. But improves safety, reduces outage time of locomotives as it reduces wear on brakes and finally improves running times as higher average speeds on descending gradients can be maintained.
- Failure to fully utilise the energy regenerated can lead to dangerously high line voltages or lead to regenerative braking failure. But because trains have a built-in protection, this energy

will be dissipated as heat through braking resistors.

- There are simulation technologies available in the market that can be used to determine the quantity of energy recuperated during regenerative braking.
- Energy recuperated from regenerative braking in kWh can be determined by calculation.
- Rand value of savings from regenerative braking can be determined by calculation.
- There are technologies available in the market as retrofit for regenerative braking.
- Retrofitting the entire fleet of locomotives is not economically feasible. But once locomotives reach a major overhaul age, retrofitting becomes economical. Locomotive re-manufacture is more favoured nowadays compared to standard overhaul as it allows introduction of new technology.
- AC drive technology retrofit converters have low capital cost, low maintenance cost and more reliable than DC converters.
- Retrofitting trains will require re-training of electricians and mechanics. It will also require new tools to repair AC equipment.
- There is a service provider capable of doing this retrofit in South Africa.

Chapter 3

Equipment and Network Information Used to Calculate Energy Recuperated

This chapter provides the details and information that will be used to calculate the energy recuperated from regenerative braking per month in Kwazulu-Natal. It first provides technical data on the type of train, the 10M5, that will be used in this research. Secondly it provides information on the station layout. Thirdly it provides information on the distances between stations, line gradients, line speeds and train masses. Finally, it shows how the Excel spreadsheets used to calculate the energy recuperated during regenerative braking and its Rand value were developed.

3.1 Technical Data of the 10M5 Train

The 10M5 is an upgrade of the 5M2. The significant difference between the two trains is the micro – controller. The 10M5 is fitted with a micro - controller that controls its movement. Tables 3.1 and 3.2 show the technical data of the 10M5 motor coach and the 10M5 trailer coach respectively.

Table 3.1 Technical data of a 10M5 motor coach

Nominal voltage	3 000 Vdc
Number of traction motors per coach	4
Total power, 1 hour rating, weak field	1820 h.p.
Total power continuous rating, weak field	1296 h.p.
Length over end panels	18.38 m
Bogie wheelbase	2.74 m
Overall wheelbase	15.24 m
Width over body	2.82 m
Maximum height with lowered pantograph	4.14 m
Nominal control voltage	110 Vdc
Nominal air pressure	4.9 kg/m^2
Total mass in working order	53 000 kg
Mass of a fully equipped pair of bogies	25 822 kg
Mass of fully equipped body	37 178 kg
Mass of a traction motor	2 700 kg
Mass of a complete wheel pair	1 899 kg
Axle load (axle 1)	16 200 kg
Axle load (axle 2)	16 500 kg
Axle load (axle 3)	14 000 kg
Axle load (axle 4)	14 000 kg

Table 3.2 Technical data of a 10M5 trailer coach

Wheel arrangement	Bo-Bo
Maximum service speed	97 km/h
Length over end panels	18.38 m
Bogie wheelbase	2.74 m
Overall wheelbase	15.24 m
Width over body	2.82 m
Maximum height	3.65 m
Total mass in working order	32 000 kg
Mass of a fully equiped pair of bogies	6 400 kg
Mass of fully equipped body	25 600 kg
Mass of a complete wheel pair	972 kg
Axle load	8 000 kg
Axle load (axle 2)	16 500 kg
Axle load (axle 3)	14 000 kg
Axle load (axle 4)	14 000 kg

3.2 Station Layout

The total size of the Metrorail network is three hundred and one single track kilometres. Appendix A shows the network with all railway stations. Below is a list of outside stations:

- Kelso
- Crossmoor
- KwaMashu
- Pine town and
- Umlazi

3.3 Station Distances and Line Gradients

According to Section 2.4.2, for energy recuperated during regenerative braking to be determined, it is important that the braking distances and gradients between stations be known. Appendices C.1 to J.2 show the braking distances and gradients between stations. Chapter 4 discusses the station distances and gradients in detail.

3.4 Line Speeds

According to Section 2.4.2, for energy recuperated during regenerative braking to be determined, it is important that the maximum speed before braking be known. On railways, speed is determined by the curve radius, the condition and design of the tracks and spacing between overhead structures. It is also determined by the distance between stations so that a train can have enough braking time. Table 3.3 shows the maximum speeds allowed between stations. Since there are curves between stations, these maximum speeds cannot be maintained at all times.

Table 3.3 Maximum speeds allowed between stations

Maximum speeds allowed between stations (km/h)	
Reunion - Kelso	90
Durban - Congella	90
Congella - Reunion	90
Duffs Road - Red Hill - Umgeni	60
Umgeni - Durban	75
Rossburgh - Bellair	75
Bellair- Pinetown	75
Duffs Road - Kwa Mashu	75
Merebank - Crossmoor	90
Reunion - Umlazi	75
Duff's Road - Bridge City	75
Umgeni - Effingham	75

3.5 Determining the Train Mass

According to Section 2.4.2, for energy recuperated during regenerative braking to be determined, the total mass of trains running in that corridor including passengers needs to be known. This mass is determined by the number of trains, configuration of these trains and the number of commuters in these trains.

To determine this mass, the correct assumption will be that during the morning and afternoon peaks, the trains are hundred percent full and during off peak, Saturday and Sunday, the trains twenty percent full. The maximum number of people that can be carried by a motor coach is one hundred and sixty and trailer coach can carry two hundred. For this exercise the mass per passenger will be assumed to be seventy five kilogram. The first step in determining the train masses will be to find the number of trains running in various corridors. Appendix B shows the number of trains running in various corridors. This number includes trains travelling toward a destination and trains returning from that destination. It then needs to be divided by two to get the number of trains travelling in one direction. The reason for dividing by two is that when a train is travelling in a particular direction, the slope might be positive and in the reverse direction, the same slope is negative.

From Appendix B, the total number of trains running during peak, off peak and weekend can be calculated. Table 3.4 shows the total number of trains running during peak, off peak and weekend. This was obtained by adding morning peak and afternoon peak together, adding Saturday and Sunday together and leaving off peak trains separately.

Table 3.4 The number of trains running during peak, off peak and weekends

Corridor	**Peak**	**Off-peak**	**Weekend service**
Durban-KwaMashu	40	61	88
Durban-Umlazi	48	66	89
Durban-Kelso	24	42	43
Durban-Stanger	14	26	45
Durban-Cato ridge	10	19	36
Durban-Pinetown	11	19	24
Durban-Crossmoor	14	24	28
Durban-West	11	9	15
Total	172	266	368

Using information on Table 3.4, the total number of trains running per month can be determined using the data in Table 3.5. This number has already been divided by two to get the number of trains travelling in one direction.

Table 3.5 Total number of trains running in one direction per month

Corridor	**Peak**	**Total peak trains per month**	**Off-peak**	**Total off-peak trains per month**	**Weekend service**	**Total weekend trains per month**
Durban-KwaMashu	20	440	30	660	44	176
Durban-Umlazi	24	528	33	726	45	180
Durban-Kelso	12	264	21	462	22	88
Durban-Stanger	7	154	13	286	23	92
Durban-Cato ridge	5	110	10	220	18	72
Durban-Pinetown	6	132	10	220	12	48
Durban-Crossmoor	7	154	12	264	14	56
Durban-West	6	132	5	110	8	32

The second step is to know the configuration of these trains. Table 3.6 shows the configuration of trains running in various corridors.

Table 3.6 Configuration of trains running in various corridors

Corridor	**Number of motor coaches**	**Number of trailer coaches**	**Total coaches**
Durban-KwaMashu	3	9	12
Durban-Umlazi	3	9	12
Durban-Kelso	3	9	12
Durban-Stanger	3	9	12
Durban-Cato ridge	3	8	11
Durban-Pinetown	3	6	9
Durban-Crossmoor	3	9	12
Durban-West	3	9	12

Using the information in Tables 3.5 and 3.6 and the information in Section 3.5, the third step is to determine the total mass of each train with passengers. Tables 3.7 and 3.8 show the total mass of all trains running in various corridors during peak and off-peak periods respectively.

Table 3.7 Total peak mass per train

Corridor	Number of motor coaches	Number of trailer coaches	Total peak mass
Durban-KwaMashu	3	9	449280
Durban-Umlazi	3	9	449280
Durban-Kelso	3	9	449280
Durban-Stanger	3	9	449280
Durban-Cato ridge	3	8	417080
Durban-Pinetown	3	6	352680
Durban-Crossmoor	3	9	449280
Durban-West	3	9	449280

Table 3.8 Total off-peak mass per train

Corridor	Number of motor coaches	Number of trailer coaches	Total off-peak mass
Durban-KwaMashu	3	9	447456
Durban-Umlazi	3	9	447456
Durban-Kelso	3	9	4447456
Durban-Stanger	3	9	447456
Durban-Cato ridge	3	8	415416
Durban-Pinetown	3	6	351336
Durban-Crossmoor	3	9	447456
Durban-West	3	9	447456

Because the ridership during the weekend is the same as the ridership during off peak, the total mass per train running during the weekend can be assumed to be equal to the mass of trains running during off-peak. Table 3.9 shows the total weekend mass per train, which is that same as for the off-peak.

Table 3.9 Total weekend mass per train

Corridor	Number of motor coaches	Number of trailer coaches	Total weekend mass
Durban-KwaMashu	3	9	447456
Durban-Umlazi	3	9	447456
Durban-Kelso	3	9	447456
Durban-Stanger	3	9	447456
Durban-Cato ridge	3	8	415416
Durban-Pinetown	3	6	351336
Durban-Crossmoor	3	9	447456
Durban-West	3	9	447456

The next step is to determine to total number of peak, off-peak and weekend trains running in one direction per month. In determining the peak and the off-peak number of trains per month, the assumption would be that the month has twenty two week days. With the weekend trains, the assumption would be that the month has four weekends. Table 3.10 shows the total number of trains running in one direction per month.

Table 3.10 Total number of trains running in one direction per month

Corridor	Total peak trains per month	Total off-peak trains per month	Total weekend trains per month	Total number of trains per month
Durban-KwaMashu	440	660	176	1276
Durban-Umlazi	528	726	180	1434
Durban-Kelso	264	462	88	814
Durban-Stanger	154	286	92	532
Durban-Cato ridge	110	220	72	402
Durban-Pinetown	132	220	48	400
Durban-Crossmoor	154	264	56	474
Durban-West	132	110	32	274

To determine the total mass of all trains with passengers per corridor per month then the information in Tables 3.7 and 3.10 can be used. The starting point will be the peak trains, followed by off-peak trains and finally weekend trains. Tables 3.11, 3.12 and 3.13 show the total mass of all trains with passengers per corridor per month during peak, off-peak and weekend respectively.

Table 3.11 Total peak mass of all trains with passengers per corridor per month

Corridor	Total peak trains per month	Total peak mass per train	Total peak mass per month
Durban-KwaMashu	440	449280	197683200
Durban-Umlazi	528	449280	237219840
Durban-Kelso	264	449280 1	18609920
Durban-Stanger	154	449280	69189120
Durban-Cato ridge	110	417080	45878800
Durban-Pinetown	132	352680	46553760
Durban-Crossmoor	154	449280	69189120
Durban-West	132	449280	59304960

Table 3.12 Total off-peak mass of all trains with passengers per corridor per month

Corridor	Total off-peak trains per month	Total off-peak mass per train	Total off-peak mass per month
Durban-KwaMashu	660	447456	295320960
Durban-Umlazi	726	447456	324853056
Durban-Kelso	462	447456	206724672
Durban-Stanger	286	447456	127972416
Durban-Cato ridge	220	415416	91391520
Durban-Pinetown	220	351336	77293920
Durban-Crossmoor	264	447456	118128384
Durban-West	110	447456	49220160

Table 3.13 Total weekend mass of all trains with passengers per corridor per month

Corridor	Total weekend trains per month	Total weekend mass per train	Total weekend mass per month
Durban-KwaMashu	176	447456	78752256
Durban-Umlazi	180	447456	80542080
Durban-Kelso	88	447456	39376128
Durban-Stanger	92	447456	41165952
Durban-Cato ridge	72	415416	29909952
Durban-Pinetown	48	351336	16864128
Durban-Crossmoor	56	447456	25057536
Durban-West	32	447456	14318592

Using information on Tables 3.11, 3.12 and 3.13, The total mass of all trains with passengers for all corridors can be determined. Table 3.14 shows the mass of all trains with passengers per corridor per month.

Table 3.14 Mass of all trains with passengers per corridor per month

Corridor	Mass of all trains with passengers per month
Durban-KwaMashu	571756416
Durban-Umlazi	642614976
Durban-Kelso	364710720
Durban-Stanger	238327488
Durban-Cato ridge	167180272
Durban-Pinetown	140711808
Durban-Crossmoor	212375040
Durban-West	122843712

3.6 Development of an Excel Spreadsheet to Calculate Energy Recuperated in Wh/Tonne

Section 2.4.2 shows how energy recuperated during regenerative braking can be calculated. Since these calculations have to be done for each and every descending slope, curve, all areas where there is speed reduction and stops, a better option is to use an Excel spreadsheet since it is quicker and also minimises possibilities of errors. The sections below show how the spreadsheets were developed.

3.6.1 Spreadsheet Development for Calculation of the Energy Recuperated on a Gradient

Section 2.4.2 shows that energy recuperated on a gradient can be calculated using equation (2.4). This is the energy recuperated when the train reduces speed on a slope. This formula was then entered into the Excel spreadsheet with format shown in the table below. The gradient (B2), initial velocity (B3), final velocity (B4) and acceleration (B5) are inputs and braking distance (B6), % gradient (B7) and Wh/tonne are outputs. The acceleration of -0.8 m/s^2 was taken experimentally on current Metrorail trains and is also comfortable for commuters. Braking distance is calculated using Newton's laws of motion, $v^2 = u^2 + 2as$. Table 3.15 shows the spreadsheet developed.

Table 3.15 Gradient operation data

Gradient (1:n) (B2)	124.5
Initial velocity (km/h) (B3)	70
Final velocity (km/h) (B4)	19
Acceleration (m/s^2) (B5)	-0.8
Braking distance (km) (B6)	0.219
% Gradient (B7)	0.80
Wh/tonne	34.27

The equations as entered into the Excel spreadsheet are

$$\text{Braking distance (B6)} = \frac{\left(\left(\text{B4}\frac{1000}{3600}\right)^2 - \left(\text{B3}\frac{1000}{3600}\right)^2\right)}{2 \times \text{B5} \times 1000} \tag{3.1}$$

$$\%\text{G} = \frac{1}{\text{B2}} \times 100 \tag{3.2}$$

$$\text{Wh/tonne} \; = 0.75\left(0.01072 \times 1.1 \times \left(\text{B3}^2 - \text{B4}^2\right) - \text{B6} \times (27.25 \times \text{B7} + 0.2778 \times 50)\right) \tag{3.3}$$

3.6.2 Spreadsheet Developed to Calculate the Energy Recuperated on a Level Track

Section 2.4.2 shows that energy recuperated on a level track can be determined using equation (2.3). This is the energy recuperated when the train reduces speed on a level track. The only difference between this formula and the one for evaluating the energy recuperated on the gradient is that in this case %G is zero. So the same spreadsheet used for evaluating energy recuperated on a gradient is used when evaluating energy recuperated on a level track but with %G (B7) made zero. The input and output information is also the same. Table 3.16 shows the spreadsheet developed.

Table 3.16 Level operation data

Gradient (1:*n*) (B2)	Infinity
Initial velocity (km/h) (B3)	70
Final velocity (km/h) (B4)	19
Acceleration (m/s^2) (B5)	-0.8
Braking distance (km) (B6)	0.219
% Gradient (B7)	0.00
Wh/tonne	37.86

The equations as entered into the Excel spreadsheet are

$$\text{Braking distance (B6)} = \frac{\left(\left(\text{B4}\frac{1000}{3600}\right)^2 - \left(\text{B3}\frac{1000}{3600}\right)^2\right)}{2 \times \text{B5} \times 1000} \tag{3.4}$$

$$\%\text{G} = 0 \tag{3.5}$$

$$\text{Wh/tonne } = 0.75\left(0.01072 \times 1.1 \times \left(\text{B3}^2 - \text{B4}^2\right) - \text{B6} \times (0.2778 \times 50)\right) \tag{3.6}$$

3.6.3 Spreadsheet Developed to Calculate the Energy Recuperated on a Downward Gradient when a Train is Maintaining a Constant Speed

Section 2.4.2 shows that the energy recuperated on a downward gradient when maintaining a constant speed can be evaluated using:

$$\text{Energy recuperated} = 0.75F_t\left(\frac{1000}{3600}\right)vt \tag{3.7}$$

This formula was then entered into the Excel spreadsheet with format shown in the table below. The inputs are distance (E2) and speed (E3). Regenerative braking distance (E4), % Gradient (E5), F_t (N/tonne) (E6) and Energy recuperated (Wh/tonne) (E7) are outputs. Table 3.17 shows the spreadsheet developed.

Table 3.17 Downward operation data

Distance (km) (E2)	0.12
Speed (km/h) (E3)	70
Regenerative braking duration (s) (E4)	6.17
% Gradient (E5)	0.33
F_t (N/tonne) (E6)	-17.66
Energy recuperated (Wh/tonne)	0.44

The equations as entered into the Excel spreadsheet are

$$\text{Regenerative braking distance (E4)} = 3600 \times \frac{\text{E2}}{\text{E3}} \tag{3.8}$$

$$\text{\% Gradiant (E5)} = \frac{1}{\text{B2}} \times 100 \tag{3.9}$$

$$F_t \text{ (Wh/tonne) (E6) } = 98 \times \text{E2} - 50 \tag{3.10}$$

$$\text{Energy recuperated (Wh/tonne)} = 0.75 \times \text{E6} \times 0.2778 \times \frac{\text{E4} \times \text{E3}}{3600} \tag{3.11}$$

3.7 Development of an Excel Spreadsheet to Calculate the Rand Value of Energy Recuperated

Metrorail gets it electricity supply directly Eskom with a time of use tariff (TOU) known Transflex 2. This tariff is divided into low demand season and high demand season. Electricity price is higher during high demand season than low demand season. The low demand season is in April, May, October, November, December, January, February and March. For June and September, half of the month is in high demand season and half is low demand season. July and August are high demand season. The low and high demand seasons are further subdivided into peak, standard and off-peak. Electricity is most expensive during peak, followed by standard and off peak is the cheapest. Tables 3.18 and 3.19 show the start and end times for the peak, standard and off-peak for both the low demand season and high demand season respectively.

Table 3.18 Transflex 2 low season demand

	Peak		Standard			Off-peak	
Weekdays	07:00 - 10:00	18:00 - 20:00	06:00 - 07:00	10:00 - 18:00	20:00 - 22:00	22:00 - 06:00	
Saturday			07:00 - 12:00	18:00 - 20:00		12:00 - 18:00	20:00 - 07:00
Sunday						01:00 - 24:00	

Table 3.19 Transflex 2 high season demand

	Peak		Standard		Off-peak	
Weekdays	06:00 - 9:00	17:00 - 19:00	09:00 - 17:00	19:00 - 22:00	22:00 - 06:00	
Saturday			07:00 - 12:00	18:00 - 20:00	12:00 - 17:00	20:00 - 07:00
Sunday					01:00 - 24:00	

20 % of trains travel during peak, 44 % travel during standard and 36 % travel during off peak. This information was then used to split the energy recuperated per month during regenerative braking into peak energy, standard energy and off peak energy. The tariff rates were used to determine the Rand value of the total energy recuperated during peak, standard and off-peak. This Rand value is the savings in energy due to regenerative braking. When calculating the Rand value of the energy, two calculations were done for April, using the old tariff and the new tariff. Eskom annual tariff increases starts on the 16th April every year and therefore half of April calculation was done using the old tariff and the other half using the new tariff. Half the month also means half the energy recuperated. Meaning that 2,628,732 kWh obtained in Chapter 4 was divided by two for that particular calculation. For June and September, two calculations were done, half the month being high demand season and half the month being low demand season. For the remaining months, low demand season, only one calculation was done. Appendix K shows the spreadsheet developed.

Chapter 4

Determining the Regenerative Braking Energy at Various Sections in the Network

In this chapter, the energy recuperated during regenerative braking is determined. This is done per rail corridor. Information from Section 2.4.2 on how energy recuperated during regenerative braking is calculated is used. An overall system efficiency of 75 % is assumed. The maximum acceleration and deceleration of the train is taken as $0.8 m/s^2$ and $-0.8 m/s^2$ respectively. The calculations are carried out using data from Metrorail trains. The performance of the trains is such that it is comfortable for commuters. Section 2.1.2 indicated that the dynamic braking effect diminishes below 16 to 19 km/h and friction braking kicks in thereafter. For this exercise, 19 km/h is used as the lowest speed at which dynamic braking exists.

In railway practice, the gradient is expressed as the rise (in meters) for a track distance of 100 m and is called the percentage gradient [8]. Appendices C.1 to J.2 show how the energy recuperated during regenerative braking is determined for all corridors. The first corridor for this exercise is the Crossmoor line.

4.1 Crossmoor Line

According to Appendix A, the Crossmoor line starts from Merebank and ends up at Crossmoor. It is divided into the up line and the down line. The up line starts at Merebank and the down line starts at Crossmoor. The up line starts from kilometre point 0.378 and end up at kilometre point 12.471. The distance between Merebank and Crossmoor is the difference between these two: 12.093 km. The Crossmoor line has five stations. According to Table 3.3, the maximum speed allowed on the Crossmoor line is 90 km/h. Due to safety, this speed cannot be maintained on all curves and when approaching stations. This line has several gradients and curves.

Below are the stations on the Crossmoor line:

- Merebank
- Havenside
- Bayview
- Wescliff
- Chartsglen
- Crossmoor

From Merebank to Crossmoor, the slope is generally upwards, with only three downward slopes. According to Appendix C.1, the Watt-hour per tonne recuperated from Merabank to Crossmoor, the up line, is 247.43 and the energy recuperated per month is 52,547.96 kWh. On the return line from Crossmoor to Merebank, the slope is generally downward, with only three upward slopes (i.e., the reverse of the upline). According to Appendix C.2, the Watt-hour per tonne recuperated from Crossmoor to Merebank, the down line, is 470.69 and the energy recuperated per month is 99,962.81 kWh. Table 4.1 shows the total energy that can be recuperated on the Crossmoor line per month.

Table 4.1 Total energy that can be recuperated on the Crossmoor line per month

Energy recuperated on the Crossmoor up line	52,547.96 kWh
Energy recuperated on the Crossmoor down line	99,962.81 kWh
Total energy recuperated on the Crossmoor line	152,510.77 kWh

4.1.1 Umlazi Line

Appendix A shows that Umlazi line starts at Reunion and finishes at Umlazi. It is devided into the up line and the down line. The up line is from Reunion sand the down line is from Umlazi. The line is 10.084 km and has four stations. According to Table 3.3, the maximum speed allowed on the Umlazi line is 75 km/h. This line too has several gradients and curves. The stations are:

- Reunion
- Zwelethu
- KwaMnyandu
- Lindokuhle
- Umlazi

From Reunion to Umlazi, all slopes are positive except five. According to Appendix D.1, the Watt-hour per tonne recuperated on the Umlazi up line is 142.41 and the energy recuperated per month is 91,514.8 kWh.

On the return line from Umlazi to Reunion, the down line, Appendix D.2 shows that the Watt-hour per tonne recuperated is 343.58 and the energy recuperated is 220,789.65 kWh. Table 4.2 shows the total kWh that can be recuperated on the Umlazi line per month.

Table 4.2 Total energy that can be recuperated on the Umlazi line per month

Energy recuperated on the Umlazi up line	91,514.80 kWh
Energy recuperated on the Umlazi down line	220,789.65 kWh
Total energy recuperated on the Umlazi line	312,304.45 kWh

4.2 South Coast Line

According to Appendix A, the South coast line starts from Reunion station and end up at Kelso station, from kilometre point 8.659 to 59.256. The length of this line is 50.597 km. This line is single line in certain sections and double line in other sections. It is not divided into the Up and down line like the previous two corridors. According to Table 3.3, the maximum speed allowed on the South coast line is 90 km/h. The South Coast line has sixteen stations. This is the longest Metrorail line in KwaZulu-Natal. It has multiple gradients. Below are the stations on the South coast line:

- Reunion
- Pelgrim
- Isipingo
- Umbongintwini
- Phahla
- Amanzimtoti
- Doonside
- Warner beach

- Winkelspruit
- Illovo beach
- Karridene
- Umgababa
- Ilfracombe
- Umkomaas
- Claustal
- Renishaw
- Scottburgh
- Park Rynie
- Kelso

According to Appendix E.1, the Watt-hour per tonne recuperated on the South coast line, from Reunion station to Kelso station is 1264.68 and the energy recuperated per month is 461,242.35 kWh.

On the return line, from Kelso station to Reunion station, Appendix E.2 shows that the Watt-hour per tonne recuperated 1157.35 and the energy recuperated per month is 422,097.35 kWh. Table 4.3 shows the total kWh recuperated on the South coast line per month

Table 4.3 Total energy that can be recuperated on the South Coast line per month

Energy recuperated from Reunion to Kelso	461,242.35 kWh
Energy recuperated from Kelso to Reunion	422,097.95 kWh
Total energy recuperated on the South coast line	883,340.30 kWh

4.3 KwaMashu Line

According to Appendix A, the KwaMashu line starts at Duffsroad and ends at KwaMashu. It is divided into the up and down lines. It goes from kilometre point 0 to kilometre point 4.450 so it is a short line of 4.450 km. The up line is from Duffsroad to KwaMashu and the down line from KwaMashu to Duffsroad. From Duffsroad station to KwaMashu station, all the slopes are positive except four. According to Table 3.3, the maximum speed allowed on the KwaMashu line is 90 km/h. But due to safety, this speed cannot be maintained on curves. This line has only two stations. Below are the stations on the KwaMashu line.

- Duffsroad
- Thembalihle
- KwaMashu

According to Appendix F.1, the Watt-hour per tonne recuperated on the KwaMashu up line is 65.28 and the energy recuperated per month is 37,324.26 kWh.

Appendix F.2 shows that the Watt-hour per tonne recuperated on the KwaMashu down line is 87.5 and the energy recuperated per month is 50,028.68 kWh. All the slopes are negative except four. Table 4.4 shows the total kWh recuperated on the KwaMashu line per month.

Table 4.4 Total energy that can be recuperated on the KwaMashu line per month

Energy recuperated on the KwaMashu up line	37,324.26 kWh
Energy recuperated on the KwaMashu down line	50,028.69 kWh
Total energy recuperated on the KwaMashu line	87,352.95 kWh

4.4 Greenwood Park Line

According to Appendix A, the Greenwood Park line starts at Umgeni and finishes at Duffsroad. Like the South Coast line, some sections on this line are single line and some are double line. It starts at kilometre point 5.000 and finishes at kilometre point 14.580 so it is 9.580 km long. From Umgeni to Duffsroad, the number of positive and negative slopes almost balance out. According to Table 3.3, the maximum speed allowed on the Greenwood Park line is 60 km/h. This line has five stations. Below are the stations on the Greenwood Park line.

- Umgeni station
- Briardene station
- Greenwood Park station
- Redhill station
- Avoca station
- Duffsroad station

According to Appendix G.1, the Watt-hour per tonne recuperated from Umgeni to Duffsroad on the Greenwood Park line is 209.11 and the energy recuperated per month is 33,879.32 kWh.

Appendix G.2 shows that the Watt-hour per tonne recuperated from Duffsroad to Umgeni on the Greenwood Park line is 242.77 and the energy recuperated per month is 39,332.8 kWh. The number of positive and negative slopes is almost equal. Table 4.5 shows the energy recuperated on the Greenwood Park line per month:

Table 4.5 Total energy that can be recuperated on the Greenwood Park line per month

Energy recuperated from Umgeni station to Duffsroad station	33,879.32 kWh
Energy recuperated from Duffsroad station to Umgeni station	39,332.80 kWh
Total energy recuperated on the Greenwood Park line	73,212.12 kWh

4.5 Pinetown Line

According to Appendix A, the Pinetown line starts at Rossburghand finishes at Pinetown. Like the South Coast line and the Greenwood Park lines, this line is a single line on certain sections and double line on other sections. It starts from kilometre point 7.460 and end up at kilometre point 27.070 so it is 19.61 km long. From Rossburgh to Pinetown, all the slopes are ascending except four. According to Table 3.3, the maximum speed allowed on the Pinetown line is 75 km/h. This line has eleven stations. Below are the stations.

- Rossburgh station
- Seaview station
- Bellair station
- Hillary station
- Poets corner station
- Malvern station
- Escombe station
- Northdene station

- Mosely station
- Glen Park station
- Sarnia station
- Pinetown station

According to Appendix H.1, the Watt-hour per tonne recuperated from Rossburgh to Pinetown is 232.86 and the energy recuperated per month is 32,766.15 kWh.

On the return line, Pinetown to Rossburgh, Appendix H.2 shows that the Watt-hour per tonne recuperated 451.16 and the energy recuperated per month is 63,483.64 kWh. The number of positive and negative slopes is almost equal. Table 4.6 shows the total energy recuperated on the Pinetown line per month.

Table 4.6 Total energy that can be recuperated on the Pinetown line per month

Energy recuperated from Rossburgh station to Pinetown station	32,766.15 kWh
Energy recuperated from Pinetown station to Rossburgh station	63,483.64 kWh
Total energy recuperated on the Pinetown line	96,249.79 kWh

4.6 Effingham Line

According to Appendix A, the Effingham line starts at Duffsroad and finishes at Umgeni. The line from Duffsroad to Umgeni is called the Seaside line and the line from Umgeni to Duffsroad is called the Landside line. The Effingham line starts at kilometre point 163.710 and finishes at kilometre point 180.255 so this line is 16.545 km. From Duffsroad to Umgeni, the number of positive and negative slopes almost balances. According to Table 3.3, the maximum speed allowed on the Effingham line is 75 km/h. This line has five stations. Below are the stations on the Effingham line.

- Duffsroad station
- Effingham station
- Kenville station
- Temple station
- Umgeni station

According to Appendix I.1, the Watt-hour per tonne recuperated from Duffsroad station to Umgeni station is 169.98 and the energy recuperated per month is 110,158.40kWh.

On the return line, Appendix I.2 shows that the Watt-hour per tonne recuperated from Umgeni station to Duffsroad station is 124.56 and the energy recuperated per month is 80,723.24 kWh. Table 4.7 shows the total energy recuperated per month.

Table 4.7 Total energy that can be recuperated on the Effingham line per month

Energy recuperated from Duffsroad station to Umgeni station	110,158.40 kWh
Energy recuperated from Umgeni station to Duffsroad station	80,732.24 kWh
Total energy recuperated on the Effingham line	190,881.64 kWh

4.7 Central Area

The Central area is the area between Umgeni and Reunion. Umgeni is at kilometre point 3.26. From Umgeni to Reunion, there are more negative slopes that positive ones and the overall slope is negative. The maximum speed allowed between Reunion and Umgeni is 80 km/h as shown in

Appendices J.1 and J.2. There are twelve stations from Umgeni to Reunion. Below are the stations in the Central area.

- Umgeni station
- Moses Mabhida station
- Durban station
- Berea road station
- Dalbridge station
- Congella station
- Umbilo station
- Rossburgh station
- Clairwood station
- Montclair station
- Merebank station
- Reunion station

According to Appendix J.1, the Watt-hour per tonne recuperated from Umgeni to Reunion is 313.13 and the energy recuperated is per month is 409,170.95 kWh.

Appendix J.2 shows that the Watt-hour per tonne recuperated on the return path, from Reunion to Umgeni is 322.72 and the energy recuperated per month is 423,709.03 kWh. Table 4.8 shows the energy recuperated per month:

Table 4.8 Total energy that can be recuperated on the the Central Area per month

Energy recuperated from Umgeni station to Reunion station	409,170.95 kWh
Energy recuperated from Reunion station to Umgeni station	423,709.03 kWh
Total energy recuperated on the Central area	832,879.98 kWh

Using the information above, the total energy recuperated on the Metrorail network is 2,628,732 kWh per month. This was obtained after adding all energies recuperated on the Crossmoor, Umlazi, South coast, KwaMashu, Greenwood Park, Pinetown, Effingham and Central area.

Chapter 5

Rand Cost Savings Due to the Introduction of Regenerative Braking

This chapter presents the Rand value of savings that will be realised by introducing regenerative braking to Metrorail trains. In Chapter 4, the total energy recuperated from regenerative braking was found to be 2,628,732 kWh per month. In reality, 20 %, 44 % and 36 % of the mass is transported during peak, standard and off-peak periods respectively. Using this information and the Excel spreadsheet developed in Section 3.6, the Rand value of savings per month were calculated. Because the price of electricity is not the same throughout the year, it was advisable to calculate the total savings over a period of twelve months for the return on investment to be accurate. Otherwise it would differ from season to season making it difficult to calculate the savings. The assumption made is that the energy recuperated will be the same over twelve months.

Below is the Rand value of savings as shown on Appendix K. This is how the Rand value of savings was calculated.

5.1 Low Demand Season

April falls under the low demand season and the tariff is shown in Appendix K. From the 16th April, Eskom implements its annual tariff increase. So when calculating savings during this month, half the month was calculated using the old tariff and the other half using the new tariff. The energy savings in April is R1, 554,295.63.

May, October, November, December, January, February and March also fall under the low demand season. Therefore, when calculating savings, the whole month was calculated using a low demand season tariff. The energy saving for each one of the above-mentioned months is R1, 593,884.33 per month.

5.2 High Demand Season

July and August are classified as high demand season months. When calculating savings for these months, the whole month was calculated using high demand season tariff. The energy savings for each month is R2,907,577.38 per month.

5.3 Combination of High and Low Demand Season

June and September fall under high demand and low demand season. When calculating savings, half the month was calculated using high demand season tariff and the other half using a low demand tariff. The savings for each month is R2, 250,730.85 per month. Table 5.1 shows the financial savings per annum.

Table 5.1 Financial savings per annum

April	R 1,554,295.63
May	R 1,593,884.33
June	R 2,250,730.85
July	R 2,907,577.38
August	R 2,907,577.38
September	R 2,250,730.85
October	R 1,593,884.33
November	R 1,593,884.33
December	R 1,593,884.33
January	R 1,593,884.33
February	R 1,593,884.33
March	R 1,593,884.33
Total savings	R 23,028,102.40

5.4 Financial Evaluation of Retrofitting Regenerative Braking Technology on Current Trains

In Chapter 5, the saving made by introducing regenerative braking was calculated as R 23,028,102.40 per annum. In this chapter, the feasibility of modifying current trains in order to be able to have regenerative braking capabilities is determined.

Firstly the percentage savings in energy is determined, followed by the determination of the net present value (NPV). There are two alternatives in this project. Alternative 1 is to continue with the old type of braking system and alternative 2 is to retrofit regenerative braking technology. The NPV of each alternative will be calculated for comparison. The alternative with a higher NPV was recommended. Higher NPV means higher financial benefits.

In the calculation of NPV, the assumption was that the repo rate, which is the discount rate, is 8 % and it remains fixed for the lifespan of the retrofitted technology. According to a representative of ABB [21], the lifespan of this technology is fifteen years. The second assumption was that the

National energy regulator of South Africa will only approve inflation linked annual tariff increase of six percent to Eskom. The last assumption is that material and labour cost will only increase by 6 % per annum. Using this information, the Rand value of savings is as follows.

5.4.1 % Savings in Energy Due to Regenerative Braking

According to Section 1.2, the total energy consumed by Metrorail trains per month is 12,949,418.72 kWh. Using this information and the 2,628,732 kWh energy recuperated from regenerative braking per month, the energy savings is 20.3 %.

5.4.2 Net Present Value

Rand Value of Savings

With the assumption that Eskom will only increase the tariff by 6 % per annum implies that the savings will also increase by 6 % per annum. Using this information, the savings made from regenerative braking after one year (year 1) will be R 23,028,102.40. From the end of year 2 to the end of year 15, 6 % annual inflationary increase will be added. Table 5.2 shows the savings per annum from end of year 1 to end of year 15.

Costs to Overhaul Current Locomotives

At the moment, there is an overhaul programme done on current locomotives once a decade. This work includes refurbishment of high voltage compartment as well as refurbishment of traction motors. The cost of this refurbishment is R 8 million per motor coach. Metrorail KwaZulu-Natal is running one hundred and forty motor coaches, meaning that the total cost of refurbishment is R 1,120,000,000.00 per decade. The assumption is that refurbishment cost increases at an inflation rate of 6 % per annum when determining the value of maintenance costs for year 0, year 10 and year 15. The reason why this overhaul cost is so important is that is used to calculate the NPV of the current braking system in order to compare with the NPV of the regenerative braking technology. Table 5.2 shows the overhaul costs.

Costs to Retrofit Regenerative Braking Technology

As discussed in Section 2.8, the current Metrorail fleet can be modified by retrofitting technology readily available in the market so that they can have regenerative braking capabilities. From Section 2.7, the capital cost required is R 2,268,000,000.00.

The NPV of the two alternatives is then calculated. After this calculation, an alternative with a higher NPV is recommended.

Table 5.2 Energy savings and overhaul costs

Year	Energy savings	Overhaul costs
1	R 23 028 102.40	
2	R 24 409 788.54	
3	R 25 874 375.86	
4	R 27 426 838.41	
5	R 29 072 448.71	
6	R 30 816 795.64	
7	R 32 665 803.37	
8	R 34 625 751.58	
9	R 36 703 296.67	
10	R 38 905 494.47	R 2 126 094 385.34
11	R 41 239 824.14	
12	R 43 714 213.59	
13	R 46 337 066.40	
14	R 49 117 290.39	
15	R 52 064 327.81	R 1 422 596 943.42

NPV – alternative 1 Alternative 1 is to continue with mechanical braking when the motor coaches are not modified in order to have regenerative braking capability. The information used here is overhaul costs obtained from Table 5.2 and the overhaul investment capital. Figure 5.1

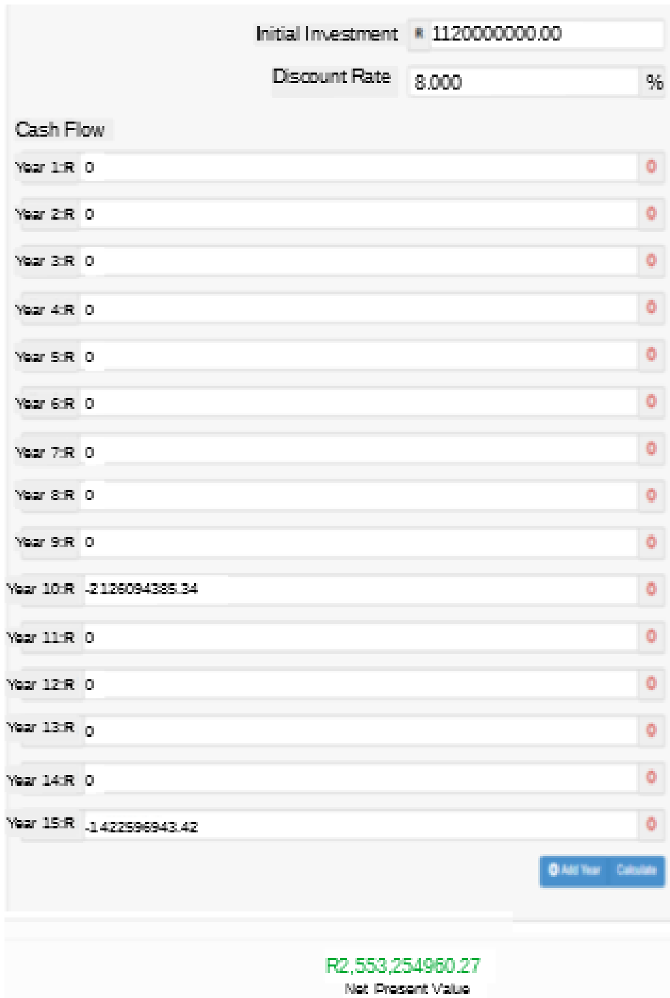

Figure 5.1 Alternative 1 NPV.

shows that the NPV - R 2,553,254,960.27.

NPV – alternative 2

Alternative 2 is to modify the motor coaches so that they can have regenerative braking capability. The information used here was obtained from Table 5.2 as energy savings and regenerative braking investment capital costs above. Appendix L shows that the NPV is -R 1,986,475,795.72.

Chapter 6

Conclusions and Recommendations

6.1 Feasibility of the Project

In Chapter 5.4, the NPV of Alternative 1 and Alternative 2 were found to be -R 2,553,254,960.27 and -R 1,986,475,795.72 respectively. This means that Alternative 2 is 22.2 % cheaper than Alternative 1 and that Metrorail needs to abandon its current motor coach overhaul programme and invest in regenerative braking technology as it has financial benefits.

To maximise financial benefits further, Metrorail must use local service providers such as Transnet to modify its motor coaches for regenerative braking because when using Foreign Service providers, the weakness of the currency can increase project costs. These service providers would then use locally manufactured equipment and local labour.

The saving projections use current electricity costs. It would have been possible to repeat the calculations with projected electricity pricing as energy costs increase. However, since the cost saving is function of the cost of electricity then, say, if there is a 10 % rise in electricity price then the cost saving would increase by 10 % for the same energy saving.

Verification of the model used is difficult to do and is outside the scope of this study. However the results seem to be in line with other studies such as [1] [9] and [25] that have carried out efficiency studies or implemented regenerative braking on trains.

6.2 Prioritisation of the Project

In Chapter 4, energies recuperated in various sections of the network were determined. This information can be used to determine phases of the retrofitting project. The highest priority will be given to trains running in sections were a lot of energy is recuperated. Table 6.1 shows how these sections can be prioritised with the South coast getting the highest priority and Greenwood Park the least priority. Central should be excluded as trains running there are going to other sections of the network.

Table 6.1 Section prioritisation

Priority	Section	Energy recuperated (kWh)
1	South Coast	883 340.30
2	Umlazi	312 304.45
3	Effingham	190 881.64
4	Crossmoor	152 510.77
5	Pinetown	96 249.79
6	KwaMashu	87 352.95
7	Greenwood Park	73 012.12

6.3 Scope of Future Work

This thesis has highlighted that the energy that can be recuperated on the Metrorail network during regenerative braking is substantial. However, the results were based on calculations and it is therefore recommended that one of the tools that can simulate regenerative braking be procured and be used to confirm this results. It is further recommended that estimates to execute the project from local service providers be obtained as opposed to foreign service providers in order to reduce the initial costs of the project. This would have a positive impact on the NPV.

Bibliography

[1] A. Adinolfi, R. Lamedica, C. Modesto, A. Prudenzi, and S. Vimercati. "Experimental assessment of energy saving due to trains regenerative braking in an electrified subway line". *IEEE Transactions on Power Delivery*, 13(4):1536–1542, 1998.

[2] L. Yu, J.H. He, H.T. Yip, F. Du, Z.Q. Bo, and J. Hu. "Simulation of regenerative braking in dc railway system based on MATLAB/simulink". In *45th International Universities Power Engineering Conference, UPEC*, page 1–5. 2010.

[3] A. Kara, K. Mardikyan, and S. Baran. "Application of regenerative braking energy to istanbul metro operation system". In *Electrical Systems for Aircraft, Railway and Ship Propulsion, ESARS*. 2012.

[4] X. Sun, H. Cai, X. Hou, M. Zhang, and H. Dong. "Regenerative braking energy utilization by multi train cooperation". In *17th IEEE International Conference on Intelligent Transportation Systems, ITSC*. 2014.

[5] J. Lee, H. Lee, and J. Kwak. "A study for improvement performance of electric brake for electric train". In *International Conference on Control, Automtion and Systems, ICCAS*, page 1309–1348. 2008.

[6] A. Bredenberg. "Regenerative braking for direct-current locomotives". *Transactions of the American Institute of Electrical Engineers*, 45:970–976, 1926.

[7] R. M. P. Goverde and G. M. Scheepmaker. "Energy-efficient train control including regenerative braking with catenary efficiency". In *IEEE International Conference on Intelligent Rail Transportation, ICIRT*. 2016.

[8] L. B. Theraja. *A Textbook of Electrical Technology*. Division of Nirja Construction & Development Co. Ltd., Ran Nagar, New Delhi, 21st ed edition, 1994.

[9] F. Flinders, R. Mathew, and W. Oghanna. "Energy savings through regenerative braking using retrofit converters". In *IEEE/ASME Joint Railroad Conference*. 1995.

[10] C. Dreyer. Electric locomotive class 6E/6E1. *RSE/TE/PRO.*, page 149, 2005.

[11] Y. Jiang, J. Liu, W. Tian, M. Shahidehpour, and M. Krishnamurthy. "Energy harvesting for the electrification of railway stations: Getting a charge from the regenerative braking of trains". *IEEE Electrification Magazine*, 2(3):39–48, 2014.

[12] J. Lee, H. Lee, and J Kwak. "A study for improvement performance of electric brake for electric train". In *International Conference on Control, Automation and Systems, ICCAS*, page 1309–1348. 2008.

[13] Z. Yang, Z. Yang, F. Lin, H. Xia, and X. Li. "Adjustment of metro train operation curve for efficiently using regenerative energy". In *IEEE International Conference on Industrial Electronics, IECON*. 2016.

[14] A. Nasri, M. Moghadam, and H. Mokhtari. "Timetable optimization for maximum usage of regenerative energy of braking in electrical railway systems". In *International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM*. 2010.

[15] P. Hu, R. Chen, H. Li, and Y. Liang. "Train operation traction energy calculation and saving in urban rail transit system". In *International Conference on Instrumentation Measurement, Computer, Communication and Control, IMCCC*, volume 2, page 505–507. 2012.

[16] S. Sanchez-Lopez. *X'trapolis mega - report on performance of new PRASA trains*. 2016.

[17] S. Song, Q. Wang, and J. Wu. "Simulation of multi-train operation and energy consumption calculation considering regenerative braking". In *33rd Chinese Control Conference, CCC*. 2014.

[18] L. Yu, J.H. He, H.T. Yip, F. Du, Z.Q. Bo, and J. Hu. "Simulation of regenerative braking in DC railway system based on MATLAB/Simulink". In *45th International Universities Power Engineering Conference, UPEC*. 2010.

[19] R.A. Uher. *Program Manual for the Train operations model*. Rail Systems Center, 2013.

[20] K.M. Watkins. "The integration of AC drive technology to Amtrak's passenger locomotives". In *IEEE/ASME Joint Railroad Conference*, page 1–5. 1993.

[21] Prabargan Govender. *Private communication with ABB*. 2018.

[22] Xin Yang, Xiang Li, Bin Ning, and Tao Tang. "A survey on energy-efficient train operation for urban rail transit". *IEEE Transactions on Power Delivery*, 17(1):2 – 13, 2016.

[23] Xin Yang, Xiang Li, Ziyou Gao, Hongwei Wang, and Tao Tang. "A cooperative scheduling model for timetable optimization in subway systems". *IEEE Transactions on Intelligent Transportation*, 14(1):438 – 447, 2012.

[24] M. Dominguez, A. Fernández-Cardador, A. P. Cucala, and R. R. Pecharroman. "Energy savings in metropolitan railway substations through regenerative energy recovery and optimal design of ATO speed profiles". *IEEE Transactions on Automation Science and Engineering*, 9(3):496 – 504, 2012.

[25] Y.V. Bocharnikov, A.M. Tobias, C. Roberts, S. Hillmansen, and C.J. Goodman. "Optimal

driving strategy for traction energy saving on DC suburban railways". *IET Electric Power Applications*, 1:675 – 682, 2007.

Appendix A

Prasa Network

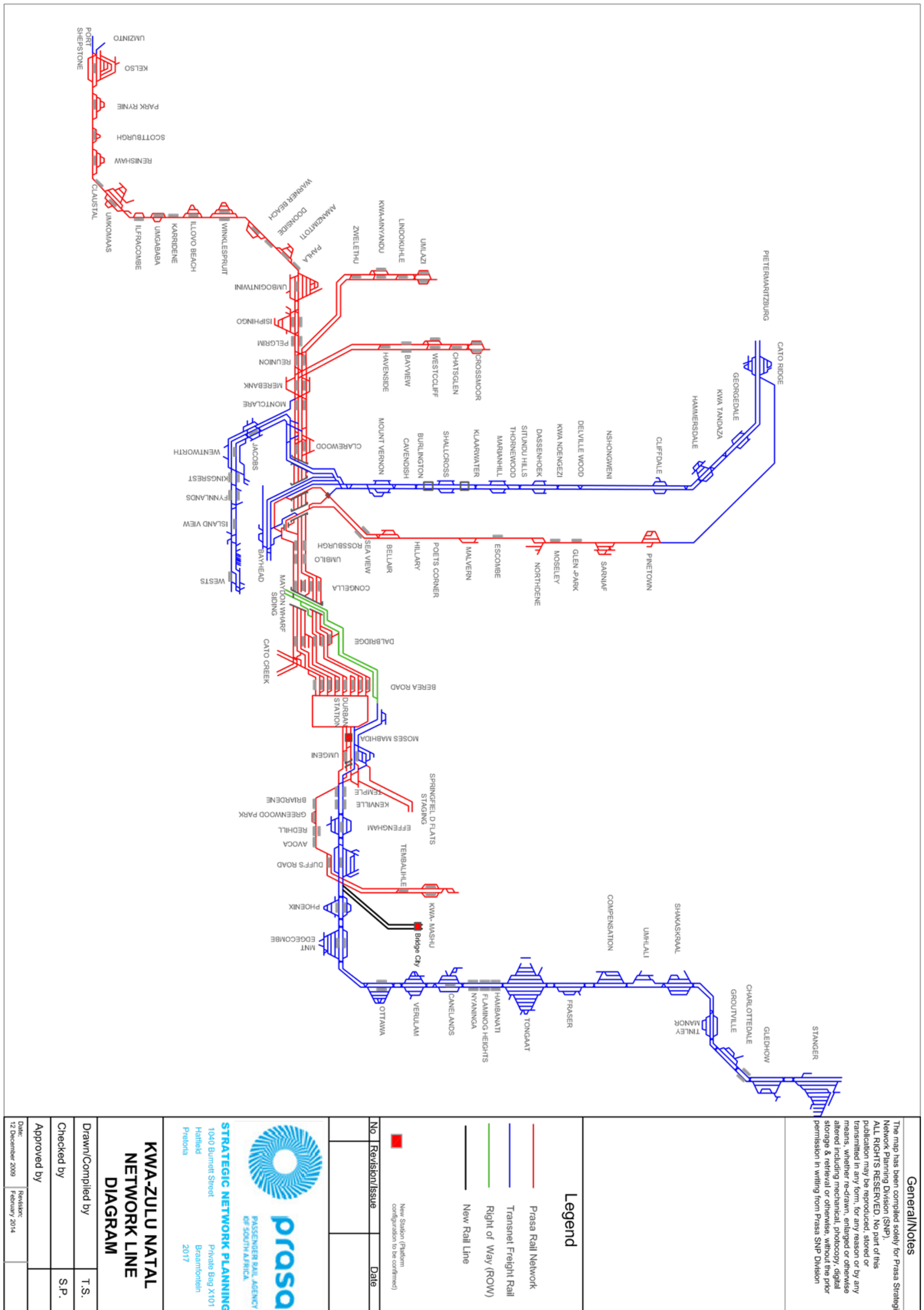

Figure A.1 Prasa Network - KwaZulu-Natal

Appendix B

List of Lines or Corridors and Number of Trains

Table B.1 Number of trains per corridor

Corridor	Weekdays				Saturday	Sunday
	AM Peak	PM Peak	Off-peak	Total	Off-peak	Off-peak
DURBAN TO KWA MASHU	23	17	61	101	52	36
DURBAN TO UMLAZI	26	22	66	114	53	36
DURBAN TO KELSO	14	10	42	66	27	16
DURBAN TO STANGER	9	5	26	40	27	18
DURBAN TO CATO RIDGE	8	2	19	29	20	16
DURBAN TO PINETOWN	6	5	19	30	16	8
DURBAN TO CROSSMOOR	8	6	24	38	21	7
DURBAN TO WESTS	6	5	9	20	11	4
Totals	100	72	266	438	227	141

Appendix C

Crossmoor Line

C.1 Merbank to Crossmoor

The curves, gradients and speeds are given in Table C.1.

Merebank to Havenside

The first curve starts at 0.428 km from Merebank station. The allowed speed at this curve is 50 km/h. The train will never exceed the speed of 5 0km/h before reaching the curve due to a short distance. This speed is the same as the curve (0.428 to 1.154 km) speed, So there will be no need to reduce speed and therefore no energy recuperated at this curve.

The second curve starts at (2.234 – 1.154 = 1.08 km) from the end of the first curve. Meaning, the train has only 1.08 km to increase speed from 50 km/h to 90 km/h and down to 60km/h for the second curve. The gradient between the first curve and the second curve (1.08 km) is 1 in 40. 50 km/h = 13.89 m/s, 90 km/h = 25 m/s and 60 km/h = 16.67m/s From 50 km/h to 90 km/h, the train requires:

$$v^2 = u^2 + 2as$$

Table C.1 Crossmoor Line curves, gradients and speeds - Merebank to Crossmoor

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Merebank	0.378			
Merebank - Havenside	0.428	1.154	+1:180	50
	2.234	2.583	+1:46	60
	2.776	3.104	+1:40	80
	3.546	3.849	+1:40	90
	3.849	3.926	+1:97	90
	3.978	4.063	-1:400	70
Havenside	4.172		+1:400	
Havenside - Bayview	4.519	5.116	+1:40	60
	5.499	6.137	+1:40	60
	6.195	6.495	+1:40	60
Bayview	6.734		+1:400	
Bayview - Westcliff	6.823	6.997	V.C.	60
	7.440	7.784	1:40	70
	8.246	8.305	+1:72.5	90
	8.305	8.360	+1:400	70
Westcliff	8.483		+1:400	
Westcliff - Chartsglen	8.621	8.735	+1:400	60
	8.770	8.857	+1:48.43	70
	8.857	8.905	+1:40	70
	8.963	9.497	+1:40	70
	9.514	9.967	+1:40	90
Chartsglen	10.327		-1:400	
Chartsglen - Crossmoor	10.453	10.659	-1:400	60
	10.659	10.780	V.C.	60
	10.780	10.821	+1:40	60
	10.836	11.116	+1:40	60
	11.638	11.187	+1:50	80
	12.225	12.459	+1:50	60
Crossmoor	12.471		+1:50	

$$25^2 = 13.89^2 + 2(0.8)s$$
$$625 = 192.9 + 1.6s$$
$$s = 270 \text{ m} = 0.27 \text{ km}$$

The train will accelerate from 50 km/h to 90 km/h in 270 m.

From 90 km/h to 60 km/h, the train requires:

$$v^2 = u^2 + 2as$$
$$16.67^2 = 25^2 + 2(-0.8)s$$
$$277.89 = 625 - 1.6s$$
$$s = 216.9 \text{ m} = 0.217 \text{ km}$$

With an ascending gradient of 1 in 40,

$$\%G = \frac{\text{Opposite}}{\text{Hypotenuse}} \times 100 = \frac{1 \times 100}{40} = 2.5$$

So, the net energy returned to the line is

$$= \eta \left[0.01072 \frac{M_e}{M} \left(V_1^2 - V_2^2\right) - (27.25dG + 0.2778rd)\right] \text{ Wh/tonne}$$
$$= 0.75 \left[0.01072 \times 1.1 \times \left(90^2 - 60^2\right) - (27.25 \times 0.217 \times 2.5 + 0.2778 \times 50 \times 0.217)\right]$$
$$= 0.75 \left[0.01072 \times 1.1 \times (8100 - 3600) - (14.78 + 3.01)\right]$$
$$= 0.75 (53.06 - 17.79) = 0.75 (35.27) = 26.45 \text{ Wh/tonne}$$

The same method is used to determine the Wh/tonne for the rest of the investigation.

There is $2.776 - 2.583 = 0.193$ km from the end of the second curve to the beginning of the third curve. There is no reduction in speed and therefore no energy recuperated at this curve. The train will then accelerate from 60 km/h to 80 km/h on the third curve.

The distance from the end of the third curve to the beginning of the fourth curve is $3.546 - 3.104 = 0.442$ km. The train will then have to accelerate from 80 km/h to 90 km/h at the end of the third curve. The allowed speed on the fourth curve is 90 km/h. The train will then maintain this speed on the fourth curve until it stops at Havenside station, point 4.172 km.

The distance from the end of the fourth curve (point 3.950) to the centre of the platform at Havenside station (point 4.17) is 0.22 km. The train must then decelerate from 90 km/h to 0 km/h in order to stop at the station. But because dynamic braking effect diminishes below 19km/h, the calculation of energy recuperated will only be done for the train decelerating from 90km/h to 19km/h. There is a descending slope of 1 in 400 at the Havenside station. Table C.2 shows the energy recuperated when the train stops at Havenside station.

Table C.2 Havenside station data

Gradient (1:*n*)	400
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.25
Wh/tonne	62.65

Havenside to Bayview

Havenside station is at km point 4.172. The distance from Havenside station to the first curve is $4.520 - 4.172 = 0.348$ km. Due to a short distance, the train will never exceed the speed of 60 km/h and therefore no need to decelerate at the curve. The speed at the curve is 60 km/h. Therefore no energy will be recuperated.

Bayview station is at km point 6.734. The train must then decelerate from 60 km/h to 0 km/h in order to stop at the station. But because dynamic braking effect diminishes below 19 km/h, the calculation of energy recuperated will only be done for the train decelerating from 60 km/h to 19 km/h. Table C.3shows the energy recuperated when the train stops at Bayview station.

Table C.3 Bayview station data

Gradient (1:n)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	26.22

Bayview to Westcliff

From Bayview station to Westcliff station all the curves have maximum speed limit of 70 km/h and therefore the train does not decelerate and therefore no energy recuperated. The train will only decelerate in order to stop at Westcliff station at km point 8.48. Table C.4shows the energy recuperated when the train stops at Westcliff station.

Table C.4 Westcliff station data

Gradient (1:n)	400
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.25
Wh/tonne	36.74

Westcliff to Chartsglen

Westcliff station is at km point 8.483. The train then accelerate from 0 to 90km/h allowed at the fourth curve from Westcliff. The train then stops at Chartsglen station, km point 10.327. This station is on a negative slope of 1 in 400. Table C.5 shows the energy recuperated.

Table C.5 Chartsglen station data

Gradient (1:n)	400
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.25
Wh/tonne	66.46

Chartsglen to Crossmoor

The train then accelerate and reach a speed of 70 km/h allowed on the third curve. It then decelerates to 60 km/h allowed on the fourth curve. The slope is 1 in 50. Table C.7 shows the energy recuperated during deceleration.

Table C.6 Chartsglen to Crossmoor gradient data

Gradient (1:n)	50
Initial velocity (km/h)	70
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.063
% Gradient	2
Wh/tonne	8.23

The train then decelerates from 60 km/h to 0 km/h in order to stop at Crossmoor. Crossmoor is at km point 12.471. The slope is 1 in 50. Table C.7 shows the energy recouped.

Table C.7 Crossmoor station data

Gradient (1:n)	50
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	2
Wh/tonne	20.63

The Wh/tonne recuperated during regenerative braking on the Crossmoor up line by adding all the energy recuperated on the sections from Merebank to Crossmoor, which is is 247.43.

From Table 3.13, the mass of all trains with passengers on the Crossmoor line per month is 212375040 kg. This equal to 212375,040 tonnes. Using this information and the total Wh/tonne, the total energy recuperated on the Crossmoor up line per month is:

$$247.43 \times 212375.040 = 52,547,956.1 = 52,547.96 \text{ kWh}$$

C.2 Crossmoor to Merbank

The curves, gradients and speeds are given in Table C.8.

Crossmoor to Chartsglen

From Crossmoor station the train accelerate to 80km/h required on the second curve. But the speed required on the third curve is 60 km/h. The train must then use regeneration braking to achieve this speed. The slope is 1 in 50 negative. Table C.9 shows the energy recuperated.

The train must then maintain this speed of 6 0km/h for the next $11.116 - 10.453 = 0.663$ km using regenerative braking. 60 km/h = 16.67 m/s and 0.663 km = 663 m. The time taken by the train to travel 0.663 km is:

$$\frac{s}{v} = \frac{663}{16.67} = 39.77 \text{ s}$$

From Section 2.4

$$F_t = (98G - r) = (98 \times 2 - 50) = 146 \text{ N/tonne}$$

Energy recuperated:

$$F_t \frac{1000}{3600} vt = 146 \times 0.2778 \times 60 \times 39.77 = 96,502 \text{ N/tonne}$$
$$= 0.0268 \text{ kWh/tonne}$$

Table C.8 Crossmoor Line curves, gradients and speeds - Crossmoor to Merebank

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Crossmoor	12.471			
Crossmoor - Chartsglen	12.459	12.225	-1:50	60
	11.187	11.638	-1:50	80
	11.116	10.836	-1:40	60
	10.821	10.780	-1:40	60
	10.780	10.659	V.C.	60
	10.659	10.453	+1:400	60
Chartsglen	10.327		+1:400	
Chartsglen - Westcliff	9.967	9.514	-1:40	90
	9.497	8.963	-1:40	70
	8.905	8.857	-1:40	70
	8.857	8.770	-1:48.43	70
	8.735	8.621	-1:400	60
Westcliff	8.483		-1:400	
Westcliff - Bayview	8.360	8.305	-1:400	70
	8.305	8.246	-1:72.5	90
	7.784	7.440	1:40	70
	6.997	6.823	V.C.	60
Bayview	6.734		-1:400	
Bayview - Havenside	6.495	6.195	-1:40	60
	6.137	5.499	-1:40	60
	5.116	4.519	-1:40	60
Havenside	4.172			
Havenside - Merebank	4.063	3.978	+1:400	70
	3.926	3.849	-1:97	90
	3.849	3.546	+1:40	90
	3.104	2.776	+1:40	80
	2.583	2.234	-1:46	60
	1.154	0.428	-1:180	50
Merebank	0.378			

Table C.9 Crossmoor to Chartsglen data

Gradient (1:n)	50
Initial velocity (km/h)	80
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.135
% Gradient	2
Wh/tonne	17.84

$$= 0.75 \times 0.0268 \text{ assuming an efficiency of 75 \%}$$

$$= 20.1 \text{ Wh/tonne}$$

The train will use regenerative braking again in order to stop Chartsglen station. Because the dynamic braking effect diminishes below 19 km/h, energy recuperated during regenerative braking will be determined until the train reaches the speed of 19 km/h. This station is on a positive slope of 1 in 400. Table C.10 shows the energy recuperated when the train stops at Chartsglen station.

Table C.10 Chartsglen station data

Gradient (1:n)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	26.22

From Chartsglen station the train accelerates to 90 km/h allowed in this section. It uses regenerative braking to reduce the speed from 90 km/h to 70 km/h allowed in the next three curves. The slope is 1 in 40 descending. Table C.11 shows the energy recuperated.

Table C.11 Chartsglen to Westcliff data - first gradient

Gradient (1:n)	40
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	2.5
Wh/tonne	34.58

From kilometre point 9.497 to kilometre point 8.770 the train will use regenerative braking to maintain the speed of 70 km/h. The distance is 9.497˘8.770 = 0.727 km. Table C.12 shows the energy recuperated when during this period.

Table C.12 Chartsglen to Westcliff data - second gradient

Distance	0.727
Initial velocity (km/h)	90
Speed (km/h)	70
Regenerative braking duration (s)	37.39
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	29.5

The train then reduce the speed from 70 km/h in order to stop at Westcliff station. The slope is 1 in 400 descending. Table C.13 shows the energy recuperated.

Table C.13 Westcliff station data

Gradient (1:n)	400
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.25
Wh/tonne	38.98

The train accelerates to 90 km/h allowed on the first curve from Westcliff. It then reduces the speed to 80 km/h. The slope is 1 in 72.5 descending. Table C.14 shows the energy recuperated.

Table C.14 Westcliff to Bayview - first gradient data

Gradient (1:n)	72.5
Initial velocity (km/h)	90
Final velocity (km/h)	80
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.082
% Gradient	1.38
Wh/tonne	16.49

The train then further reduces speed from 80 km/h to 70 km/h. The slope is 1 in 40 descending. Table C.15shows the energy recuperated.

Table C.15 Westcliff to Bayview - second gradient data

Gradient (1:n)	40
Initial velocity (km/h)	80
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.072
% Gradient	2.5
Wh/tonne	16.21

The train reduces speed from 60 km/h in order to stop at Bayview station. The slope is 1 in 400 descending. Table C.16 shows the energy recuperated.

Table C.16 Bayview station data

Gradient (1:n)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	27.82

The train then accelerate from zero to 60 km/h. It will then use regenerative braking from kilometre point 6.495 to 4.519 to maintain this speed. The slope is 1 in 40 descending. The distance is 6.495˘4.519 = 1.976 km. Table C.17 shows the energy recuperated.

Table C.17 Bayview to Havenside data

Distance	1.976
Speed (km/h)	60
Regenerative braking duration (s)	118.56
Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	80.3

The train decelerates from 60 km/h in order to stop at Havenside station. The slope is 1 in 400 descending. Table C.18 shows the energy recuperated.

Table C.18 Havenside station data

Gradient (1:*n*)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	27.82

The train accelerates from zero to 90 km/h. It then reduces the speed from 90 km/h to 80 km/h required on the fourth curve from Havenside. Table C.19 shows the energy recuperated.

Table C.19 Havenside to Merebank data - first gradient

Gradient (1:*n*)	40
Initial velocity (km/h)	90
Final velocity (km/h)	80
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.082
% Gradient	2.5
Wh/tonne	18.37

The train further reduces in speed from 80 km/h to 60 km/h. The slope is 1 in 40 descending. Table C.20 shows the energy recuperated.

Table C.20 Havenside to Merebank data - second gradient

Gradient (1:*n*)	40
Initial velocity (km/h)	80
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.135
% Gradient	2.5
Wh/tonne	30.26

The train maintains this speed from kilometre point 2.228 to kilometre point 1.012 using regenerative braking. The distance is $2.228 - 1,012 = 1.216$ km. The slope is 1 in 40 descending. Table C.21 shows the energy recuperated.

Table C.21 Havenside to Merebank data - third gradient

Distance	1.216
Speed (km/h)	60
Regenerative braking duration (s)	72.96
Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	49.4

The train reduces in speed from 60 km/h to 50 km/h required from kilometre point 0.762. The slope is 1 in 180. Table C.22 shows the energy recuperated.

Table C.22 Havenside to Merebank data - fourth gradient

Gradient (1:n)	180
Initial velocity (km/h)	60
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.053
% Gradient	0.56
Wh/tonne	9.78

The train reduces in speed from 50 km/h in order to stop at Merebank station. The slope is zero. Table C.23 shows the energy recuperated.

Table C.23 Merebank station data

Gradient (1:n)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0
Wh/tonne	27.02

The total Wh/tonne per tonne recuperated on the Crossmoor down line per month is 470.69. From Table 3.13, the mass of all trains with passengers on the Crossmoor line per month is

212375040 kg. This equal to 212375,040 tonnes. Using this information and the total Wh/tonne recuperated, the total energy recuperated on the Crossmoor down line per month is:

$$470.69 \times 212375.040 = 99,962,807.58 = 99,962.81 \text{ kWh}$$

Table C.24 shows the total kWh recuperated on the Crossmoor line per month.

Table C.24 Crossmoor line kWh recoup

Energy recuperated on the Crossmoor up line	52,547.96 kWh
Energy recuperated on the Crossmoor down line	99,962.81 kWh
Total energy recuperated on the Crossmoor line	152,510.77 kWh

Appendix D

Umlazi Line

D.1 Reunion to Umlazi

The curves, gradients and speeds are given in Table D.1.

Table D.1 Umlazi Line curves, gradients and speeds - Reunion to Umlazi

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Reunion	0.00			
Reunion - Zwelethu	0.124	0.207	0	75
	0.238	0.287	0	75
	0.450	0.575	1:62.16	60
	0.663	0.854	+1:40	60
	1.484	1.774	+1:40	60
	1.774	2.140	+1:40	70
	2.251	2.762	+1:40	75
	2.762	2.825	+1:40	75
	2.825	2.899	+1:72.16	75
Zwelethu	3.045		+1:400	
Zwelethu - KwaMnyandu	3.116	3.231	+1:400	75
	3.231	3.734	+1:40	60
	3.734	4.378	+1:66	60
	4.378	4.579	+1:123.6	60
	4.579	5.048	-1:400	60
KwaMnyandu	5.048		-1:400	
KwaMnyandu - Lindokuhle	5.224	5.424	+1:74.2	60
	5.424	5.162	+1:40	60
Lindokuhle	7.639		-1:150	
Lindokuhle - Umlazi	9.176	9.297	+1:48	60
	9.297	9.418	-1:435	60
Umlazi	10.084		-1:150	

Reunion to Zwelethu

The first curve starts at 0.124 km from Reunion. The speed allowed at this curve is 75 km/h. The train maintains this speed until it reaches 0.287 km from Reunion. It then decelerates to 60 km/h required km point (0.450 – 0.575). The slope is 1 in 62.16 ascending. Table D.2 shows the energy recuperated.

Table D.2 Reunion to Zwelethu data

Gradient (1:n)	62.16
Initial velocity (km/h)	75
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.098
% Gradient	1.61
Wh/tonne	13.68

The train accelerates until it reaches the speed of 75 km/h. It then decelerates in order to stop at Zwelethu station. The slope at Zwelethu station is 1 in 400 ascending. Table D.3 shows the energy recuperated.

Table D.3 Zwelethu station data

Gradient (1:n)	400
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	0.25
Wh/tonne	42.61

Zwelethu to KwaMnyandu

The train accelerates from zero to 60 km/h and then decelerates in order to stop at KwaMnyandu station. The slope is 1 in 400 descending. Table D.4 shows the energy recuperated.

Table D.4 KwaMnyandu station data

Gradient (1:n)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	27.82

KwaMnyandu to Lindokuhle

The train accelerates from zero to 60 km/h and then descelerates in order to stop at Lindokuhle station. The slope is 1 in 150 descending. Table D.5 shows the energy recuperated.

Table D.5 Lindokuhle station data

Gradient (1:n)	150
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.67
Wh/tonne	29.15

Lindokuhle to Umlazi

The train accelerates from zero to 60 km/h and then descelerates in order to stop at Umlazi station. Table D.6 shows the energy recuperated.

Table D.6 Umlazi station data

Gradient (1:n)	150
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.67
Wh/tonne	29.15

The Wh/tonne recouped during regenerative braking on the Umlazi up line can be obtained after adding all the energy recouped on the sections from Reunion station to Umlazi station. This is 142.41 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Umlazi line per month is 642614976 kg. This is equal to 642614.98 tonnes. Using this information, the total energy recuperated on the Umlazi up line per month is:

$$142.41 \times 642614.98 = 91,514,799.3 = 91,514.8 \text{ kWh}$$

D.2 Umlazi to Reunion

The curves, gradients and speeds are given in Table D.7.

Table D.7 Umlazi Line curves, gradients and speeds - Umlazi to Reunion

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Umlazi	10.084		+1:150	
Umlazi - Lindokuhle	9.418	9.297	+1:435	60
	9.297	9.176	-1:48	60
	9.176	7.836	-1:48	60
	7.83	6 7.639	-1:40	60
Lindokuhle	7.639		-1:1096.4	
Lindokuhle - KwaMnyandu	7.494	7.162	-1:150	60
	7.162	5.424	-1:40	60
	5.424	5.224	-1:74.2	60
KwaMnyandu	5.048		+1:400	
KwaMnyandu - Zwelethu	5.048	4.579	+1:400	60
	4.579	4.378	-1:123.6	60
	4.378	3.734	-1:66	60
	3.734	3.231	-1:40	60
	3.231	2.899	-1:400	75
Zwelethu	3.045		-1:400	
Zwelethu - Reunion	2.899	2.825	-1:72.16	75
	2.825	2.762	-1:40	75
	2.762	2.251	-1:40	75
	2.140	1.774	-1:40	70
	1.774	0.661	-1:40	60
	0.661	0.540	-1:62.16	60
	0.54	0.00	0	60
Reunion	0.00			

Umlazi to Lindokuhle

The train accelerates from zero to 60 km/h from Umlazi station. From kilometre point 9.297 to kilometre point 7.836 the speed allowed is 60 km/h and there is 1 in 40 slope descending. The distance is $9.297 - 7.836 = 1.461$ km. The train must then use regenerative braking to maintain the speed 60 km/h. The energy recuperated is given by Table D.8.

Table D.8 Umlazi to Lindokuhle data - first gradient

Distance	1.461
Initial velocity (km/h)	60
Regenerative braking duration (s)	87.66
% Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	59.36

The train decelerates in order to stop at Lindokuhle station. The slope is 1 in 1096.4 descending. Table D.9 shows the energy recuperated.

Table D.9 Lindokuhle station data

Gradient (1:n)	1096.4
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.0912
Wh/tonne	27.31

Lindokuhle to KwaMnyandu

From Lindokuhle station, the train accelerates to 60km/h. But from Kilometre point 7.162 to 5.424 there is a descending slope of 1 in 40. The train must now use regenerative braking to maintain the speed at 60 km/h. The distance covered during regenerative braking is $7.162 - 5.424 = 1.738$ km. The energy recuperated is given in Table D.10

Table D.10 Lindokuhle to KwaMnyandu data - first gradient

Distance	1.738
Initial velocity (km/h)	60
Regenerative braking duration (s)	104.28
% Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	70.61

The train further uses regenerative braking to keep the speed at 60 km/ as the slopes changes to 1 in 74 descending. The distance is $5.424 - 5.223 = 0.201$ km. Table D.11 shows the energy recuperated.

Table D.11 Lindokuhle to KwaMnyandu data - second gradient

Distance	0.201
Initial velocity (km/h)	60
Regenerative braking duration (s)	12.06
% Gradient	1.35
F_t (N/tonne)	82.3
Energy recuperated (Wh/tonne)	3.45

The train decelerates in order to stop at KwaMnyandu station. The slope is 1 in 400 ascending. Table D.12 shows the energy recuperated.

Table D.12 KwaMnyandu station data

Gradient (1:n)	400
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.25
Wh/tonne	27.82

KwaMnyandu to Zwelethu

The train accelerates from KwaMnyandu station and reach a speed of 60 km/h. But from kilometre point 4.579 to 4.378 there is a descending slope of 1 in 123.6. The distance is $4.579 - 4.378 = 0.201$ km. The train must then use regenerative braking to keep the speed at 60 km/h. Table D.13 shows the energy recuperated.

Table D.13 KwaMnyandu to Zwelethu data - first gradient

Distance	0.201
Initial velocity (km/h)	60
Regenerative braking duration (s)	12.06
% Gradient	0.809
F_t (N/tonne)	29.282
Energy recuperated (Wh/tonne)	1.23

The train further uses regenerative braking for a distance $4.378 - 3.734 = 0.644$ km. The slope is 1 in 66 descending. Table D.14 shows the energy recuperated.

Table D.14 KwaMnyandu to Zwelethu data - second gradient

Distance	0.644
Initial velocity (km/h)	60
Regenerative braking duration (s)	38.64
% Gradient	1.515
F_t (N/tonne)	98.47
Energy recuperated (Wh/tonne)	13.21

The train has a third gradient for use of regenerative braking for distance $3.734 - 3.231 = 0.503$ km. The slope is 1 in 40 descending. Table D.15 shows the energy recuperated.

Table D.15 KwaMnyandu to Zwelethu data - third gradient

Distance	0.503
Initial velocity (km/h)	60
Regenerative braking duration (s)	30.18
% Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	20.44

The train accelerates from 60 km/h to 75 km/h as allowed from kilometre point 3.231 to 2.899. It then decelerates in order to stop at Zwelethu station. The slope is 1 in 400 descending. Table D.16 shows the energy recuperated.

Table D.16 Zwelethu station data

Gradient (1:n)	400
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	0.25
Wh/tonne	45.21

Zwelethu to Reunion

From Zwelethu station, the train accelerates to 75 km/h. It then uses regenerative braking to maintain the speed at 75 km/h on a descending slope of 1 in 40. The distance is $2.825 - 2.251 = 0.574$ km. Table D.17 shows the energy recuperated.

Table D.17 Zwelethu to Reunion data - first gradient

Distance	0.574
Initial velocity (km/h)	75
Regenerative braking duration (s)	27.552
% Gradient	2.5
F_t (N/tonne)	195
Energy recuperated (Wh/tonne)	23.32

The train reduces the speed using regenerative braking from 75 km/h to 70 km/h which isrequired from kilometre point 2.251 to 1.774. The slope is 1 in 40 descending. Table D.18 shows the energy recuperated.

Table D.18 Zwelethu to Reunion data - second gradient

Gradient (1:n)	40
Initial velocity (km/h)	75
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.035
% Gradient	0.25
Wh/tonne	7.83

The train further uses regenerative braking to reduce speed from 70 km/h to 60 km/h which is required at point 1.774 to 0.66. The slope is 1 in 40. Table D.19 shows the energy recuperated.

Table D.19 Zwelethu to Reunion data - third gradient

Gradient (1:n)	40
Initial velocity (km/h)	70
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.063
% Gradient	0.25
Wh/tonne	14.05

Regenerative braking is used to maintain speed at 60 km/h on a slope of 1 in 62.16 descending. The distance is $0.661 - 0.540 = 0.121$ km. Table D.20 shows the energy recuperated.

Table D.20 Zwelethu to Reunion data - fourth gradient

Distance	0.121
Initial velocity (km/h)	60
Regenerative braking duration (s)	7.26
% Gradient	1.61
F_t (N/tonne)	107.78
Energy recuperated (Wh/tonne)	2.72

It finally decelerates in order to stop at Reunion station. The slope is zero. Table D.21 shows the energy recuperated.

Table D.21 Reunion station data

Gradient (1:n)	62.16
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.61
Wh/tonne	27.02

The total Wh/tonne recuperated on the Umlazi down line per month is 343.58. From Table

3.5(k), the mass of all trains with passengers on the Umlazi line per month is 642614976 kilograms. This is equal to 642614.98 tonnes. Using this information and the total Wh/tonne recuperated, the total energy recuperated on the Umlazi down line per month is:

$$343.58 \times 642614.98 = 220,789,654.83 \text{ Wh} = 220,789.65 \text{ kWh}$$

Table D.22 shows the total kWh recuperated on the Umlazi line per month:

Table D.22 Umlazi line kWh recoup

Energy recuperated on the Umlazi up line	91,514.8 kWh
Energy recuperated on the Umlazi down line	220,789.65 kWh
Total energy recuperated on the Umlazi line	312,304.45 kWh

Appendix E

South Coast Line

E.1 Reunion to Kelso

The curves, gradients and speeds are given in Table E.1.

Table E.1 South Coast Line curves, gradients and speeds - Reunion to Kelso

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Reunion station	8.52		0	
Reunion - Pelgrim	8.611	8.726	0	60
	8.726	9.047	+1:99	70
	9.047	9.349	0	70
	9.349	9.651	0	70
	9.852	9.913	0	70
Pelgrim station	9.923		0	
Pelgrim - Isipingo	9.923	10.695	0	90
Isipingo station	11.23		0	
Isipingo - Umbongintwini	11.361	11.401	+1:186	90
	11.401	11.542	+1:151	90
	11.663	11.824	0	90
	11.824	11.963	0	70
	11.963	12.084	0	70
	12.285	12.466	0	70
	12.728	12.848	+1:302	70
	13.049	13.149	+1:80	70
	13.270	13.411	+1:83	70
	13.609	13.701	0	50
	13.701	13.733	+1:51	50

	13.733	14.115	+1:53	70
	14.115	14.337	+1:49	70
	14.337	14.557	+1:58	70
	14.557	14.759	+1:52	70
	14.759	14.920	+1:58	70
	14.920	15.061	+1:49	70
	15.061	15.202	+1:54	70
	15.202	15.342	+1:48	70
	15.342	15.443	+1:54	70
	15.443	15.786	+1:50	70
	11.824	11.963	0	70
	11.963	12.084	0	70
	12.285	12.466	0	70
	12.728	12.848	+1:302	70
	13.049	13.149	+1:80	70
Umbongintwini station	16.32		+1:56	
Umbongintwini - Phahla	16.32	16.325	-1:386	90
	16.325	16.710	-1:314	60
	16.710	16.872	-1:163	60
	16.872	17.174	-1:52	60
	17.174	17.273	-1:106	60
	17.594	17.916	-1:62	90
	17.916	18.300	-1:59	90
	18.300	18.460	-1:62	90
	18.460	18.762	-1:61	90
	18.762	18.943	-1:220	90
Phahla station	19.06		-1:625	
Phahla - Amanzimtoti	19.124	19.265	-1:293	90
	19.265	19.406	-1:77	90
	19.406	19.467	-1:73	90
	19.467	19.747	-1:63	90
	19.747	20.130	-1:70	90
	20.130	20.393	-1:50	90
Amanzimtoti station	20.91		-1:55	
Amanzimtoti - Doonside	20.130	20.393	-1:50	80
	20.393	20.615	-1:55	80
	20.615	20.715	-1:56	80
	20.715	20.791	-1:115	80
	20.952	21.073	+1:107	60
	21.073	21.213	+1:147	60
	21.213	21.314	+1:89	60
	21.314	21.720	+1:224	70
	21.720	21.941	-1:246	70
	21.941	22.062	+1:198	70
	22.062	22.182	+1:84	70
	22.182	22.404	+1:65	70
	22.404	22.564	+1:54	90
	22.564	22.928	+1:432	90
Doonside station	22.87		-1:78	

Doonside – Warner beach	23.049	23.209	-1:56	60
	23.209	22.350	-1:75	60
	23.350	23.471	-1:317	60
	23.471	23.732	+1:780	70
	23.732	23.933	-1:264	70
Warner beach station	24.37		+1:112	
Warner beach - Winkelspruit	24.134	24.375	+1:360	90
	24.375	24.497	+1:137	90
	24.497	24.617	+1:65	90
	24.617	24.718	+1:94	90
	24.718	24.819	+1:189	90
	24.879	24.979	-1:125	70
	24.979	25.080	-1:87	70
	25.080	25.302	-1:207	70
	25.302	25.402	-1:106	70
	25.563	25.643	+1:83	90
Winkelspruit station	26.41		+1:61	
Winkelspruit – Illovo beach	26.308	26.449	-1:381	70
	26.609	26.650	-1:65	70
	26.650	26.730	-1:50	70
	26.730	26.871	-1:69	90
	26.871	27.213	-1:56	90
	27.213	27.373	-1:118	90
	27.697	27.837	+1:436	90
	28.178	28.440	-1:100	90
Illovo beach station	28.64		-1:1065	
Illovo beach - Karridene	28.984	29.246	+1:334	90
	29.246	29.468	+1:186	90
Karridene station	29.70		+1:364	
Karridene - Umgababa	29.950	30.192	+1:528	90
	30.192	30.554	+1:124	90
	30.554	31.198	+1:138	90
	31.359	31.580	-1:194	90
	31.580	31.761	-1:330	90
	31.761	31.936	-1:154	90
Umgababa station	32.17		0	
Umgababa - Ilfracombe	32.236	32.362	-1:80	70
	32.390	32.476	-1:50	70
	32.476	32.578	-1:45	70
	32.578	32.698	+1:96	70
	32.698	32.903	-1:666	70
	32.903	32.131	-1:143	70
	32.385	32.950	+1:80	80
	32.950	34.074	-1:82	80
	34.074	34.225	-1:100	80
	34.382	34.531	-1:100	80
	34.531	34.804	+1:155	90
	34.804	34.986	+1:64	90
	34.986	35.230	-1:50	90

Umgababa - Ilfracombe

	35.355	35.500	+1:100	90
	35.748	35.870	-1:66	90
	35.870	35.959	-1:400	90
	35.959	36.080	-1:125	90
	36.219	36.512	+1:100	90
	36.512	36.765	-1:500	90
	36.765	37.206	+1:333	90
	37.206	37.368	+1:60	90
Ilfracombe station	37.544		0	
Ilfracombe - Umkomaas	37.688	38.379	-1:100	90
	38.379	38.780	+1:100	90
Umkomaas station	39.41		0	
Umkomaas - Claustal	39.485	39.690	+1:600	70
	39.690	40.490	-1:600	80
	40.490	40.667	-1:165	70
	40.667	41.280	+1:115.62	70
	41.440	41.854	-1:103	70
	41.854	42.030	-1:155	70
	42.030	42.425	-1:108	70
	42.822	43.162	+1:100	90
	43.162	43.284	+1:105	90
	43.284	43.430	+1:543	70
	43.670	43.893	-1:54.52	80
Claustal station	43.990		-1:400	
Claustal - Renishaw	44.093	44.389	-1:200	70
	44.637	44.930	+1:73.8	70
	44.930	45.228	+1:198	70
	45.228	45.708	-1:618	80
	45.708	45.991	-1:116	80
	49.991	46.267	-1:116	80
	47.358	47.570	+1:100	80
Renishaw station	48.26		+1:153	
Renishaw - Scottburgh	48.459	48.926	-1:205	70
	48.926	49.466	+1:300	70
Scottburgh station	49.514		+1:2000	
Scottburgh – Park Rynie	49.768	49.930	+1:400	70
	49.930	50.099	+1:69	70
	50.099	50.241	+1:100	70
	50.241	50.443	-1:50	70
	50.443	50.595	+1:100	90
	50.595	50.840	-1:100	90
	50.840	51.159	+1:296	70
	51.159	51.354	-1:170	70
	51.354	51.464	+1:66	70
	51.464	51.592	-1:185	70
	51.592	51.666	-1:80	70
	51.666	51.774	+1:80	70
	51.774	51.865	-1:200	70
	51.865	51.986	+1:150	70
	51.986	52.149	-1:200	70

Scottburgh – Park Rynie

	52.149	52.252	-1:483	70
	52.252	52.407	+1:139	70
	52.407	52.554	+1:500	70
	52.554	52.707	+1:167	70
	52.707	52.892	-1:150	70
Park Rynie station	53.284		+1:505.5	
Park Rynie - Kelso	53.284	53.978	-1:400	70
	53.978	54.355	+1:299	80
	54.355	54.593	+1:360	70
	54.593	54.775	+1:100	70
	54.775	54.991	-1:80	70
	55.060	55.491	+1:476	70
	55.895	56.281	+1:110	70
	56.281	56.562	+1:50	70
	56.562	56.819	-1:78.3	70
	56.819	56.911	-1:50	70
	56.911	57.011	-1:55	70
	57.011	58.141	0	90
	58.141	58.445	-1:200	90
	58.445	58.686	0	70
	58.686	59.487	+1:400	70
Kelso station	59.65		+1:400	

Reunion to Pelgrim

The train accelerates from zero to 60 km/h from Reunion station. It then accelerates to 70 km/h which is allowed at kilometre point 8.726. From kilometre point 9.047 to kilometre point 9.349 the allowed speed is 70 km/h and there is a downward slope of 1 in 322. The train must then use regenerative braking to maintain the speed 70 km/h. Table E.2 shows the energy recuperated.

Table E.2 Reunion to Pelgrim data - first gradient

Distance (km/h)	0.302
Initial velocity (km/h)	70
Regenerative braking duration (s)	15.33
% Gradient	0.31
F_t (N/tonne)	-19.62
Energy recuperated (Wh/tonne)	1.23 (used)

The negative value of F_t shows that there will be no energy recuperated. The train uses regenerative braking to maintain a speed of 70 km/h allowed from kilometre point 9.349 to 9.651 and a downward slope of 1 in 95. Table E.3 shows the energy recuperated

Table E.3 Reunion to Pelgrim data - second gradient

Distance (km/h)	0.292
Initial velocity (km/h)	70
Regenerative braking duration (s)	15.02
% Gradient	1.05
F_t (N/tonne)	52.9
Energy recuperated (Wh/tonne)	3.22

Regenerative braking is then used to stop at Pelgrim station. The slope is 1 in 2200 descending. Table E.4 shows the energy recuperated.

Table E.4 Pelgrim station data

Gradient (1:n)	2200
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.05
Wh/tonne	38.07

Pelgrim to Isipingo

The train accelerates from zero to the allowed 90 km/h from kilometre point 9.923 to 10.695. It then stops at Isipingo station. The slope is 1 in 604 descending. Table E.5 shows the energy recuperated.

Table E.5 Isipingo station data

Gradient (1:n)	604
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.17
Wh/tonne	65.82

Isipingo to Umbongintwini

From Isipingo station the train accelerates to 90 km/h. It then uses regenerative braking to reduce the speed to the allowed 70 km/h from kilometre point 11.663 to 11.824 on a negative slope of 1 in 220 descending. Table E.6 shows the energy recuperated.

Table E.6 Isipingo to Umbongintwini data - first gradient

Gradient (1:n)	220
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	0.45
Wh/tonne	25.26

It then uses regenerative braking to maintain the speed at 70 km/h from kilometre point 11.824 to 11.963 on a negative slope of 1 in 90. Table E.7 shows the energy recuperated.

Table E.7 Isipingo to Umbongintwini data - second gradient

Distance (km)	0.139
Initial velocity (km/h)	70
Regenerative braking duration (s)	7.15
% Gradient	1.11
F_t (N/tonne)	58.78
Energy recuperated (Wh/tonne)	1.70

It further uses regenerative braking to keep the speed at 70 km/h from kilometre point 11.963 to 12.084 on a negative slope of 1 in 119 descending. Table E.8 shows the energy recuperated.

Table E.8 Isipingo to Umbongintwini data - third gradient

Distance (km)	0.121
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.22
% Gradient	0.84
F_t (N/tonne)	32.32
Energy recuperated (Wh/tonne)	0.81

The train uses regenerative braking to maintain the speed at 70 km/h from kilometre point 12.285 to 12.466 on a negative slope of 1 in 1422. Table E.9 shows the energy recuperated.

Table E.9 Isipingo to Umbongintwini data - fourth gradient

Distance (km)	0.181
Initial velocity (km/h)	70
Regenerative braking duration (s)	9.31
% Gradient	0.07
F_t (N/tonne)	-43.14
Energy recuperated (Wh/tonne)	1.63 (used)

The negative value of $F_t = -43.14$ shows that there will be no energy recuperated. It then reduces the speed from 70 km/h to the allowed 50 km/h from kilometre point 13.609 to 13.701. The slope is 1in 83 ascending. Table E.10 shows the energy recuperated.

Table E.10 Isipingo to Umbongintwini data - fifth gradient

Gradient (1:n)	83
Initial velocity (km/h)	70
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.116
% Gradient	1.20
Wh/tonne	17.17

It accelerates to 70 km/h and maintains this speed until it stops at Umbongintwini station. The slope is 1 in 50 ascending. Table E.11 shows the energy recuperated.

Table E.11 Umbongintwini station data

Gradient (1:n)	50
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	2.00
Wh/tonne	28.92

Umbongintwini to Phahla

From Umbongintwini station the train accelerates to 60 km/h allowed from kilometre point 16.32 to 16.325. It uses regenerative braking to maintain speed at 60km/h between kilometre point 16.325 and 16.710. The slope is 1 in 314 descending. Table E.12 shows the energy recuperated. This shows that there is no energy recuperated.

Table E.12 Umbongintwini to Phahla data - first gradient

Distance (km)	0.385
Initial velocity (km/h)	60
Regenerative braking duration (s)	23.10
% Gradient	0.32
F_t (N/tonne)	-18.64
Energy recuperated (Wh/tonne)	1.50 (used)

The uses regenerative braking to maintain the speed at 60 km/h from kilometre point 16.710 to 16.872. The slope is 1 in 163 descending. Table E.13 shows the energy recuperated.

Table E.13 Umbongintwini to Phahla data - second gradient

Distance (km)	0.162
Initial velocity (km/h)	60
Regenerative braking duration (s)	9.72
% Gradient	0.61
F_t (N/tonne)	9.78
Energy recuperated (Wh/tonne)	0.33

Regenerative braking is then used to maintain the speed at 60 km/h from kilometre point 16.872 to 17.174. The slope is 1 in 52 descending. Table E.14 shows the energy recuperated.

Table E.14 Umbongintwini to Phahla data - third gradient

Distance (km)	0.302
Initial velocity (km/h)	60
Regenerative braking duration (s)	18.12
% Gradient	1.92
F_t (N/tonne)	138.16
Energy recuperated (Wh/tonne)	8.69

The train accelerates from 60 km/h to 90 km/h allowed from kilometre point 17.594 to 17.916. From kilometre point 17.594 to 18.762 it uses regenerative braking to maintain the speed at 90 km/h. The slope is approximately 1 in 60. Table E.15 shows the energy recuperated.

Table E.15 Umbongintwini to Phahla data - fourth gradient

Distance (km)	1.168
Initial velocity (km/h)	90
Regenerative braking duration (s)	46.72
% Gradient	1.67
F_t (N/tonne)	113.66
Energy recuperated (Wh/tonne)	27.66

It then uses regenerative braking in order to stop at Phahla station. The average slope between point 18.762 and 19.06 is 1 in 325. Table E.16 shows the energy recuperated.

Table E.16 Phahla station data

Gradient (1:n)	325
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.31
Wh/tonne	66.90

Phahla to Amanzimtoti

The train accelerates from zero to 90 km/h allowed from kilometre point 19.124 to 20.393. From kilometre point 19.265 to 20.393 it uses regenerative braking to maintain the speed at 90 km/h. On average the slope is 1 in 66 descending. Table E.17 shows the energy recuperated.

Table E.17 Phahla to Amanzimtoti data - first gradient

Distance (km)	1.269
Initial velocity (km/h)	90
Regenerative braking duration (s)	50.76
% Gradient	1.52
F_t (N/tonne)	98.96
Energy recuperated (Wh/tonne)	26.16

It then uses regenerative braking in order to stop at Amanzimtoti station. The slope is 1 in 55 descending. Table E.18 shows the energy recuperated.

Table E.18 Amanzimtoti station

Gradient (1:n)	55
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	1.82
Wh/tonne	78.42

Amanzimtoti to Doonside

From Amanzimtoti to Doonside the train accelerate to the allowed 80 km/h from kilometre point 20.130 to 20.791. From 20.393 to 20.715 it uses regenerative braking to maintain the speed at 80 km/h. The slope is 1 in 55 descending. Table E.19 shows the energy recuperated.

Table E.19 Amanzimtoti to Doonside data - first gradient

Distance (km)	0.322
Initial velocity (km/h)	80
Regenerative braking duration (s)	14.49
% Gradient	1.82
F_t (N/tonne)	128.36
Energy recuperated (Wh/tonne)	8.61

It then uses regenerative braking to maintain the speed at 80 km/h allowed between point 20.715 and 20.791.The slope is 1 in 115 descending. Table E.20 shows the energy recuperated.

Table E.20 Amanzimtoti to Doonside data - second gradient

Distance (km)	0.076
Initial velocity (km/h)	80
Regenerative braking duration (s)	3.42
% Gradient	0.87
F_t (N/tonne)	35.26
Energy recuperated (Wh/tonne)	0.56

The train uses regenerative braking to decelerate to 60 km/h required at 20.952. The slope is 0. Table E.21 shows the energy recuperated.

Table E.21 Amanzimtoti to Doonside data - third gradient

Gradient (1:n)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.87
Wh/tonne	27.02

The train maintains this speed up to kilometre point 21.314. It then increases to a speed of 70 km/h and maintains it up to kilometre point 22.404. The train then increases this speed to the allowed 90 km/h from point 22.404 to 22.928 and then decelerates in order to stop at Doonside station. The slope is 1 in 432 ascending. Table E.22 shows the energy recuperated.

Table E.22 Doonside station data

Gradient (1:*n*)	432
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.23
Wh/tonne	62.79

Doonside to Warner Beach

The train accelerates to 60 km/h and uses regenerative braking to maintain this speed on a negative slope of 1 in 75 between point 23.209 and 22.350. Table E.23 shows the energy recuperated.

Table E.23 Doonside to Warner Beach data - first gradient

Distance (km)	0.859
Initial velocity (km/h)	60
Regenerative braking duration (s)	51.54
% Gradient	1.33
F_t (N/tonne)	80.34
Energy recuperated (Wh/tonne)	14.38

It continues to use regenerative braking to maintain this speed between 23.350 and 23.471 on a negative slope of 1 in 317. Table E.24shows the energy recuperated. There is no energy recuperated in this case.

Table E.24 Doonside to Warner Beach data - second gradient

Distance (km)	0.121
Initial velocity (km/h)	60
Regenerative braking duration (s)	7.16
% Gradient	0.32
F_t (N/tonne)	-18.54
Energy recuperated (Wh/tonne)	0.47 (used)

The train accelerates to 70 km/h and uses regenerative braking to reduce the speed in order to stop at Warner Beach station. The slope is 1 in 264 descending. Table E.25 shows the energy recuperated.

Table E.25 Warner Beach station data

Gradient (1:n)	264
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.38
Wh/tonne	39.56

Warner Beach to Winkelspruit

The train accelerates to the allowed speed of 90 km/h from kilometre point 24.134 to 24.718. It then decelerates to the allowed 70 km/h between kilometre point 24.879 and 25.402. The train must then use regenerative to reduce the speed from 90 km/h to 70 km/h. The slope is 1 in 189 descending. Table E.26 shows the energy recuperated.

Table E.26 Warner Beach station to Winkelspruit data - first gradient

Gradient (1:n)	189
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	0.53
Wh/tonne	25.02

It then uses regenerative braking to maintain the speed of 70 km/h from kilometre point 24.879 to 24.979 on a negative slope of 1 in 125. Table E.27 shows the energy recuperated.

Table E.27 Warner Beach to Winkelspruit data - second gradient

Distance (km)	0.10
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.14
% Gradient	0.8
F_t (N/tonne)	28.40
Energy recuperated (Wh/tonne)	0.59

It then uses regenerative braking to maintain a speed of 70 km/h from kilometre point 24.979 to 25.080 on a negative slope of 1 in 87. Table E.28 shows the energy recuperated.

Table E.28 Warner Beach to Winkelspruit data - third gradient

Distance (km)	0.101
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.19
% Gradient	1.15
F_t (N/tonne)	62.7
Energy recuperated (Wh/tonne)	1.32

It again uses regenerative braking to maintain the speed of 70 km/h from kilometre point 25.080 to 25.302 on a negative slope of 1 in 207. Table E.29 shows the energy recuperated. There is no energy recuperated in this case.

Table E.29 Warner Beach to Winkelspruit data - fourth gradient

Distance (km)	0.222
Initial velocity (km/h)	70
Regenerative braking duration (s)	11.42
% Gradient	0.48
F_t (N/tonne)	-2.96
Energy recuperated (Wh/tonne)	0.14 (used)

The train uses regenerative braking to maintain the speed of 70 km/h from kilometre point 25.302 to 25.402 on a negative slope of 1 in 106. Table E.30 shows the energy recuperated.

Table E.30 Warner Beach to Winkelspruit data - fifth gradient

Distance (km)	0.10
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.14
% Gradient	0.94
F_t (N/tonne)	42.12
Energy recuperated (Wh/tonne)	0.88

It finally uses regenerative braking in order to stop at Winkelspruit station. The slope is an average 1 in 72. able E.31 shows the energy recuperated.

Table E.31 Winkelspruit station data

Gradient (1:n)	72
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	1.39
Wh/tonne	31.65

Winkelspruit to Illovo Beach

The train accelerates to the allowed 70 km/h from kilometre point 26.408 to 26.730. It then uses regenerative braking to maintain the speed at 70 km/h on a negative slope of 1 in 65 between kilometre point 26.609 to 26.650. Table E.32 shows the energy recuperated.

Table E.32 Winkelspruit to Illovo Beach data - first gradient

Distance (km)	0.041
Initial velocity (km/h)	70
Regenerative braking duration (s)	2.11
% Gradient	1.54
F_t (N/tonne)	100.92
Energy recuperated (Wh/tonne)	0.86

It again uses regenerative braking to maintain the speed at 70 km/h on a slope of 1 in 50 descending between kilometre point 26.650 to 26.730. Table E.33 shows the energy recuperated.

Table E.33 Winkelspruit to Illovo Beach data - second gradient

Distance (km)	0.08
Initial velocity (km/h)	70
Regenerative braking duration (s)	4.11
% Gradient	2.0
F_t (N/tonne)	146
Energy recuperated (Wh/tonne)	2.43

It then accelerates to 90 km/h allowed from kilometre point 26.730 to 28.440. It then uses regenerative braking to maintain the speed at 90 km/h between kilometre point 26.871 to 27.213 on a slope of 1 in 56 descending. Table E.34 shows the energy recuperated.

Table E.34 Winkelspruit to Illovo Beach data - third gradient

Distance (km)	0.342
Initial velocity (km/h)	70
Regenerative braking duration (s)	17.59
% Gradient	1.79
F_t (N/tonne)	125.42
Energy recuperated (Wh/tonne)	8.94

Th train again uses regenerative braking to maintain the speed at 90 km/h between kilometre point 27.213 to 27.373 on a slope of 1 in 118 descending. Table E.35 shows the energy recuperated.

Table E.35 Winkelspruit to Illovo Beach data - fourth gradient

Distance (km)	0.16
Initial velocity (km/h)	90
Regenerative braking duration (s)	6.40
% Gradient	0.85
F_t (N/tonne)	33.3
Energy recuperated (Wh/tonne)	1.11

It finally uses regenerative braking to stop at Illovo Beach station. The average gradient is 1 in 582.5 descending. Table E.36 shows the energy recuperated.

Table E.36 Illovo Beach station data

Gradient (1:n)	582.5
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.17
Wh/tonne	65.87

Illovo Beach to Karridene

The train accelerates to 90 km/h and uses regenerative braking to stop at Karridene station. The slope is an average 1 in 275 ascending. Table E.37 shows the energy recuperated.

Table E.37 Karridene station data

Gradient (1:n)	275
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.36
Wh/tonne	61.78

Karridene to Umgababa

The train again accelerates to 90 km/h and uses regenerative braking to maintain the speed at 90 km/h between kilometre point 31.359 to 31.580 on a slope of 1 in 194 descending. Table E.38 shows the energy recuperated.

Table E.38 Karridene to Umgababa data - first gradient

Distance (km)	0.221
Initial velocity (km/h)	90
Regenerative braking duration (s)	8.84
% Gradient	0.52
F_t (N/tonne)	0.96
Energy recuperated (Wh/tonne)	0.04

The train uses regenerative braking in order to stop at Umgababa station. The slope is an average 1 in 242 descending. Table E.39 shows the energy recuperated.

Table E.39 Umgababa station data

Gradient (1:n)	242
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.41
Wh/tonne	67.71

Umgababa to Ilfracombe

From Umgababa station the train accelerates to 70 km/h. It then uses regenerative braking to maintain the speed at 70 km/h between kilometre point 32.698 to 32.903. The slope is 1 in 666 descending. Table E.40 shows that no energy is recuperated.

Table E.40 Umgababa to Ilfracombe data - first gradient

Distance (km)	0.205
Initial velocity (km/h)	70
Regenerative braking duration (s)	10.54
% Gradient	0.15
F_t (N/tonne)	-35.3
Energy recuperated (Wh/tonne)	1.51 (used)

It then accelerates to 80 km/h required between kilometre point 32.950 and 43.804. It then uses regenerative braking to maintain the speed at 80 km/h between kilometre point 32.950 and 34.074 at a slope of 1 in 82 descending. Table E.41 shows the energy recuperated.

Table E.41 Umgababa to Ilfracombe data - second gradient

Distance (km)	1.124
Initial velocity (km/h)	80
Regenerative braking duration (s)	50.58
% Gradient	1.22
F_t (N/tonne)	69.56
Energy recuperated (Wh/tonne)	16.29

The train uses regenerative braking to maintain the speed at 80 km/h between kilometre point 34.074 and 34.531 at a slope of 1 in 100 descending. Table E.42 shows the energy recuperated.

Table E.42 Umgababa to Ilfracombe data - third gradient

Distance (km)	0.457
Initial velocity (km/h)	80
Regenerative braking duration (s)	20.57
% Gradient	1.0
F_t (N/tonne)	48.0
Energy recuperated (Wh/tonne)	4.57

It then accelerates to 9 0km/h and uses regenerative braking to maintain the speed at 90 km/h between kilometre point 34.986 and 35.230 at a slope of 1 in 50 descending. Table E.43shows the energy recuperated.

Table E.43 Umgababa to Ilfracombe data - fourth gradient

Distance (km)	0.244
Initial velocity (km/h)	90
Regenerative braking duration (s)	10.98
% Gradient	2.0
F_t (N/tonne)	146.0
Energy recuperated (Wh/tonne)	7.42

It continues to use regenerative braking to maintain the speed at 90 km/h between kilometre point 35.748 and 35.870 at a slope of 1 in 66 descending. Table E.44 shows the energy recuperated.

Table E.44 Umgababa to Ilfracombe data - fifth gradient

Distance (km)	0.122
Initial velocity (km/h)	90
Regenerative braking duration (s)	4.88
% Gradient	1.52
F_t (N/tonne)	98.96
Energy recuperated (Wh/tonne)	2.52

It continues to use regenerative braking to maintain the speed at 90km/h between kilometre point 35.870 to 35.959 at a slope of 1 in 400 descending. Table E.45 shows that no energy is recuperated.

Table E.45 Umgababa to Ilfracombe data - sixth gradient

Distance (km)	0.089
Initial velocity (km/h)	90
Regenerative braking duration (s)	3.56
% Gradient	0.25
F_t (N/tonne)	-25.5
Energy recuperated (Wh/tonne)	0.47 (used)

It continues to use regenerative braking to maintain the speed at 90 km/h between kilometre point 35.959 to 36.080 at a slope of 1 in 125 descending. Table E.46 shows the energy recuperated.

Table E.46 Umgababa to Ilfracombe data - seventh gradient

Distance (km)	0.121
Initial velocity (km/h)	90
Regenerative braking duration (s)	4.84
% Gradient	0.80
F_t (N/tonne)	28.4
Energy recuperated (Wh/tonne)	0.72

It further continues to use regenerative braking to maintain the speed at 90 km/h between kilometre point 36.512 to 36.765 at a slope of 1 in 500 descending. Table E.47 shows there is energy recuperated.

Table E.47 Umgababa to Ilfracombe data - eighth gradient

Distance (km)	0.253
Initial velocity (km/h)	90
Regenerative braking duration (s)	10.12
% Gradient	0.20
F_t (N/tonne)	-30.4
Energy recuperated (Wh/tonne)	1.60 (used)

The train uses regenerative braking to stop at Ilfracombe station. The slope is an average 1 in 196.5 ascending. Table E.48 shows the energy recuperated.

Table E.48 Ilfracombe station data

Gradient (1:n)	196.5
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.51
Wh/tonne	60.67

Ilfracombe to Umkomaas

The train accelerates to 90 km/h and uses regenerative braking to stop at Umkomaas station. The slope is an average 1 in 50 ascending. Table E.49 shows the energy recuperated.

Table E.49 Umkomaas station data

Gradient (1:n)	50
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	2.00
Wh/tonne	49.30

Umkomaas to Claustal

The train accelerates to the allowed 80 km/h between points 39.690 and 40.490. It then reduces the speed to the allowed 70 km/h between 4o.490 and 40.667 using regenerative braking. The slope is 1 in 165 descending. Table E.50 shows the energy recuperated.

Table E.50 Umkomaas to Claustal data - first gradient

Gradient (1:n)	165
Initial velocity (km/h)	80
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.072
% Gradient	0.61
Wh/tonne	13.41

It continues to use regenerative braking to maintain the speed at 70 km/h between kilometre points 41.440 to 41.854 at a slope of 1 in 103 descending. Table E.51 shows the energy recuperated.

Table E.51 Umkomaas to Claustal data - second gradient

Distance (km)	0.414
Initial velocity (km/h)	70
Regenerative braking duration (s)	21.29
% Gradient	0.98
F_t (N/tonne)	46.04
Energy recuperated (Wh/tonne)	3.97

The train uses regenerative braking to maintain the speed at 70 km/h between kilometre points 41.854 to 42.030 at a slope of 1 in 155 descending. Table E.52 shows the energy recuperated.

Table E.52 Umkomaas to Claustal data - third gradient

Distance (km)	0.176
Initial velocity (km/h)	70
Regenerative braking duration (s)	9.05
% Gradient	0.65
F_t (N/tonne)	13.7
Energy recuperated (Wh/tonne)	0.50

It continues to use regenerative braking to maintain the speed at 70 km/h between kilometre points 42.030 to 42.425 at a slope of 1 in 108 descending. Table E.53 shows the energy recuperated.

Table E.53 Umkomaas to Claustal data - fourth gradient

Distance (km)	0.395
Initial velocity (km/h)	70
Regenerative braking duration (s)	20.31
% Gradient	0.93
F_t (N/tonne)	41.14
Energy recuperated (Wh/tonne)	3.39

The train finally decelerates from 70 km/h using regenerative braking in order to stop at Claustal station. The slope is 1 in 54.52 descending. Table E.54 shows the energy recuperated.

Table E.54 Claustal data station

Gradient (1:n)	54.52
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.2019
% Gradient	1.83
Wh/tonne	46.07

Claustal to Renishaw

The train accelerates from zero to the allowed 80 km/h between kilometre points 45.228 and 45.708. It uses regenerative braking to maintain the speed at 80 km/h between kilometre points 45.708 and 46.267 on a negative slope of 1 in 116 descending.Table E.55 shows the energy recuperated.

Table E.55 Claustal to Renishaw data - first gradient

Distance (km)	0.559
Initial velocity (km/h)	80
Regenerative braking duration (s)	25.16
% Gradient	0.86
F_t (N/tonne)	34.28
Energy recuperated (Wh/tonne)	3.99

It then uses regenerative braking to stop at Renishaw station. The slope is an average 1 in 126.5 ascending. Table E.56 shows the energy recuperated.

Table E.56 Renishaw data station

Gradient (1:n)	126.5
Initial velocity (km/h)	80
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.291
% Gradient	0.79
Wh/tonne	45.67

Renishaw to Scottburgh

The train accelerates to 70 km/h and immediately uses regenerative braking to stop at Scottburgh station. The slope is 1 in 300 ascending. Table E.57 shows the energy recuperated.

Table E.57 Scottburgh data station

Gradient (1:n)	300
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.33
Wh/tonne	36.37

Scottburgh to Park Rynie

The train accelerates to the allowed 70 km/h speed and uses regenerative braking to maintain this speed between kilometre points 50.241 and 50.443 on a downward slope of 1 in 50 descending. Table E.58 shows the energy recuperated.

Table E.58 Scottburgh to Park Rynie data - first gradient

Distance (km)	0.202
Initial velocity (km/h)	70
Regenerative braking duration (s)	10.39
% Gradient	2.0
F_t (N/tonne)	146.0
Energy recuperated (Wh/tonne)	6.14

It continues to use regenerative braking to maintain this speed between kilometre points 50.595 and 50.840 on a downward slope of 1 in 100 descending. Table E.59 shows the energy recuperated.

Table E.59 Scottburgh to Park Rynie data - second gradient

Distance (km)	0.245
Initial velocity (km/h)	70
Regenerative braking duration (s)	12.60
% Gradient	1.0
F_t (N/tonne)	48.0
Energy recuperated (Wh/tonne)	2.45

It continues to use regenerative braking to maintain this speed between kilometre points 51.159 and 51.354 on a downward slope of 1 in 170 descending. Table E.60 shows the energy recuperated.

Table E.60 Scottburgh to Park Rynie data - third gradient

Distance (km)	0.195
Initial velocity (km/h)	70
Regenerative braking duration (s)	10.03
% Gradient	0.59
F_t (N/tonne)	7.82
Energy recuperated (Wh/tonne)	0.32

The train uses regenerative braking to maintain this speed between kilometre points 51.464 and 51.592 on a downward slope of 1 in 185 descending. Table E.61 shows the energy recuperated.

Table E.61 Scottburgh to Park Rynie data - fourth gradient

Distance (km)	0.128
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.58
% Gradient	0.54
F_t (N/tonne)	2.92
Energy recuperated (Wh/tonne)	0.08

One a further gradient, the train continues to use regenerative braking to maintain this speed between kilometre points 51.592 and 51.666 on a downward slope of 1 in 80 descending. Table E.62 shows the energy recuperated.

Table E.62 Scottburgh to Park Rynie data - fifth gradient

Distance (km)	0.074
Initial velocity (km/h)	70
Regenerative braking duration (s)	3.81
% Gradient	1.25
F_t (N/tonne)	72.5
Energy recuperated (Wh/tonne)	1.12

It continues to use regenerative braking to maintain this speed between kilometre points 51.774 and 51.865 on a downward slope of 1 in 200 descending. Table E.63 shows that no energy is recuperated.

Table E.63 Scottburgh to Park Rynie data - sixth gradient

Distance (km)	0.091
Initial velocity (km/h)	70
Regenerative braking duration (s)	4.68
% Gradient	0.5
F_t (N/tonne)	-1.0
Energy recuperated (Wh/tonne)	0.02 (used

The train uses regenerative braking to maintain this speed between kilometre points 51.986 and 52.149 on a downward slope of 1 in 200 descending. Table E.64 again shows that no energy is recuperated.

Table E.64 Scottburgh to Park Rynie data - seventh gradient

Distance (km)	0.163
Initial velocity (km/h)	70
Regenerative braking duration (s)	8.38
% Gradient	0.5
F_t (N/tonne)	-1.0
Energy recuperated (Wh/tonne)	0.3 (used)

It continues to use regenerative braking to maintain this speed between kilometre points 52.149 and 52.252 on a downward slope of 1 in 483 descending. Table E.65 shows that no energy is recuperated.

Table E.65 Scottburgh to Park Rynie data - eighth gradient

Distance (km)	0.103
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.30
% Gradient	0.21
F_t (N/tonne)	-29.42
Energy recuperated (Wh/tonne)	0.63 (used)

It then uses regenerative braking to stop at Park Rynie station. The slope is 1 in 505 ascending. Table E.66 shows the energy recuperated.

Table E.66 Park Rynie station

Gradient (1:n)	505
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.20
Wh/tonne	36.98

Park Rynie to Kelso

The train accelerates to the allowed 80 km/h between kilometre points 53.978 and 54.355. It then uses regenerative braking to reduce the speed to 70 km/h allowed from kilometre points 54.355 to Kelso station. The slope is 1 in 299 ascending. Table E.67 shows the energy recuperated.

Table E.67 Park Rynie to Kelso data - first gradient

Gradient (1:n)	299
Initial velocity (km/h)	80
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.072
% Gradient	0.33
Wh/tonne	12.02

It then uses regenerative braking to maintain the speed of 70 km/h between kilometre points 54.775 and 54.991 on a downward slope of 1 in 80 descending. Table E.68 shows the energy recuperated.

Table E.68 Scottburgh to Park Rynie data - second gradient

Distance (km)	0.216
Initial velocity (km/h)	70
Regenerative braking duration (s)	11.11
% Gradient	1.25
F_t (N/tonne)	75.44
Energy recuperated (Wh/tonne)	4.04

The train uses regenerative braking to maintain a speed of 70 km/h between kilometre points 56.819 and 57.811 on a downward slope of average 1 in 52.5 descending. Table E.69 shows the energy recuperated.

Table E.69 Scottburgh to Park Rynie data - third gradient

Distance (km)	0.992
Initial velocity (km/h)	70
Regenerative braking duration (s)	51.02
% Gradient	1.9
F_t (N/tonne)	136.2
Energy recuperated (Wh/tonne)	28.15

It then accelerates to 90 km/h and uses regenerative braking to maintain this speed between kilometre points 58.141 and 58.445 on a slope of average 1 in 200 descending. Table E.70 shows that no energy is recuperated.

Table E.70 Scottburgh to Park Rynie data - fourth gradient

Distance (km)	0.304
Initial velocity (km/h)	90
Regenerative braking duration (s)	12.16
% Gradient	0.5
F_t (N/tonne)	-1.0
Energy recuperated (Wh/tonne)	0.06 (used)

The train uses regenerative braking to reduce the speed from 90 km/h to 70 km/h on an incline of 1 in 200 descending. Table E.71 shows the energy recuperated.

Table E.71 Park Rynie to Kelso data - fifth gradient

Gradient (1:n)	200
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	0.50
Wh/tonne	28.27

It finally uses regenerative braking to stop at Kelso station. The slope is 1 in 400 ascending. Table E.72 shows the energy recuperated.

Table E.72 Kelso station data

Gradient (1:n)	400
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.25
Wh/tonne	36.74

The total Wh/tonne recuperated during regenerative braking on the South Coast line from Reunion to Kelso is 1264.68 Wh/tonne. This was obtained after adding all the energies recuperated in this section. From Table 3.13, the mass of all trains with passengers on the Reunion to Kelso line per month is 364,710,720 kg. This is equal to 364,710.72 tonnes. Using this information and the total Wh/tonne from the above tables, the total energy recuperated on the Reunion to Kelso line per month is:

$1264.68 \times 364710.72 = 461,242,353.37$ Wh $= 461,242.35$ kWh

.

E.2 Kelso to Reunion

The curves, gradients and speeds are given in Table E.73.

Table E.73 South Coast Line curves, gradients and speeds - Kelso to Reunion

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Kelso station	59.65		-1:400	
Kelso - Park Rynie	59.487	58.686	-1:400	70
	58.686	58.445	0	70
	58.445	58.141	+1:200	90
	58.141	57.011	0	90
	57.011	56.911	+1:55	70
	56.911	56.819	+1:50	70
	56.819	56.562	+1:78.3	70
	56.562	56.281	-1:50	70
	56.281	55.895	-1:110	70
	55.491	55.060	-1:476	70
	54.991	54.775	+1:80	70
	54.775	54.593	-1:100	70
	54.593	54.355	-1:360	70
	54.355	53.978	-1:299	80
	53.978	53.284	+1:400	70
Park Rynie station	53.284		-1:505.5	
Park Rynie - Scottburgh	52.892	52.707	+1:150	70
	52.707	52.554	-1:167	70
	52.554	52.407	-1:500	70
	52.407	52.252	-1:139	70
	52.252	52.149	+1:483	70
	52.149	51.986	+1:200	70
	51.986	51.865	-1:150	70
	51.865	51.774	+1:200	70
	51.774	51.666	-1:80	70
	51.666	51.592	+1:80	70
	51.592	51.464	+1:185	70
	51.464	51.354	-1:66	70
	51.354	51.159	+1:170	70
	51.159	50.840	-1:296	70
	50.840	50.595	+1:100	90
	50.595	50.443	-1:100	90
	50.443	50.241	+1:50	70
	50.241	50.099	-1:100	70
	46.267	49.991	+1:116	80
	50.099	49.930	-1:69	70
	49.930	49.768	-1:400	70
Scottburgh station	49.514		-1:2000	
Scottburgh - Renishaw	49.466	48.926	-1:300	70

	48.926	48.459	+1:205	70
Renishaw station	48.26		-1:153	
Renishaw - Claustal	47.570	47.358	-1:100	80
	45.991	45.708	+1:116	80
	45.708	45.228	+1:618	80
	45.228	44.930	-1:198	70
	44.930	44.637	-1:73.8	70
	44.389	44.093	+1:200	70
Claustal station	43.990		+1:400	
Claustal - Umkomaas	43.893	43.670	+1:54.52	80
	43.430	43.284	+1:543	70
	43.284	43.162	-1:105	90
	43.162	42.822	-1:100	90
	42.425	42.030	+1:108	70
	42.030	41.854	+1:155	70
	41.854	41.440	+1:103	70
	41.280	40.667	-1:115.62	70
	40.667	40.490	+1:165	70
	40.490	39.690	+1:600	80
	39.690	39.485	-1:600	70
Umkomaas station	39.41		0	
Umkomaas - Ilfracombe	38.780	38.379	-1:100	90
	38.379	37.688	+1:100	90
Ilfracombe station	37.544		0	
Ilfracombe - Umgababa	37.368	37.206	-1:60	90
	37.206	36.765	-1:333	90
	36.765	36.512	+1:500	90
	36.512	36.219	-1:100	90
	36.080	35.959	+1:125	90
	35.959	35.870	+1:400	90
	35.870	35.748	+1:66	90
	35.500	35.355	-1:100	90
	35.230	34.986	+1:50	90
	34.986	34.804	-1:64	90
	34.804	34.531	-1:155	90
	34.531	34.382	+1:100	80
	34.225	34.074	+1:100	80
	34.074	32.950	+1:82	80
	32.131	32.903	+1:143	70
	32.903	32.698	+1:666	70
	32.698	32.578	-1:96	70
	32.578	32.476	+1:45	70
	32.476	32.390	+1:50	70
	32.950	32.385	-1:80	80
	32.362	32.236	+1:80	70
Umgababa station	32.17		0	
Umgababa - Karredene	31.936	31.761	+1:154	90
	31.761	31.580	+1:330	90
	31.580	31.359	+1:194	90
Umgababa - Karredene	31.198	30.554	-1:138	90

	30.554	30.192	-1:124	90
	30.192	29.950	-1:528	90
Karredene station	29.70		-1:364	
Karredene - Ilovo Beach	29.468	29.246	-1:186	90
	29.246	28.984	-1:334	90
Illovo Beach station	28.64		+1:1065	
Illovo beach - Winkelspruit	28.440	28.178	+1:100	90
	27.837	27.697	-1:436	90
	27.373	27.213	+1:118	90
	27.213	26.871	+1:56	90
	26.871	26.730	+1:69	90
	26.730	26.650	+1:50	70
	26.650	26.609	+1:65	70
	26.449	26.308	+1:381	70
Winkelspruit station	26.41		-1:61	
Winkelspruit - Warner Beach	25.643	25.563	-1:83	90
	25.402	25.302	+1:106	70
	25.302	25.080	+1:207	70
	25.080	24.979	+1:87	70
	24.979	24.879	+1:125	70
	24.819	24.718	-1:189	90
	24.718	24.617	-1:94	90
	24.617	24.497	-1:65	90
	24.497	24.375	-1:137	90
	24.375	24.134	-1:360	90
Warner Beach station	24.37		-1:112	
Warner Beach - Doonside	23.933	23.732	+1:264	70
	23.732	23.471	-1:780	70
	23.471	23.350	+1:317	60
	22.350	23.209	+1:75	60
	23.209	23.049	+1:56	60
Doonside station	22.87		+1:78	
Doonside - Amanzimtoti	22.928	22.564	-1:432	90
	22.564	22.404	-1:54	90
	22.404	22.182	-1:65	70
	22.182	22.062	-1:84	70
	22.062	21.941	-1:198	70
	21.941	21.720	+1:246	70
	21.720	21.314	-1:224	70
	21.314	21.213	-1:89	60
	21.213	21.073	-1:147	60
	21.073	20.952	-1:107	60
Amanzimtoti station	20.91		+1:55	
Amanzimtoti - Phahla	20.791	20.715	+1:115	80
	20.715	20.615	+1:56	80
	20.615	20.393	+1:55	80
	20.393	20.130	+1:50	90
	20.393	20.130	+1:50	80
	20.130	19.747	+1:70	90

Amanzimtoti - Phahla

	19.747	19.467	+1:63	90
	19.467	19.406	+1:73	90
	19.406	19.265	+1:77	90
	19.265	19.124	+1:293	90
Phahla station	19.06		+1:625	
Phahla - Umbongontwini	18.943	18.762	+1:220	90
	18.762	18.460	+1:61	90
	18.460	18.300	+1:62	90
	18.300	17.916	+1:59	90
	17.916	17.594	+1:62	90
	17.273	17.174	+1:106	60
	17.174	16.872	+1:52	60
	16.872	16.710	+1:163	60
	16.710	16.325	+1:314	60
Umbongintwini station	16.32		-1:56	
Umbongintwini - Isipingo	16.325	16.32	+1:386	90
	15.786	15.443	-1:50	70
	15.443	15.342	-1:54	70
	15.342	15.202	-1:48	70
	15.202	15.061	-1:54	70
	15.061	14.920	-1:49	70
	14.920	14.759	-1:58	70
	14.759	14.557	-1:52	70
	14.557	14.337	-1:58	70
	14.337	14.115	-1:49	70
	14.115	13.733	-1:53	70
	13.733	13.701	-1:51	50
	13.701	13.609	0	50
	13.411	13.270	-1:83	70
	13.270	13.149	-1:63	70
	13.149	13.049	-1:80	70
	12.848	12.728	-1:302	70
	12.466	12.285	+1:1422	70
	12.084	11.963	+1:119	70
	11.963	11.824	+1:90	70
	11.824	11.663	+1:220	90
	11.542	11.401	-1:151	90
	11.401	11.361	-1:186	90
Isipingo station	11.23		+1:604	
Isipingo - Pelgrim	10.695	9.923	+1:2200	90
Pelgrim station	9.923		+1:2200	
Pelgrim - Reunion	9.913	9.852	+1:422	70
	9.651	9.349	+1:95	70
	9.349	9.047	+1:322	70
	9.047	8.726	-1:99	70
	8.726	8.611	0	60
Reunion station	8.52		+1:275	

Kelso to Park Rynie

The train accelerates from zero to 90 km/h as required from points 58.445 to 58.141. It then uses regenerative braking to reduce the speed from 90 km/h to 70 km/h required from points 57.011 to 56.911. The gradient is zero. Table E.74 shows the energy recuperated.

Table E.74 Kelso to Park Rynie data - first gradient

Gradient (1:n)	0
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	0.0
Wh/tonne	26.69

The train uses regenerative braking to maintain this speed from points 56.562 to 56.281 on a negative slope of 1 in 50. Table E.75 shows the energy recuperated.

Table E.75 Kelso data to Park Rynie data - second gradient

Distance (km)	0.281
Initial velocity (km/h)	70
Regenerative braking duration (s)	14.45
% Gradient	2.0
F_t (N/tonne)	146
Energy recuperated (Wh/tonne)	8.55

It continues to use regenerative braking to maintain this speed from points 56.281 to 55.895 on a negative slope of 1 in 110. Table E.76 shows the energy recuperated.

Table E.76 Kelso data to Park Rynie data - third gradient

Distance (km)	0.386
Initial velocity (km/h)	70
Regenerative braking duration (s)	19.85
% Gradient	0.91
F_t (N/tonne)	39.18
Energy recuperated (Wh/tonne)	3.15

It further continues to use regenerative braking to maintain this speed from points 55.491 to 55.060 on a negative slope of 1 in 476. Table E.77 shows that no energy is recuperated.

Table E.77 Kelso data to Park Rynie data - fourth gradient

Distance (km)	0.431
Initial velocity (km/h)	70
Regenerative braking duration (s)	12.17
% Gradient	0.21
F_t (N/tonne)	29.42
Energy recuperated (Wh/tonne)	2.84 (used)

The train continues to use regenerative braking to maintain this speed from points 54.775 to 54.593 on a negative slope of 1 in 100. Table E.78 shows the energy recuperated.

Table E.78 Kelso data to Park Rynie data - fifth gradient

Distance (km)	0.182
Initial velocity (km/h)	70
Regenerative braking duration (s)	9.36
% Gradient	1.0
F_t (N/tonne)	48.0
Energy recuperated (Wh/tonne)	1.82

The train accelerates to 80 km/h and uses regenerative braking to stop at Park Rynie station. The slope is 1 in 400 ascending. Table E.79 shows the energy recuperated.

Table E.79 Park Rynie station data

Gradient (1:n)	400
Initial velocity (km/h)	80
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.291
% Gradient	0.25
Wh/tonne	48.89

Park Rynie to Scottburgh

The train accelerates from zero to 70 km/h. It uses regenerative braking to maintain this speed from points 51.986 to 51.865 on a negative slope of 1 in 150. Table E.80 shows the energy recuperated.

Table E.80 Park Rynie to Scottburgh data - first gradient

Distance (km)	0.121
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.22
% Gradient	0.67
F_t (N/tonne)	15.66
Energy recuperated (Wh/tonne)	0.39

It continues to use regenerative braking to maintain this speed from points 51.774 to 51.666 on a negative slope of 1 in 80. Table E.81 shows the energy recuperated.

Table E.81 Park Rynie to Scottburgh data - second gradient

Distance (km)	0.108
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.55
% Gradient	1.25
F_t (N/tonne)	72.5
Energy recuperated (Wh/tonne)	1.63

The train uses regenerative braking to maintain this speed from points 51.464 to 51.354 on a negative slope of 1 in 66. Table E.82 shows the energy recuperated.

Table E.82 Park Rynie to Scottburgh data - third gradient

Distance (km)	0.11
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.56
% Gradient	1.52
F_t (N/tonne)	98.96
Energy recuperated (Wh/tonne)	2.27

It continues to use regenerative braking to maintain this speed from points 51.159 to 50.840 on a negative slope of 1 in 296. Table E.83 shows that no energy is recuperated.

Table E.83 Park Rynie to Scottburgh data - fourth gradient

Distance (km)	0.319
Initial velocity (km/h)	70
Regenerative braking duration (s)	16.41
% Gradient	0.34
F_t (N/tonne)	-16.68
Energy recuperated (Wh/tonne)	1.11 (used)

It then accelerates from 70 km/h to 90 km/h allowed from points 50.840 to 50.443. It then uses regenerative braking to reduce the speed from 90 km/h to 70 km/h on a negative slope of 1 in 100. Table E.84 shows the energy recuperated.

Table E.84 Park Rynie to Scottburgh data - fifth gradient

Gradient (1:n)	100
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	1.0
Wh/tonne	29.85

The train accelerates from 70 km/h to 80 km/h and uses regenerative braking to stop at Scottburgh station. The slope is an average 1 in 833 descending. Table E.85 shows the energy recuperated.

Table E.85 Scottburgh station data

Gradient (1:n)	833
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.12
Wh/tonne	38.40

Scottburgh to Renishaw

From Scottburgh station the train accelerates from zero to 70 km/h and uses regenerative braking to stop at Renishaw station. The slope is 1 in 400 descending. Table E.86 shows the energy recuperated.

Table E.86 Renishaw station data

Gradient (1:n)	400
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.25
Wh/tonne	38.98

Renishaw to Claustal

From Renishaw station the train accelerates from zero to 80 km/h and uses regenerative braking to reduce the speed to 70 km/h. The slope is 1 in 618 ascending. Table E.87 shows the energy recuperated.

Table E.87 Renishaw to Claustal data - first gradient

Gradient (1:n)	618
Initial velocity (km/h)	80
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.072
% Gradient	0.16
Wh/tonne	12.27

It then uses regenerative braking to maintain the speed at 70 km/h on a negative slope of 1 in 198 from kilometre points 45.228 to 44.930. Table E.88 shows that there is no energy recuperated.

Table E.88 Renishaw to Claustal data - second gradient

Distance (km)	0.298
Initial velocity (km/h)	70
Regenerative braking duration (s)	15.33
% Gradient	0.51
F_t (N/tonne)	-0.02
Energy recuperated (Wh/tonne)	0

It continues to use regenerative braking to maintain this speed of 70 km/h on a negative slope of 1 in 73.8 from kilometre points 44.930 to 44.637. Table E.89 shows the energy recuperated.

Table E.89 Renishaw to Claustal data - third gradient

Distance (km)	0.293
Initial velocity (km/h)	70
Regenerative braking duration (s)	15.07
% Gradient	1.36
F_t (N/tonne)	83.28
Energy recuperated (Wh/tonne)	5.08

The train uses regenerative braking to stop at Claustal station. The slope is an average 1 in 300 ascending. Table E.90 shows the energy recuperated.

Table E.90 Claustal station data

Gradient (1:n)	300
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.33
Wh/tonne	36.37

Claustal to Umkomaas

From Claustal station the train accelerates to the allowed 90 km/h from points 43.162 to 42.822. It then uses regenerative braking to reduce the speed to the allowed 70 km/h from point 42.425 to

39.485. The slope is 1 in 100 descending. Table E.91 shows the energy recuperated.

Table E.91 Claustal to Umkomaas data - first gradient

Gradient (1:n)	100
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	1.00
Wh/tonne	29.85

It then uses regenerative braking to maintain this speed on a negative slope of 1 in 115.62 between points 41.280 and 40.667. Table E.92 shows the energy recuperated.

Table E.92 Claustal to Umkomaas data - second gradient

Distance (km)	0.613
Initial velocity (km/h)	70
Regenerative braking duration (s)	31.53
% Gradient	0.86
F_t (N/tonne)	34.28
Energy recuperated (Wh/tonne)	4.38

The train accelerates to 80 km/h and uses regenerative braking to stop at Umkomaas station. The slope is 1 in 600 descending. Table E.93 shows the energy recuperated.

Table E.93 Umkomaas station data

Gradient (1:n)	600
Initial velocity (km/h)	80
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.291
% Gradient	0.17
Wh/tonne	51.37

Umkomaas to Ilfracombe

From Umkomaas station the train accelerates to 90 km/h and uses regenerative braking to stop at Ilfracombe station. The slope is an average 1 in 100 ascending. Table E.94 shows the energy recuperated.

Table E.94 Ilfracombe station data

Gradient (1:n)	100
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	1.0
Wh/tonne	56.93

Ilfracombe to Umgababa

From Ilfracombe station the train accelerates to the line speed of 90 km/h and uses regenerative braking to maintain this speed between points 35.500 and 35.355 on a negative slope of 1 in 100 descending. Table E.95 shows the energy recuperated.

Table E.95 Ilfracombe to Umgababa data - first gradient

Distance (km)	0.145
Initial velocity (km/h)	90
Regenerative braking duration (s)	5.80
% Gradient	1.0
F_t (N/tonne)	48
Energy recuperated (Wh/tonne)	1.45

It continues to use regenerative braking to maintain this speed between points 34.986 and 34.804 on a negative slope of 1 in 64. Table E.96 shows the energy recuperated.

Table E.96 Ilfracombe to Umgababa data - second gradient

Distance (km)	0.182
Initial velocity (km/h)	90
Regenerative braking duration (s)	7.28
% Gradient	1.56
F_t (N/tonne)	102.88
Energy recuperated (Wh/tonne)	3.90

The train uses regenerative braking to reduce the speed from 90 km/h to 80 km/h allowed at points 34.531 on a negative slope of 1 in 155. Table E.97 shows the energy recuperated.

Table E.97 Ilfracombe to Umgababa data - third gradient

Gradient (1:n)	155
Initial velocity (km/h)	90
Final velocity (km/h)	80
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.082
% Gradient	0.65
Wh/tonne	15.26

It again uses regenerative braking to reduce the speed from 80 km/h to the allowed 70 km/h at point 32.131 on a positive slope of 1 in 82. Table E.98 shows the energy recuperated.

Table E.98 Ilfracombe to Umgababa data - fourth gradient

Gradient (1:n)	82
Initial velocity (km/h)	80
Final velocity (km/h)	80
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.072
% Gradient	0.22
Wh/tonne	10.71

The train uses regenerative braking to maintain the speed at 70 km/h between points 32.698 and 32.578 on a negative slope of 1 in 96. Table E.99 shows the energy recuperated.

Table E.99 Ilfracombe to Umgababa data - fifith gradient

Distance (km)	0.12
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.17
% Gradient	1.04
F_t (N/tonne)	51.92
Energy recuperated (Wh/tonne)	1.3

It then accelerates to 80 km/h and uses regenerative braking to stop at Umgababa station. The slope is an average 1 in 80 descending. Table E.100 shows the energy recuperated.

Table E.100 Umgababa station data

Gradient (1:n)	80
Initial velocity (km/h)	80
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.291
% Gradient	1.25
Wh/tonne	57.82

Umgababa to Karredene

From Umgababa station the train accelerates to 90 km/h and uses regenerative braking to maintain this speed between points 31.198 and 30.554 on a negative slope of 1 in 138. Table E.101 shows the energy recuperated.

Table E.101 Umgababa to Karredene data - first gradient

Distance (km)	0.644
Initial velocity (km/h)	90
Regenerative braking duration (s)	25.76
% Gradient	0.72
F_t (N/tonne)	20.56
Energy recuperated (Wh/tonne)	2.76

It continues to use regenerative braking to maintain this speed between points 30.554 and

30.192 on a negative slope of 1 in 124. Table E.102 shows the energy recuperated.

Table E.102 Umgababa to Karredene data - second gradient

Distance (km)	0.362
Initial velocity (km/h)	90
Regenerative braking duration (s)	14.48
% Gradient	0.81
F_t (N/tonne)	29.38
Energy recuperated (Wh/tonne)	2.22

Finally it uses regenerative braking to stop at Karredene station. The slope is an average 1 in 446 descending. Table E.103 shows the energy recuperated.

Table E.103 Karredene station data

Gradient (1:n)	464
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.22
Wh/tonne	66.20

Karredene to Illovo Beach

From Karredene the train accelerates to 50 km/h and use regenerative braking to stop at Illovo Beach station. The slope is 1 in 334 descending. Table E.104 shows the energy recuperated.

Table E.104 Illovo Beach station data

Gradient (1:n)	334
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.30
Wh/tonne	18.47

Illovo Beach to Winkelspruit

From Illovo Beach station the accelerates to 90 km/h and use regenerative braking to stop at Winkelspruit station. The slope is an average 1 in 165 ascending. Table E.105 shows the energy recuperated.

Table E.105 Winkelspruit station data

Gradient (1:*n*)	165
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.61
Wh/tonne	59.93

Winkelspruit to Warner Beach

From Winkelspruit the train accelerates to 90 km/h and uses regenerative braking to stop at Warner Beach station. The slope is an average 1 in 159 descending. Table E.106 shows the energy recuperated.

Table E.106 Warner Beach station data

Gradient (1:*n*)	159
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.63
Wh/tonne	69.35

Warner Beach to Doonside

From Warner Beach station the train uses regenerative braking to reduce the speed from 70 km/h to 60 km/h on a negative slope of 1 in 780 descending. Table E.107 shows the energy recuperated.

Table E.107 Warner Beach to Doonside data - first gradient

Gradient (1:n)	780
Initial velocity (km/h)	70
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.063
% Gradient	0.13
Wh/tonne	11.01

It then uses regenerative braking to stop at Doonside station. The slope is an average 1 in 131.5 ascending. Table E.108 shows the energy recuperated.

Table E.108 Doonside station data

Gradient (1:n)	131.5
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.76
Wh/tonne	24.59

Doonside to Amanzimtoti

From Doonside station even though the speed allowed from points 22.928 and 22.404 is 90 km/h, the train will not reach this speed due to short distance. The maximum speed the train will reach is 70 km/h. It will then use regenerative braking to maintain this speed of 70 km/h from kilometre points 22.404 and 22.182 on a negative slope of 1 in 65. Table E.109 shows the energy recuperated.

Table E.109 Doonside to Amanzimtoti data - first gradient

Distance (km)	0.222
Initial velocity (km/h)	70
Regenerative braking duration (s)	11.42
% Gradient	1.54
F_t (N/tonne)	100.92
Energy recuperated (Wh/tonne)	4.67

It continues to use regenerative braking from kilometre points 22.182 and 22.062 to maintain this speed on a negative slope of 1 in 84. Table E.110 shows the energy recuperated.

Table E.110 Doonside to Amanzimtoti data - second gradient

Distance (km)	0.12
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.17
% Gradient	1.19
F_t (N/tonne)	66.62
Energy recuperated (Wh/tonne)	1.67

The trains uses regenerative braking from kilometre points 22.062 and 21.941 to maintain this speed on a negative slope of 1 in 198. Table E.111 shows that no energy is recuperated.

Table E.111 Doonside to Amanzimtoti data - third gradient

Distance (km)	0.121
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.22
% Gradient	0.51
F_t (N/tonne)	-0.02
Energy recuperated (Wh/tonne)	0.0

The train finally uses regenerative braking to stop at Amanzimtoti station. The slope is an average 1 in 142 descending. Table E.112 shows the energy recuperated.

Table E.112 Amanzimtoti station data

Gradient (1:n)	141
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.70
Wh/tonne	41.01

Amanzimtoti to Phahla

From Amanzimtoti station the train accelerates and reaches a speed of 90km/h and thereafter uses regenerative braking to stop Phahla station. The slope is an average 1 in 200 ascending. Table E.113 shows the energy recuperated.

Table E.113 Phahla station data

Gradient (1:n)	200
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.50
Wh/tonne	60.74

Phahla to Umbongintwini

From Phahla station the train accelerates and reaches a speed of 90 km/h and thereafter uses regenerative braking to stop Umbongintwini station. The slope is an average 1 in 139 ascending. Table E.114 shows the energy recuperated.

Table E.114 Umbongintwini station data

Gradient (1:n)	139
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	0.72
Wh/tonne	59.07

Umbongintwini to Isipingo

From Umbongintwini station the train accelerates and reaches a speed of 70 km/h and thereafter uses regenerative braking to maintain this speed between kilometre points 15.443 and 14.115 on an average slope of 1 in 52.75 descending. Table E.115 shows the energy recuperated.

Table E.115 Umbongintwini to Isipingo data - first gradient

Distance (km)	1.328
Initial velocity (km/h)	70
Regenerative braking duration (s)	68.30
% Gradient	1.9
F_t (N/tonne)	136.2
Energy recuperated (Wh/tonne)	37.67

It then uses regenerative braking to reduce the speed from 70 km/h to 50 km/h on a negative slope of 1 in 53 descending. Table E.116 shows the energy recuperated.

Table E.116 Umbongintwini to Isipingo data - second gradient

Gradient (1:n)	53
Initial velocity (km/h)	70
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.116
% Gradient	1.89
Wh/tonne	24.48

The train accelerates to 70 km/h again and uses regenerative braking to maintain this speed between kilometre points 13.149 and 13.049 on a negative slope of 1 in 80 descending. Table E.117 shows the energy recuperated.

Table E.117 Umbongintwini to Isipingo data - third gradient

Distance (km)	0.1
Initial velocity (km/h)	70
Regenerative braking duration (s)	5.14
% Gradient	1.25
F_t (N/tonne)	72.5
Energy recuperated (Wh/tonne)	1.51

It continues to use regenerative braking to maintain this speed between kilometre points 12.848

and 12.728 on a negative slope of 1 in 302 descending. Table E.118 shows that no energy is recuperated.

Table E.118 Umbongintwini to Isipingo data - fourth gradient

Distance (km)	0.12
Initial velocity (km/h)	70
Regenerative braking duration (s)	6.17
% Gradient	0.33
F_t (N/tonne)	-17.66
Energy recuperated (Wh/tonne)	0.44 (used)

Due to short distance, the train will not reach the allowed 90 km/h from kilometre point 11.824 to Isipingo station. So from 70 km/h it will just use regenerative braking to stop at Isipingo station. The slope is 1 in 121.75 ascending. Table E.119 shows the energy recuperated.

Table E.119 Isipingo station data

Gradient (1:n)	121.5
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.82
Wh/tonne	34.19

Isipingo to Pelgrim

Due to short distance, the train will not reach the allowed 90 km/h from Isipingo and Pelgrim. It will only reach 50 km/h and stop at Pelgrim station. The slope is 1 in 2200 ascending. Table E.120 shows the energy recuperated.

Table E.120 Pelgrim station data

Gradient (1:n)	2200
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.05
Wh/tonne	17.75

Pelgrim to Reunion

From Pelgrim station the train accelerates to 70 km/h and uses regenerative braking to stop at Reunion station. The slope is an average 1 in 124.5 ascending. Table E.121 shows the energy recuperated.

Table E.121 Reunion station data

Gradient (1:n)	124.5
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.80
Wh/tonne	34.27

The total Wh/tonne recuperated during regenerative braking on the South Coast line from on Kelso to Reunion is 1157.35 Wh/tonne. This was obtained after adding all the energies recuperated in this section. From Table 3.13, the mass of all trains with passengers on the Kelso to Reunion per month is 364,710,720 kg as stated in the previous section. This is equal to 364,710.72 tonnes. Using this information and the total Wh/tonne from the above tables, the total energy recuperated on the Kelso to Reunion line per month is:

$1157.35 \times 364710.72 = 422,097,951.79$ Wh $= 422,097.95$ kWh

Table E.122 shows the total kWh recuperated on the Kelso line per month:

Table E.122 Kelso line kWh recoup

Energy recuperated from Reunion to Kelso	461,242.35 kWh
Energy recuperated from Kelso to Reunion	422,097.95 kWh
Total energy recuperated on the South coast line	883,340.30 kWh

Appendix F

KwaMashu Line

F.1 Duffsroad to KwaMashu

The curves, gradients and speeds are given in Table F.1.

Table F.1 KwaMashu Line curves, gradients and speeds - Duffsroad to KwaMashu

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Duffsroad station	0.023		-1:325	
Duffsroad - Thembalihle	0.133	0.380	-1:500	30
	0.380	0.435	-1:245	30
	0.435	0.448	0	50
	0.448	1.024	+1:55	70
	1.024	1.418	-1:77.9	50
	1.418	1.717	+1:400	30
	1.717	1.817	+1:400	30
	1.827	1.928	+1:400	20
Thembalihle station	2.070		0	
Thembalihle - KwaMashu	2.125	2.244	+1:480	20
	2.244	2.271	0	20
	2.271	2.532	+1:480	20
	2.532	2.631	+1:55	50
	2.804	2.399	+1:55	70
	3.654	4.151	+1:60	70
KwaMashu station	4.450		+1:400	

Duffsroad to Thembalihle

The train accelerates from zero to 70 km/h from Duffsroad station. It then uses regenerative braking to reduce the speed to 50 km/h allowed between kilometre points 1.024 and 1.418. The slope is 1 in 55 ascending. Table F.2 shows the energy recuperated.

Table F.2 Duffsroad to Thembalihle data - first gradient

Gradient (1:n)	55
Initial velocity (km/h)	70
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.116
% Gradient	1.82
Wh/tonne	15.72

It then uses regenerative braking to further reduce the speed from 50 km/h to 30 km/h. The slope is 1 in 77.9 descending. Table F.3 shows the energy recuperated.

Table F.3 Duffsroad to Thembalihle data - second gradient

Gradient (1:n)	77.9
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	1.28
Wh/tonne	15.37

It then uses regenerative braking to stop at Thembalihle station. The slope is 1 in 400 ascending. Table F.4 shows the energy recuperated.

Table F.4 Thembalihle station data

Gradient (1:*n*)	400
Initial velocity (km/h)	30
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.026
% Gradient	0.25
Wh/tonne	4.36

Thembalihle to KwaMashu

From Thembalihle station the train accelerates to 70 km/h and uses regenerative braking to stop at KwaMashu station. The slope is an average 1 in 57.5. Table F.5 shows the energy recuperated.

Table F.5 KwaMashu station data

Gradient (1:*n*)	55.7
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	1.80
Wh/tonne	29.83

The total Wh/tonne recuperated during regenerative braking on the KwaMashu up line per month is 65.28.

From Table 3.13, the mass of all trains with passengers on the KwaMashu up line per month is 571,756,416 kg. This is equal to 571,756.416 tonnes. Using this information and the total Wh/tonne on the above table, the total energy recuperated on the KwaMashu up line per month is:

$65.28 \times 571,756.416 = 37,324,258.84 \text{ Wh} = 37,324.26 \text{ kWh}$

F.2 KwaMashu to Duffsroad

The curves, gradients and speeds are given in Table F.6.

Table F.6 KwaMashu Line curves, gradients and speeds - KwaMashu to Duffsroad

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
KwaMashu station	4.450		-1:400	
	4.151	3.654	-1:60	70
KwaMashu - Thembalihle	2.399	2.804	-1:55	70
	2.631	2.532	-1:55	50
	2.532	2.271	-1:480	20
	2.271	2.244	0	20
	2.244	2.125	-1:480	20
Thembalihle station	2.070		0	
Thembalihle - Duffsroad	1.928	1.827	-1:400	20
	1.817	1.717	-1:400	30
	1.717	1.418	-1:400	30
	1.418	1.024	+1:77.9	50
	1.024	0.448	-1:55	70
	0.448	0.435	0	50
	0.435	0.380	+1:245	30
	0.380	0.133	+1:500	30
Duffsroad station	0.023		+1:325	

KwaMashu to Thembalihle

The train accelerates from zero to 70 km/h from KwaMashu station. It then uses regenerative braking to reduce the speed to the allowed 50 km/h from kilometre point 2.631 to 2.532. The slope is 1 in 55 descending. Table F.7 shows the energy recuperated.

Table F.7 KwaMashu to Thembalihle data - first gradient

Gradient (1:n)	55
Initial velocity (km/h)	70
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.116
% Gradient	1.82
Wh/tonne	24.32

It continues to use regenerative braking to reduce the speed from 50 km/h to the allowed 20 km/h from kilometre point 2.532 to 2.271. The slope is 1 in 55 descending. Table F.8 shows the energy recuperated.

Table F.8 KwaMashu to Thembalihle data - second gradient

Gradient (1:n)	55
Initial velocity (km/h)	50
Final velocity (km/h)	20
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.101
% Gradient	1.82
Wh/tonne	21.28

It uses regenerative braking to maintain the speed at 20 km/h allowed between kilometre point 2.532 and 2.271 on a negative slope of 1 in 480. Table F.9 shows that no energy is recuperated.

Table F.9 KwaMashu to Thembalihle data - third gradient

Distance (km)	0.261
Initial velocity (km/h)	20
Regenerative braking duration (s)	46.98
% Gradient	0.21
F_t (N/tonne)	-29.42
Energy recuperated (Wh/tonne)	1.60 (used)

It finally uses regenerative braking to stop at Thembalihle station. The slope is 1 in 480 descending. Table F.10 shows the energy recuperated.

Table F.10 Thembalihle station data

Gradient (1:n)	480
Initial velocity (km/h)	20
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.002
% Gradient	0.21
Wh/tonne	0.33

Thembalihle to Duffsroad

From Thembalihle station the train accelerates to 30 km/h and uses regenerative braking to maintain this speed between kilometre points 1.717 and 1.418. The slope is 1 in 400 descending. Table F.11 shows that no energy is recuperated.

Table F.11 Thembalihle to Duffsroad data - first gradient

Distance (km)	0.299
Initial velocity (km/h)	30
Regenerative braking duration (s)	35.88
% Gradient	0.25
F_t (N/tonne)	-25.5
Energy recuperated (Wh/tonne)	1.59 (used)

The train accelerates to 70 km/h and use regenerative braking to reduce the speed to the allowed 50 km/h from point 0.448 to 0.435. The slope is 1 in 55 descending. Table F.12 shows the energy recuperated.

Table F.12 Thembalihle to Duffsroad data - second gradient

Gradient (1:n)	55
Initial velocity (km/h)	70
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.116
% Gradient	1.82
Wh/tonne	24.32

It finally uses regenerative braking to stop at Duffsroad station. The slope is an average 1 in 356.7 ascending. Table F.13 shows the energy recuperated.

Table F.13 Duffsroad station data

Gradient (1:n)	357.7
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.28
Wh/tonne	17.25

The total energy recuperated on the KwaMashu down line is 87.50 Wh/tonne.

From Table 3.13, the mass of the trains with passengers on the KwaMashu down line per month is 571,756,416 kg. This is equal to 571,756.416 tonnes. Using this information and the total Wh/tonne on the above tables, the total energy recuperated on the KwaMashu down line per month is:

$87.50 \times 571,756.416 = 50,028,686.4$ Wh $= 50,028.69$ kWh

Table F.14 shows the total kWh recuperated on the KwaMashu line per month.

Table F.14 KwaMashu line kWh recoup

Energy recuperated on the KwaMashu up line	37,324.26 kWh
Energy recuperated on the KwaMashu down line	50,028.69 kWh
Total energy recuperated on the KwaMashu line	87,352.95 kWh

Appendix G

Greenwood Park Line

G.1 Umgeni to Duffsroad

The curves, gradients and speeds are given in Table G.1.

Table G.1 Greenwood Park Line curves, gradients and speeds - Umgeni to Duffsroad

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Umgeni station	5.000		0	
Umgeni - Briardene	5.112	5.145	0	40
	5.157	5.249	0	50
	5.249	5.407	0	30
	5.457	5.565	0	40
	5.829	6.018	+1:40	60
	6.018	6.439	0	30
Briardene station	6.53		+1:400	
Briardene - Greenwood Park	6.53	6.759	+1:40	60
	6.759	6.806	+1:40	40
	6.806	7.092	+1:40	60
	7.092	7.425	+1:40	50
Greenwood Park station	7.690		+1:40	
Greenwood Park - Redhill	2.804	2.399	+1:55	60
	7.789	7.929	+1:400	60
	7.929	8.024	+1:41	60
	8.024	8.294	+1:41	60
	8.294	8.594	+1:43	60
	8.594	8.696	+1:40	60
Greenwood Park - Redhill	8.696	8.809	+1:40	30

Redhill station	8.830		+1:104	
Redhill - Avoca	8.830	9.179	+1:104	30
	9.179	9.290	-1:30	60
	9.290	9.479	-1:30	60
	9.479	9.473	-1:32	60
	9.473	9.584	-1:32	60
	9.584	9.654	-1:32	30
	9.654	9.704	-1:32	30
	9.704	9.807	-1:30	30
	9.807	10.817	-1:30	50
	10.817	11.189	-1:30	50
	11.189	11.324	-1:57	50
Avoca station	11.510		0	
Avoca - Duffsroad	11.510	11.964	0	60
	11.965	12.299	+1:57	60
	12.299	12.329	0	60
	12.329	12.426	+1:107	60
	12.426	12.582	+1:107	30
	12.637	12.874	+1:107	50
	12.874	13.014	+1:35	50
	13.014	13.220	+1:35	30
	13.220	13.411	+1:35	40
	13.471	13.839	+1:35	30
	13.839	13.919	+1:35	50
	13.919	13.999	-1:68	50
	13.999	14.125	-1:68	50
	14.125	14.219	-1:68	30
	14.219	14.472	-1:772	30
Duffsroad station	14.580		-1:772	

Umgeni to Briardene

Umgeni station it at kilometre point 5.000. The train accelerates from zero to a maximum speed of 60 km/h before using regenerative braking to reduce the speed to the allowed 30 km/h from kilometre point 6.018. The slope is 1 in 40 ascending. Table G.2 shows the energy recuperated.

Table G.2 Umgeni to Briardene data - first gradient

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.130
% Gradient	2.50
Wh/tonne	15.87

It then uses regenerative braking to stop at Briardene station. The slope is 0. Table G.3 shows the energy recuperated.

Table G.3 Briardene station data

Gradient (1:n)	40
Initial velocity (km/h)	30
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.026
% Gradient	2.50
Wh/tonne	4.50

Briardene to Greenwood Park

From Briardene station the train accelerates to the allowed 60 km/h at point 6.806 and uses regenerative braking to reduce the speed to the allowed 50 km/h at point 7.092. The slope is 1 in 40 ascending. Table G.4 shows the energy recuperated.

Table G.4 Briardene to Greenwood Park data - first gradient

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.53
% Gradient	2.50
Wh/tonne	6.47

It then uses regenerative braking to stop at Greenwood Park station. The slope is 0. Table G.5 shows the energy recuperated.

Table G.5 Greenwood Park station data

Gradient (1:n)	40
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	2.50
Wh/tonne	12.57

Greenwood Park to Redhill

From Greenwood Park station it accelerates to 60 km/h and use regenerative braking to stop at Redhill station. The slope is 1 in 40 ascending. Table G.6 shows the energy recuperated.

Table G.6 Redhill station - first gradient

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	2.50
Wh/tonne	19.04

Redhill to Avoca

From Redhill station the train accelerates to the allowed 60 km/h at point 9.290. It then uses regenerative braking to maintain this speed on a downward slope of 1 in 30 between points 9.290 and 9.479. Table G.7 shows the energy recuperated.

Table G.7 Redhill to Avoca data - first gradient

Distance (km)	0.189
Initial velocity (km/h)	60
Regenerative braking duration (s)	11.34
% Gradient	3.13
F_t (N/tonne)	256.74
Energy recuperated (Wh/tonne)	10.11

It then uses regenerative braking to reduce the speed from 60 km/h to the allowed 30 km/h at point 9.584 on a downward slope of 1 in 32. Table G.8 shows the energy recuperated.

Table G.8 Redhill to Avoca data - second gradient

Gradient (1:n)	32
Initial velocity (km/h)	60
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.130
% Gradient	3.13
Wh/tonne	30.84

The train uses regenerative braking to maintain this speed from points 9.584 to 9.807 on a downward slope of 1 in 32. Table G.9 shows the energy recuperated.

Table G.9 Redhill to Avoca data - third gradient

Distance (km)	0.372
Initial velocity (km/h)	50
Regenerative braking duration (s)	26.78
% Gradient	3.33
F_t (N/tonne)	276.34
Energy recuperated (Wh/tonne)	21.42

It then uses regenerative braking to stop at Avoca station. The slope is 1 in 57 descending. Table G.10 shows the energy recuperated.

Table G.10 Avoca station data

Gradient (1:n)	57
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	1.75
Wh/tonne	21.54

Avoca to Duffsroad

From Avoca station the train accelerates to 60 km/h and uses regenerative braking to reduce the speed to 30 km/h allowed at point 12.426. The slope is 1 in 107 ascending. Table G.11 shows the energy recuperated.

Table G.11 Avoca to Duffsroad data - first gradient

Gradient (1:n)	107
Initial velocity (km/h)	60
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.130
% Gradient	0.93
Wh/tonne	20.04

It then accelerates to 50 km/h allowed from points 12.637 to 13.014. Again it uses regenerative braking to reduce the speed to 30 km/h allowed at point 13.014. The slope is 1 in 35 ascending. Table G.12 shows the energy recuperated.

Table G.12 Avoca to Duffsroad data - second gradient

Gradient (1:*n*)	35
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	2.86
Wh/tonne	8.84

Between points 13.220 and 13.211 the train accelerates to 40 km/h and uses regenerative braking to reduce the speed to the allowed 30 km/h at point 13.471. The slope is 1 in 35 ascending. Table G.13 shows the energy recuperated.

Table G.13 Avoca to Duffsroad data - third gradient

Gradient (1:*n*)	35
Initial velocity (km/h)	40
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.034
% Gradient	2.86
Wh/tonne	3.87

Again it accelerates to 50 km/h and uses regenerative braking to reduce the speed to 30 km/h required at point 14.125. The slope is 1 in 68 descending. Table G.14 shows the energy recuperated.

Table G.14 Avoca to Duffsroad data - fourth gradient

Gradient (1:*n*)	68
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	1.47
Wh/tonne	15.67

The train uses regenerative braking to maintain a speed of 30 km/h between points 14.125 and 14.219 on a negative slope of 1 in 68. Table G.15 shows the energy recuperated.

Table G.15 Avoca to Duffsroad data - fifth gradient

Distance (km)	0.094
Initial velocity (km/h)	30
Regenerative braking duration (s)	11.28
% Gradient	1.47
F_t (N/tonne)	94.06
Energy recuperated (Wh/tonne)	1.84

It finally uses regenerative braking to stop at Duffsroad station. The slope is 1 in 772 descending. Table G.16 shows the energy recuperated.

Table G.16 Duffsroad station data

Gradient (1:n)	772
Initial velocity (km/h)	30
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.026
% Gradient	0.13
Wh/tonne	4.56

The total Wh/tonne recuperated during regenerative braking from Umgeni to Duffsroad on the Greenwood Park line is 209.11. This was obtained after adding all the energies recuperated on the section. From Table 3.13, the mass of all trains with passengers from Durban to Kwa-Mashu is 571,756,416 kg. The mass of all trains with passengers from Durban to Stanger is 238,327,488 kg. The total mass of all trains with passengers from Durban to Plus Durban to Stanger is 810,083,904 kg. This is equal to 810,083.9 tonnes. But only 20 % of this mass is travel on the Greenwood Park line and 80 % travels on the Effingham line. Therefore only 162,016.8 tonnes travel on the Greenwood Park line. Using this information and the total Wh/tonne above, the total energy recuperated on the Umgeni to Duffsroad line per month is:

$209.11 \times 162,016.8 = 33,879,328.9$ Wh $= 33,879.32$ kWh

G.2 Duffsroad to Umgeni

The curves, gradients and speeds are given in Table G.17.

Table G.17 Greenwood Park Line curves, gradients and speeds - Duffsroad to Umgeni

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Duffsroad station	14.580		+1:772	
Duffsroad - Avoca	14.472	14.	+1:772	30
	14.219	14.125	+1:68	30
	14.125	13.999	+1:68	50
	13.999	13.919	+1:68	50
	13.919	13.839	-1:35	50
	13.839	13.471	-1:35	30
	13.411	13.220	-1:35	40
	13.220	13.014	-1:35	30
	13.014	12.874	-1:35	50
	12.874	12.637	-1:107	50
	12.582	12.426	-1:107	30
	12.426	12.329	-1:107	60
	12.329	12.299	0	60
	12.299	11.965	-1:57	60
Avoca station	11.510		0	
Avoca - Redhill	11.964	11.510	0	60
	11.324	11.189	+1:57	50
	11.189	10.817	+1:30	50
	10.817	9.807	+1:30	50
	9.807	9.704	+1:30	30
	9.704	9.654	+1:32	30
	9.654	9.584	+1:32	30
	9.473	9.479	+1:32	60
	9.584	9.473	+1:32	60
	9.479	9.290	+1:30	60
	9.290	9.179	+1:30	60
Redhill station	8.830		-1:104	
Redhill - Greenwood Park	9.179	8.830	-1:104	30
	8.809	8.696	-1:40	30
	8.696	8.594	-1:40	60
	8.594	8.294	-1:43	60
	8.294	8.024	-1:41	60
	8.024	7.929	-1:41	60
	7.929	7.899	-1:400	60
	7.899	7.804	-1:55	60
Greenwood Park station	7.690		-1:40	
Greenwood Park - Briardene	7.425	7.092	-1:40	50
	7.092	6.806	-1:40	60
	6.806	6.759	-1:40	40

Briardene station	6.53		-1:400	
Briardene - Umgeni	6.759	6.53	-1:40	60
	6.439	6.018	0	30
	6.018	5.829	-1:40	60
	5.565	5.457	0	40
	5.407	5.249	0	30
	5.249	5.157	0	50
	5.145	5.112	0	40
Umgeni station	5.000		0	

Duffsroad to Avoca

The train accelerates from zero to 50 km/h from Duffsroad station and uses regenerative braking to reduce the speed to 30km/h allowed at point 13.839. The slope is 1 in 35 descending. Table G.18 shows the energy recuperated.

Table G.18 Duffsroad to Avoca data - first gradient

Gradient (1:n)	35
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	2.86
Wh/tonne	17.85

It again accelerates to 40 km/h allowed at point 13.411 and uses regenerative braking to reduce the speed to the allowed 30 km/h at point 13.220. The slope is 1 in 35 descending. Table G.19 shows the energy recuperated.

Table G.19 Duffsroad to Avoca data - second gradient

Gradient (1:n)	35
Initial velocity (km/h)	40
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.034
% Gradient	2.86
Wh/tonne	7.81

It accelerates to 50 km/h and uses regenerative braking to reduce the speed to 30 km/h on a negative slope of 1 in 107. Table G.20 shows the energy recuperated.

Table G.20 Duffsroad to Avoca data - third gradient

Gradient (1:n)	107
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	0.93
Wh/tonne	14.82

It then accelerates to 60 km/h and use regenerative braking to stop at Avoca station. The slope is an average 1 in 19 descending. Table G.21 shows the energy recuperated.

Table G.21 Avoca data

Gradient (1:n)	19
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	5.26
Wh/tonne	43.82

Avoca to Redhill

From Avoca station the train accelerates to 50 km/h and uses regenerative braking to reduce the speed to the allowed 30 km/h at point 9.807. The slope is 1 in 30 ascending. Table G.22 shows the energy recuperated.

Table G.22 Avoca to Redhill data - first gradient

Gradient (1:*n*)	30
Initial velocity (km/h)	50
Final velocity (km/h)	30
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.077
% Gradient	3.33
Wh/tonne	8.09

It then accelerates to 60 km/h and uses regenerative braking to stop at Redhill station. The slope is 1 in 30 ascending. Table G.23 shows the energy recuperated.

Table G.23 Redhill station data

Gradient (1:*n*)	30
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	3.33
Wh/tonne	16.38

Redhill to Greenwood Park

From Redhill station the train accelerates to 60 km/h and use regenerative braking to stop at Greenwood Park station. The slope is an average 1 in 94 descending. Table G.24 shows the energy recuperated.

Table G.24 Greenwood Park station data

Gradient (1:n)	94
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.06
Wh/tonne	30.41

Greenwood Park to Briardene

From Greenwood Park station the train accelerates to 60 km/h and uses regenerative braking to stop at Briardene station. The slope is 1 in 40 descending. Table G.25 shows the energy recuperated.

Table G.25 Briardene station data

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	2.50
Wh/tonne	35.00

Briardene to Umgeni

From Briardene station it accelerates to 60 km/h and uses regenerative braking to stop at Umgeni station. The slope is zero. Table G.26 shows the energy recuperated.

Table G.26 Umgeni station data

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	2.50
Wh/tonne	27.02

The total energy recuperated on the Greenwood Park line in the direction from Duffsroad to Umgeni is 242.77 Wh/tonne. From Table 3.13, the mass of all trains with passengers from Durban to Kwa-Mashu is 571,756,416 kg. The mass of all trains with passengers from Durban to Stanger is 238,327,488 kg. The total mass of all trains with passengers from Durban to Plus Durban to Stanger is 810,083,904 kg. This is equal to 810,083.9 tonnes. But only 20 % of this mass travel on the Greenwood Park line and 80 % travel on the Effingham line. Therefore only 162,016.8 tonnes travel on the Greenwood Park line. Using this information and the total Wh/tonne above, the total energy recuperated on the Duffsroad to Umgeni line per month is:

$242.77 \times 162,016.8 = 39,332,816.5$ Wh $= 39,332.8$ kWh

Table G.27 shows the total kWh recuperated on the Greenwood Park line per month.

Table G.27 Greenwood Park line kWh recoup

Energy recuperated from Umgeni to Duffsroad	33,879.32 kWh
Energy recuperated from Duffsroad to Umgeni	39,332.8 kWh
Total energy recuperated on the Greenwood Park line	73,212.12 kWh

Appendix H

Pinetown Line

H.1 Rossburgh to Pinetown

The curves, gradients and speeds are given in Table H.1.

Table H.1 Pinetown Line curves, gradients and speeds - Rossburgh to Pinetown

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Rossburgh station	7.460		+1:40	
Rossburgh - Seaview	9.035	9.095	+1:46	50
	9.095	9.201	+1:50	50
	9.201	9.874	+1:50	75
	9.874	10.099	+1:58.5	50
Seaview station	10.190		+1:670	
Seaview - Bellair	10.190	10.329	+1:670	50
	10.329	10.594	+1:171	50
	10.594	10.645	+1:50	50
	10.695	10.882	+1:65	40
	10.882	10.937	+1:50	50
	10.937	11.055	+1:85	50
	11.055	11.314	+1:55.5	50
	11.314	11.496	+1:125.2	50
Bellair station	11.496		+1:92	
Bellair - Hillary	11.612	11.947	+1:300	70
	11.947	12.225	+1:38	70
	12.225	12.315	+1:38	50
	12.315	12.502	+1:1000	50

Hillary station	13.352		+1:30	
Hillary - Poets corner	13.352	13.621	+1:400	60
	13.621	13.881	+1:31	70
	13.881	14.029	+1:32	70
	14.029	14.180	+1:31	70
	14.180	14.627	+1:32	50
Poets corner station	14.830		+1:31	
Poets corner - Malvern	15.003	15.149	+1:31	60
	15.220	15.416	+1:31	70
	15.416	15.658	+1:33	75
	15.658	15.682	+1:33	75
	15.682	15.880	+1:34.6	60
Malvern station	16.110		0	
Malvern - Escombe	16.110	16.532	0	75
	16.532	16.581	1:178.6	75
	16.581	16.801	+1:178.6	60
	16.801	17.212	+1:28	60
	17.212	17.534	+1:28	75
	17.534	17.840	+1:28	60
	17.850	18.991	+1:28	50
	17.991	18.055	+1:43.8	50
Escombe station	18.16		+1:43.5	
Escombe - Northdene	18.310	18.591	+1:40	50
	18.591	18.811	+1:56	40
	18.811	18.992	0	40
	19.002	19.066	0	40
	19.066	19.236	+1:48	40
	19.236	19.771	+1:33	60
	19.771	19.996	-1:60	60
	19.996	20.235	+1:60	50
Northdene station	20.490		0	
Northdene - Mosely	20.740	20.889	+1:39.2	50
	20.899	21.197	+1:37.9	50
Mosely station	22.150		0	
Mosely - Glen Park	22.402	22.483	+1:50	75
	22.483	22.653	+1:61	50
Glen Park station	23.070		0	
Glen Park - Sarnia	23.436	23.497	+1:87	75
	23.947	24.088	-1:157	60
	24.088	24.328	-1:157	75
Sarnia station	24.470		-1:157	
multirow5*Sarnia - Pinetown	24.490	24.691	0	75
	24.691	25.144	+1:31	60
	25.144	25.579	+1:60	60
	25.579	25.997	+1:40	50
	25.997	26.699	+1:40	70
Pinetown station	27.070		0	

Rossburgh to Seaview

Rossburgh station it at kilometre point 7.460. From this station the train accelerates from zero to the allowed 75 km/h at point 9.201 and used regenerative braking to stop at Seaview station. The slope is an average of 1 in 54.2 ascending. Table H.2 shows the energy recuperated.

Table H.2 Seaview station data

Gradient (1:*n*)	54.2
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	1.85
Wh/tonne	34.34

Seaview to Bellair

From Seaview station the train accelerates to 50 km/h and used regenerative braking to reduce the speed to 40 km/h allowed at point 10.695. The slope is 1 in 50 ascending. Table H.3 shows the energy recuperated.

Table H.3 Seaview to Bellair data - first gradient

Gradient (1:*n*)	50
Initial velocity (km/h)	50
Final velocity (km/h)	40
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.043
% Gradient	2.00
Wh/tonne	5.73

It then accelerates to 50 km/h and uses regenerative braking to stop at Bellair station. The slope is an average 1 in 90.6 ascending. Table H.4 shows the energy recuperated.

Table H.4 Bellair station data

Gradient (1:*n*)	90.6
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	1.10
Wh/tonne	15.52

Bellair to Hillary

It accelerates to 70 km/h and uses regenerative braking to stop at Hillary station. The slope is an average of 1 in 358.6 ascending. Table H.5 shows the energy recuperated.

Table H.5 Hillary station data

Gradient (1:*n*)	358.6
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.28
Wh/tonne	36.62

Hillary to Poets Corner

From Hillary station the train accelerates to 70 km/h and uses regenerative braking to stop at Poets Corner. The slope is 1 in 31 ascending. Table H.6 shows the energy recuperated.

Table H.6 Poets Corner station data

Gradient (1:*n*)	31
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	3.23
Wh/tonne	23.43

Poets Corner to Malvern

Poets Corner is at kilometre point 14.830. Due to short distance of only 1.28 km between Poets Corner and Malvern and an ascending slope, the train can only reach maximum speed of 40 km/h. The train therefore only accelerates to 40 km/h and uses regenerative braking to stop at Malvern station. The slope is 1 in 33 ascending. Table H.7 shows the energy recuperated.

Table H.7 Malvern station data

Gradient (1:*n*)	33
Initial velocity (km/h)	40
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.060
% Gradient	3.03
Wh/tonne	6.63

Malvern to Escombe

Malvern station is at kilometre point 16.110. From Malverne station it accelerates to the allowed 75 km/h at point 17.212 and uses regenerative braking to stop at Escombe station. The slope is an average of 1 in 28.7 ascending. Table H.8 below shows the energy recuperated.

Table H.8 Escombe station data

Gradient (1:*n*)	28.7
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	3.48
Wh/tonne	25.83

Escombe to Northdene

Escombe station is at kilometre point 18.16. From Escombe station the train accelerates to 40 km/h and uses regenerative braking to stop at Northdene station. The slope is an average zero. Table H.9 shows the energy recuperated.

Table H.9 Northdene station data

Gradient (1:n)	0
Initial velocity (km/h)	40
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.060
% Gradient	0
Wh/tonne	10.34

Northdene to Mosely

From Northdene to Mosely, the train accelerates to 50 km/h and uses regenerative braking to stop at Mosely station. The slope is an average of 1 in 38 ascending. Table H.10 shows the energy recuperated.

Table H.10 Mosely station data

Gradient (1:n)	38
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	2.63
Wh/tonne	12.29

Mosely to Glen Park

The distance between Mosely and the next station, Glen Park is 1 km. Due to this short distance and a positive slope, the train can only reach 50 km/h. The slope is an average of 1 in 55.5 ascending.

Table H.11 shows the energy recuperated.

Table H.11 Glen Park station data

Gradient (1:n)	55.5
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	1.8
Wh/tonne	14.04

Glen Park to Sarnia

The distance between Glen Park and Sarnia is 1.4 km. The train only accelerates to 60 km/h and use regenerative braking to stop at Sarnia station. The slope is 1 in 157 descending. Table H.12 shows the energy recuperated.

Table H.12 Sarnia station data

Gradient (1:n)	157
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.64
Wh/tonne	29.05

Sarnia to Pinetown

From Sarnia to Pinetown station the train accelerates to 60 km/h and uses regenerative braking to stop at Pinetown station. The slope is 1 in 40 ascending. Table H.13 shows the energy recuperated.

Table H.13 Pinetown station data

Gradient (1:n)	40
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	2.50
Wh/tonne	19.04

The total energy recuperated during regenerative braking from Rossburgh station to Pinenetown station is 232.86 Wh/tonne. This was obtained after adding all the energies recuperated on the section. From Table 3.13, the mass of all trains with passengers on the Pinetown line from Rossburgh to Pinetown is 140,711,808 kg. This is equal to 140,711.81 tonnes. Using this information and the total Wh/tonne above, the total energy recuperated is:

$232.86 \times 140,711.808 = 32,766,151.6 \text{ Wh} = 32,766.15 \text{ kWh}$

H.2 Pinetown to Rossburgh

The curves, gradients and speeds are given in Table H.14.

Table H.14 Pinetown Line curves, gradients and speeds - Pinetown to Rossburgh

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Pinetown station	27.070		0	
Pinetown - Sarnia	26.699	25.997	-1:40	70
	25.997	25.579	-1:40	50
	25.579	25.144	-1:60	60
	25.144	24.691	-1:31	60
	24.691	24.490	0	75
Sarnia station	24.470		+1:157	
Sarnia - Glen Park	24.328	24.088	+1:157	75
	24.088	23.947	+1:157	60
	23.497	23.436	-1:87	75
Glen Park station	23.070		0	
Glen Park - Mosely	22.653	22.483	-1:61	50
	22.483	22.402	-1:50	75
Mosely station	22.150		0	
Mosely - Northdene	21.197	20.899	-1:37.9	50
	20.889	20.740	-1:39.2	50
Northdene station	20.490		0	
Northdene - Escombe	20.235	19.996	-1:60	50
	19.996	19.771	+1:60	60
	19.771	19.236	-1:33	60
	19.236	19.066	-1:48	40
	19.066	19.002	0	40
	18.992	18.811	0	40
	18.811	18.591	-1:56	40
	18.591	18.310	-1:40	50
Escombe station	18.16		-1:43.5	
Escombe - Malvern	18.055	17.991	-1:43.8	50
	17.991	17.850	-1:28	50
	17.840	17.534	-1:28	60
	17.534	17.212	-1:28	75
	17.212	16.801	-1:28	60
	16.801	16.581	-1:178.6	60
	16.581	16.532	-1:178.6	75
Malvern station	16.110		0	
Malvern - Poets corner	16.532	16.110	0	75
	15.880	15.682	-1:34.6	60
	15.682	15.658	-1:33	75
	15.658	15.416	-1:33	75
	15.416	15.220	-1:31	70
Malvern - Poets corner	15.149	15.003	-1:31	60

Poets corner station	14.830		-1:31	
Poets corner - Hillary	14.627	14.180	-1:32	50
	14.180	14.029	-1:31	70
	14.029	13.881	-1:32	70
	13.881	13.621	-1:31	70
Hillary station	13.352		-1:30	
Hillary - Bellair	13.621	13.352	-1:400	60
	12.502	12.315	-1:1000	50
	12.315	12.225	-1:38	50
	12.225	11.947	-1:38	70
Bellair station	11.496		-1:92	
Bellair - Seaview	11.612	11.496	-1:92	60
	11.496	11.314	-1:125.2	50
	11.314	11.055	-1:55.5	50
	11.055	10.937	-1:85	50
	10.937	10.882	-1:50	50
	10.882	10.695	-1:65	40
	10.695	10.645	-1:50	40
	10.645	10.594	-1:50	50
	10.594	10.329	-1:171	50
Seaview station	10.190		-1:670	
Seaview - Rossburgh	10.329	10.190	-1:670	50
	10.099	9.874	-1:58.5	50
	9.874	9.201	-1:50	75
	9.201	9.095	-1:50	50
	9.095	9.035	-1:46	50
Rossburgh station	7.460		-1:40	

Pinetown to Sarnia

Pinetown station is at kilometre point 27.070. From Pinetown station the train accelerate to a maximum speed of 60km/h and use regenerative braking to stop at Sarnia station. The slope is 1 in 31 descending. Table H.15 shows the energy recuperated.

Table H.15 Sarnia station data

Gradient (1:n)	31
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	3.23
Wh/tonne	37.32

Sarnia to Glen Park

Sarnia station is at kilometre point 24.47. From Sarnia station, the train accelerates to 60 km/h and uses regenerative braking to stop at Glen Park station. The slope is zero. Table H.16 shows the energy recuperated.

Table H.16 Glen Park station data

Gradient (1:n)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	3.23
Wh/tonne	27.02

Glen Park to Mosely

Glen Park station is situated at kilometre point 23.070. From Glen Park station, the train accelerates to 50 km/h and uses regenerative braking to stop at Mosely station. The slope is zero. Table H.17 shows the energy recuperated.

Table H.17 Mosely station data

Gradient (1:*n*)	0
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	3.23
Wh/tonne	17.84

Mosely to Northdene

Mosely station is situated at kilometre point 22.150. From Mosely station, the train accelerates to 50 km/h and uses regenerative braking to stop at Northdene station. The slope is 1 in 39 descending. Table H.18 shows the energy recuperated.

Table H.18 Northdene station data

Gradient (1:*n*)	39
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	2.56
Wh/tonne	23.25

Northdene to Escombe

Northdene station is situated at kilometre point 20.490. From Northdene station, the train accelerates to 60 km/h and uses regenerative braking to reduce the speed to 40 km/h required from kilometre point 19.236. The slope is 1 in 33 descending. Table H.19 shows the energy recuperated.

Table H.19 Northdene to Escombe data - first gradient

Gradient (1:n)	33
Initial velocity (km/h)	60
Final velocity (km/h)	40
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.096
% Gradient	0.096
Wh/tonne	22.66

It then uses regenerative braking to maintain the speed at 40 km/h required between kilometre point 19.236 and 19.066. The slope is 1 in 48 descending. Table H.20 shows the energy recuperated.

Table H.20 Northdene to Escombe data - second gradient

Distance (km)	0.017
Initial velocity (km/h)	40
Regenerative braking duration (s)	15.30
% Gradient	3.03
F_t (N/tonne)	246.94
Energy recuperated (Wh/tonne)	8.75

It again uses regenerative braking to maintain the speed at 40km/h between kilometre point 18.811 and 18.591. The slope is 1 in 56 descending. Table H.21 shows the energy recuperated.

Table H.21 Northdene to Escombe data - third gradient

Distance (km)	0.022
Initial velocity (km/h)	40
Regenerative braking duration (s)	19.80
% Gradient	3.03
F_t (N/tonne)	246.94
Energy recuperated (Wh/tonne)	11.32

Finally it uses regenerative braking to stop at Escombe station. The slope is 1 in 40 descending. Table H.22 shows the energy recuperated.

Table H.22 Escombe station data

Gradient (1:*n*)	40
Initial velocity (km/h)	40
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.060
% Gradient	2.50
Wh/tonne	13.39

Escombe to Malvern

Escombe station is situated at kilometre point 18.16. From Escombe station, the train accelerates to a maximum speed of 75 km/h and uses regenerative braking to reduce the speed to 60 km/h allowed at kilometre point 17.212. The slope is 1 in 28 descending. Table H.23 shows the energy recuperated.

Table H.23 Escombe to Malvern data - first gradient

Gradient (1:*n*)	28
Initial velocity (km/h)	75
Final velocity (km/h)	60
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.098
% Gradient	3.57
Wh/tonne	24.02

Finally it uses regenerative braking to stop at Malvern station. The slope is 1 in 178.6 descending. Table H.24 shows the energy recuperated.

Table H.24 Malvern station data

Gradient (1:*n*)	178.6
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.56
Wh/tonne	28.81

Malvern to Poets Corner

Malvern station is situated at kilometre point 16.110. From Malvern station the train accelerates to 75 km/h and uses regenerative braking to stop at Poets corner station. The slope is 1 in 31 descending. Table H.25 shows the energy recuperated.

Table H.25 Poets Corner station data

Gradient (1:*n*)	31
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	3.23
Wh/tonne	60.65

Poets Corner to Hillary

Poets Corner is situated at kilometre point 14.830. From Poets Corner it accelerates to 70 km/h and uses regenerative braking to stop at Hillary station. The slope is 1 in 31 descending. Table H.26 shows the energy recuperated.

Table H.26 Hillary station data

Gradient (1:n)	31
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	3.23
Wh/tonne	52.29

Hillary to Bellair

Hillary station is located at kilometre point 13.352. From Hillary station, the train accelerates to 70 km/h and uses regenerative braking to stop at Bellair station. The slope is 1 in 38 descending. Table H.27 shows the energy recuperated.

Table H.27 Bellair station data

Gradient (1:n)	38
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	2.63
Wh/tonne	49.64

Bellair to Seaview

Bellair station is situated at kilometre point 11.69. From Bellair station the train accelerates to 50 km/h and uses regenerative braking to reduce the speed to the allowed 40 km/h between kilometre point 10.882 and 10.695. The gradient is 1 in 50 descending. Table H.28 shows the energy recuperated.

Table H.28 Bellair to Seaview data - first gradient

Gradient (1:*n*)	50
Initial velocity (km/h)	50
Final velocity (km/h)	40
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.043
% Gradient	2.00
Wh/tonne	9.28

It then uses regenerative braking to stop at Seaview station. The gradient is an average of 1 in 420.5 descending. Table H.29 shows the energy recuperated.

Table H.29 Seaview station data

Gradient (1:*n*)	420.5
Initial velocity (km/h)	40
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.060
% Gradient	0.24
Wh/tonne	10.63

Seaview to Rossburgh

Seaview station is situated at kilometre point 10.190. From Seaview the train accelerates to 75 km/h and uses regenerative braking to reduce the speed to the allowed 50 km/h at kilometre point 9.201. The slope is 1 in 50 descending. Table H.30 shows the energy recuperated.

Table H.30 Seaview to Rossburgh data - first gradient

Gradient (1:*n*)	50
Initial velocity (km/h)	75
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.151
% Gradient	2.00
Wh/tonne	32.23

It then uses regenerative braking to stop at Rossburgh station. The slope is 1 in 40 descending. Table H.31 shows energy recuperated.

Table H.31 Rossburgh station data

Gradient (1:*n*)	50
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	2.00
Wh/tonne	22.06

The total energy recuperated during regenerative braking from Pinetown to Rossburgh station 451.16 Wh/tonne. This was obtained after adding all the energies recuperated on this section. Table 3.13, the mass of all trains with passengers from Pinetown to Rossburgh per month is 140,711,808 kg. This is equal to 140,711.808 tonnes. Using this information and the total Wh/tonne above, the total energy recuperated per month is:

$451.16 \times 140,711.808 = 63,483,539.3 \text{ Wh} = 63,483.64 \text{ kWh}$

Table H.32 shows the total kWh recuperated on the Pinetown line per month.

Table H.32 Pinetown line kWh recoup

Energy recuperated from Rossburgh to Pinetown	32,766.15 kWh
Energy recuperated from Pinetown to Rossburgh	63,483.64 kWh
Total energy recuperated on the Pinetown line	96,249.79 kWh

Appendix I

Effingham Line

I.1 Duffsroad to Umgeni

The curves, gradients and speeds are given in Table I.1.

Table I.1 Effingham Line curves, gradients and speeds - Duffsroad to Umgeni

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Duffsroad station	163.71		+1:245	
Duffsroad - Effingham	163.71	163.295	+1:245	70
	163.295	163.375	+1:1039	70
	163.375	163.491	+1:359.7	70
	163.491	163.780	+1:359.7	75
	163.780	163.900	+1:138.5	75
	163.900	164.070	+1:175	60
	163.070	163.470	-1:89	60
	167.470	164.690	-1:56.5	60
	164.690	164.785	-1:55	60
	164.785	164.970	+1:100	50
	164.970	165.140	+1:135	50
	165.140	165.380	-1:105	50
	165.380	165.530	-1:55	50
	165.530	165.750	-1:59.5	50
	165.750	166.010	-1:55	50
	166.010	166.123	-1:68.54	60
	166.123	166.645	-1:55	75
	166.645	166.745	-1:62.9	60
	166.745	166.958	-1:51	60

Effingham station	167.35		-1:100	
Effingham - Kemville	167.793	168.158	+1:2300	70
	168.158	168.753	+1:74	50
	168.753	168.953	-1:57.6	50
	168.953	169.233	-1:62	60
	169.233	169.556	+1:74	60
Kenville station	169.68		+1:69	
Kenville - Temple	169.853	170.025	+1:76	60
	170.025	170.343	+1:67	60
	170.343	170.693	-1:96	60
	170.693	170.853	-1:121	60
	170.853	171.333	-1:55.7	50
Temple station	171.52		+1:760	
Temple - Umgeni	171.613	171.754	-1:65.4	75
	171.754	172.033	-1:50	70
	172.033	172.283	-1:66.2	60
	172.283	172.984	0	60
Umgeni station	180.255		-1:131	

Duffsroad to Effingham

Duffsroad station is at location point 163.71. From Duffsroad station the train accelerates to 60 km/h and uses regenerative braking to maintain this speed between 163.070 and kilometre point 163.470. The slope is 1 in 89 descending. Table I.2 shows the energy recuperated.

Table I.2 Duffsroad to Effingham data - first gradient

Distance (km)	0.4
Initial velocity (km/h)	60
Regenerative braking duration (s)	24.00
% Gradient	1.12
F_t (N/tonne)	59.76
Energy recuperated (Wh/tonne)	4.98

It further uses regenerative braking to maintain this speed between kilometre point 164.470 and 164.690. The slope is 1 in 56.5 descending. Table I.3 shows the energy recuperated.

Table I.3 Duffsroad to Effingham data - second gradient

Distance (km)	0.22
Initial velocity (km/h)	60
Regenerative braking duration (s)	13.20
% Gradient	1.77
F_t (N/tonne)	123.46
Energy recuperated (Wh/tonne)	5.66

It then uses regenerative braking to reduce the speed to the allowed 50 km/h at kilometre point 164.785. The slope is 1 in 55 descending. Table I.4 shows the energy recuperated.

Table I.4 Duffsroad to Effingham data - third gradient

Gradient (1:n)	55
Initial velocity (km/h)	60
Final velocity (km/h)	50
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.053
% Gradient	1.82
Wh/tonne	11.15

The train uses regenerative braking to maintain the 50 km/h speed between kilometre point 165.140 and 165.380. The slope is 1 in 105 descending. Table I.5 shows the energy recuperated.

Table I.5 Duffsroad to Effingham data - fourth gradient

Distance (km)	0.24
Initial velocity (km/h)	50
Regenerative braking duration (s)	17.28
% Gradient	0.95
F_t (N/tonne)	43.1
Energy recuperated (Wh/tonne)	2.16

It continues to use regenerative braking to maintain this speed from kilometre point 165.380 to 166.123. The slope is an average of 1 in 55 descending. Table I.6 shows the energy recuperated.

Table I.6 Duffsroad to Effingham data - fifth gradient

Distance (km)	0.743
Initial velocity (km/h)	50
Regenerative braking duration (s)	53.50
% Gradient	1.82
F_t (N/tonne)	128.36
Energy recuperated (Wh/tonne)	19.87

It then uses regenerative braking to stop at Effingham station. The slope is 1 in 56 descending. Table I.7 shows the energy recuperated.

Table I.7 Effingham station data

Gradient (1:n)	56
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	1.79
Wh/tonne	21.61

Effingham to Kenville

Effingham is at kilometre point 167.35. From Effingham to Kenville it accelerates to 60 km/h and uses regenerative braking to stop at Kenville station. The slope is an average of 1 in 71.5 descending. Table I.8 shows the energy recuperated.

Table I.8 Kenville station data

Gradient (1:n)	71.5
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.40
Wh/tonne	31.48

Kenville to Temple

Kenville station is at kilometre point 169.68. From Kenville station it accelerates to 60 km/h and uses regenerative braking to stop at Temple station. The slope is 1 in 55.7 descending. Table I.9 shows the energy recuperated.

Table I.9 Temple station data

Gradient (1:n)	55.7
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.80
Wh/tonne	32.75

Temple to Umgeni

Temple station is at kilometre point 171.52. From Temple station it accelerates to 60 km/h and uses regenerative braking to stop at Umgeni station. The slope is 0. Table I.10 shows the energy recuperated.

Table I.10 Umgeni station data

Gradient (1:n)	55.7
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.80
Wh/tonne	27.02

The total energy recuperated during regenerative braking from Duffsroad station to Umgeni station is 169.98 Wh/tonne. From Table 3.13, the mass of all trains with passengers from Durban to KwaMashu is 571,756,416 kg. The mass of all trains with passengers from Durban to Stanger is 238,327,488 kg. The total mass of all trains with passengers from Durban to KwaMashu plus

Durban to Stanger is 810,083,904 kg. This is equal to 810,083.9 tonnes. But only 20 % of this mass travel through the Greenwood Park line and 80 % travels through the Effingham line. Therefore 648,067.12 tonnes travel through the Effingham line. Using this information and the total Wh/tonne above, the total energy recuperated on the Duffsroad to Umgeni line per month is:

$169.98 \times 648,067.12 = 110,158,449.06$ Wh $= 110,158.4$ kWh

I.2 Umgeni to Duffsroad

The curves, gradients and speeds are given in Table I.11.

Table I.11 Effingham Line curves, gradients and speeds - Umgeni to Duffsroad

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Umgeni station	180.255		+1:131	
Umgeni - Temple	172.984	172.283	0	60
	172.283	172.033	+1:66.2	60
	172.033	171.754	+1:50	70
	171.754	171.613	+1:65.4	75
Temple station	171.52		-1:760	
Temple - Kenville	171.333	170.853	+1:55.7	50
	170.853	170.693	+1:121	60
	170.693	170.343	+1:96	60
	170.343	170.025	-1:67	60
	170.025	169.853	-1:76	60
Kenville station	169.68		-1:69	
Kenville - Effingham	169.556	169.233	-1:74	60
	169.233	168.953	+1:62	60
	168.953	168.753	+1:57.6	50
	168.753	168.158	-1:74	50
	168.158	167.793	-1:2300	70
Effingham station	167.35		+1:100	
Effingham - Duffsroad	166.958	166.745	+1:51	60
	166.745	166.645	+1:62.9	60
	166.645	166.123	+1:55	75
	166.123	166.010	+1:68.54	60
	166.010	165.750	+1:55	50
	165.750	165.530	+1:59.5	50
	165.530	165.380	+1:55	50
	165.380	165.140	+1:105	50
	165.140	164.970	-1:135	50
	164.970	164.785	-1:100	50
	164.785	164.690	+1:55	60
	164.690	164.470	+1:56.5	60
	163.470	164.070	+1:89	60
	164.070	163.900	-1:175	60
	163.900	163.780	-1:138.5	75
	163.780	163.491	-1:359.7	75
	163.491	163.375	-1:359.7	70
	163.375	163.295	-1:1039	70
Duffsroad station	163.71		-1:245	

Umgeni to Temple

Umgeni station is at kilometre point 180.255. From Umgeni Temple the train accelerates to 60 km/h and uses regenerative braking to stop at Temple station. The slope is an average 1 in 57.5 ascending. Table I.12 shows the energy recuperated.

Table I.12 Temple station data

Gradient (1:n)	57.5
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.74
Wh/tonne	21.47

Temple to Kenville

Temple station is at kilometre point 171.52. From Temple station the train accelerates to 60 km/h and uses regenerative braking to stop at Kenville station. The slope is an average of 1 in 70.6 descending. Table I.13 shows the energy recuperated.

Table I.13 Kenville station data

Gradient (1:n)	70.6
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.42
Wh/tonne	31.54

Kenville to Effingham

Kenville station is at kilometre point 169.68. From Kenville station, the train accelerates to 50 km/h and uses regenerative braking to stop at Effingham station. The slope is 1 in 100 ascending.

Table I.14 shows the energy recuperated.

Table I.14 Effingham station data

Gradient (1:n)	100
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.00
Wh/tonne	23.83

Effingham to Duffroad

Effingham station is at kilometre point 167.35. From Effingham station, the train accelerates to 50 km/h and uses regenerative braking to maintain this speed on a downward slope of 1 in 135 between kilometre point 165.140 and kilometre point 164.970. Table I.15 shows the energy recuperated.

Table I.15 Effingham to Duffroad data - first gradient

Distance (km)	0.17
Initial velocity (km/h)	50
Regenerative braking duration (s)	12.24
% Gradient	0.74
F_t (N/tonne)	22.52
Energy recuperated (Wh/tonne)	0.80

It again uses regenerative braking to maintain this speed between kilometre point 164.970 and 164.785. The slope is 1 in 100 descending. Table I.16 shows the energy recuperated.

Table I.16 Effingham to Duffroad data - second gradient

Distance (km)	0.185
Initial velocity (km/h)	50
Regenerative braking duration (s)	13.32
% Gradient	1.00
F_t (N/tonne)	48.0
Energy recuperated (Wh/tonne)	1.85

The train accelerates to 60 km/h and uses regenerative braking to maintain this speed between kilometre point 164.070 and 163.900. The slope is 1 in 175 descending. Table I.17 shows the energy recuperated.

Table I.17 Effingham to Duffroad data - third gradient

Distance (km)	0.17
Initial velocity (km/h)	60
Regenerative braking duration (s)	10.20
% Gradient	0.57
F_t (N/tonne)	5.86
Energy recuperated (Wh/tonne)	0.21

It then accelerates to 75 km/h and uses regenerative braking to stop at Duffsroad station. The slope is an average 1 in 547.9 descending. Table I.18 shows the energy recuperated.

Table I.18 Duffsroad station data

Gradient (1:n)	547.9
Initial velocity (km/h)	75
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.254
% Gradient	0.18
Wh/tonne	44.86

The total energy recuperated during regenerative braking from Umgeni station to Duffsroad station is 124.56 Wh/tonne. From Table 3.13, as already stated, the mass of all trains with passengers from Durban to KwaMashu is 571,756,416 kg. The mass of all trains with passengers from Durban to Stanger is 238,327,488 kg. The total mass of all trains with passengers from Durban to KwaMashu plus Durban to Stanger is 810,083,904 kg. This is equal to 810,083.9 tonnes. But only 20 % of this mass travel through the Greenwood Park line and 80 % travels through the Effingham line. Therefore 648,067.12 tonnes travel on the the Effingham line. Using this information and the total Wh/tonne above, the total energy recuperated on the Umgeni to Duffsroad line per month is:

$124.56 \times 648,067.12 = 80,723,240.47$ Wh $= 80,723.24$ kWh

Table I.19 shows the total kWh recuperated on the Effingham line per month.

Table I.19 Effingham line kWh recoup

Energy recuperated from Duffsroad to Umgeni	110,158.4 kWh
Energy recuperated from Umgeni to Duffsroad	80,723.24 kWh
Total energy recuperated on the Effingham line	190,881.64 kWh

Appendix J

Central Area

J.1 Umgeni to Reunion

The curves, gradients and speeds are given in Table J.1.

Table J.1 Central Area curves, gradients and speeds - Umgeni to Reunion

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Umgeni station	3.26		0	
Moses Mabhida	1.500		0	
Durban station	0.00		-1:110	
Durban - Berea Road	1.093	1.347	+1:379	50
	1.379	1.567	-1:1053	50
	1.567	1.747	-1:273.7	50
Berea Road station	1.8		-1:330	
Berea Road - Dalbridge	1.863	1.957	-1:330	60
	1.957	2.157	-1:764	60
	2.157	2.357	0	50
	2.357	2.418	-1:1600	50
	2.418	2.582	-1:1600	50
	2.582	2.832	-1:546	60
Dalbridge station	3.3		0	
Dalbridge - Congella	3.452	3.627	+1:320	60
	3.627	3.692	0	60
	3.692	3.817	-1:220	60
	3.817	4.152	0	60
	4.152	4.292	+1:248	60
Congela station	4.66		0	

Congella - Umbilo	5.002	5.159	-1:330	60
	5.159	5.278	+1:1466	60
	5.278	5.782	+1:740	60
	5.782	6.082	0	80
Umbilo station	6.41		-1:3359	
Umbilo - Rossburgh	6.412	6.768	+1:96	80
	6.768	6.968	+1:640	80
Rossburgh station	7.46		0	
Rossburgh station	0.00		0	
Rossburgh - Clairwood	0.00	1.000	0	60
	1.000	2.000	0	60
Clairwood station	2.000		0	
Clairwood - Montclair	2.331	2.431	+1:229	70
	2.431	2.794	-1:982	70
	2.794	2.975	0	70
	2.975	3.176	+1:318	70
	3.176	3.236	0	70
	3.236	3.317	+1:388	70
Montclair station	3.336		-1:135	
Montclair - Merebank	3.538	3.880	-1:712	70
	3.880	4.041	-1:182	70
	4.041	4.746	0	70
	5.065	5.528	+1:119	70
Merebank station	5.840		+1:153	
Merebank - Reunion	6.232	6.715	+1:1544	70
	6.916	7.158	-1:55	70
	7.158	7.279	-1:94	70
	7.459	7.902	+1:298	90
	8.163	8.365	-1:96	70
	8.365	8.566	-1:96	90
Reunion station	8.559		-1:275	

Umgeni to Moses Mabhida

Umgeni station is kilometre point 3.260. From Umgeni the train accelerates to 50 km/h and uses regenerative braking to stop at Moses Mabhida station. The gradient is zero. Table J.2 shows the energy recuperated.

Table J.2 Moses Mabhida station data

Gradient (1:n)	0
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.18
Wh/tonne	17.84

Umgeni to Durban

Moses Mabhida station is at kilometre point 1.500. From Moses Mabhida station, the train accelerates to 50 km/h and uses regenerative braking to stop at Durban station. The slope is zero. Table J.3 shows the energy recuperated.

Table J.3 Durban station data

Gradient (1:n)	0
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.18
Wh/tonne	17.84

The total energy recuperated during regenerative braking from Umgeni station to Durban is 35.68 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Umgeni to Durban line is 810,083,904 kg. This is equal to 810,083.9 tonnes. This was obtained after adding the mass of all trains from KwaMashu to Durban and trains from Stanger to Durban. Using this information and the total Wh/tonne above, the total energy recuperated is:

$35.68 \times 810,083.9 = 28,903,793.6 \text{ Wh} = 28,903.79 \text{ kWh}$

Durban to Berea Road

Durban station is at kilometre point 0.00. From Durban station the train accelerates to 50 km/h and uses regenerative braking to stop at Berea Road station. The slope is 1 in 273.7 descending. Table J.4 shows the energy recuperated.

Table J.4 Berea Road station data

Gradient (1:n)	273.7
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.37
Wh/tonne	18.61

Berea Road to Dalbridge

Berea road is at kilometre point 1.80. From Berea Road the train accelerates to 50 km/h and uses regenerative braking to stop at Dalbridge station. The slope is 1 in 546 descending. Table J.5 shows the energy recuperated.

Table J.5 Berea Road station data

Gradient (1:n)	546
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.18
Wh/tonne	18.23

Dalbridge to Congela

Dalbridge station is at kilometre point 3.30. From Dalbridge station the train accelerates to 60 km/h and uses regenerative braking to stop at Congela station. The slope is zero. Table J.6 shows the energy recuperated.

Table J.6 Congela station data

Gradient (1:*n*)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0
Wh/tonne	27.02

Congela to Umbilo

Congela station is at kilometre point 4.66. From Congela station the train accelerates to 60 km/h and uses regenerative braking to stop at Umbilo station. The slope is 1 in 3359 descending. Table J.7 shows the energy recuperated.

Table J.7 Umbilo station data

Gradient (1:*n*)	3359
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.03
Wh/tonne	27.11

Umbilo to Rossburgh

Umbilo station is at kilometre point 6.41. Even though the maximum speed allowed between Umbilo and Rossburgh is 80 km/h, the train can only reach a maximum speed of 60 km/h due to short distance. The distance between Umbilo and Rossburgh is 1.05 km. Therefore the train only reaches a speed of 60 km/h and use regenerative braking to stop at Rossburgh station. The slope is zero. Table J.8 shows the energy recuperated.

Table J.8 Rossburgh station data

Gradient (1:*n*)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.03
Wh/tonne	27.02

The total energy recuperated during regenerative braking from Durban station to Rossburgh station is 117.99 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Durban to Rossburgh line is 1,650,436,528 kg. This is equal to 1,650,436.5 tonnes. This was obtained after adding the mass of all trains from Durban to Umlazi, Durban to Kelso, Durban to Cato Ridge, Durban to Pine town, Durban to Crossmoor and Durban to West. Using this information and the total Wh/tonne above, the total energy recuperated is:

$117.99 \times 1,650,436.50 = 194,735,002.6 \text{ Wh} = 194,735 \text{ kWh}$

Rossburgh to Clairwood

Rossburgh station is at kilometre point 0.00. From Rossburgh station the train accelerates to 60 km/h and uses regenerative braking to stop at Clairwood station. The slope is zero. Table J.9 shows the energy recuperated.

Table J.9 Clairwood station data

Gradient (1:*n*)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.03
Wh/tonne	27.02

Clairwood to Montclair

Clairwood station is at kilometre point 2.00. Even though the maximum speed allowed between Clairwood and Montclair is 70 km/h, the train can only reach a maximum speed of 60 km/h due to the short distance. The distance between Clairwood and Montclair is 1.336 km. Therefore the train only reaches a speed of 60 km/h and the train uses regenerative braking to stop at Montclair station. The slope is an average 1 in 194 ascending. Table J.10 shows the energy recuperated.

Table J.10 Montclair station data

Gradient (1:n)	194
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0.52
Wh/tonne	25.37

The total energy recuperated during regenerative braking from Rossburgh station to Montclair station is 52.39 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Rossburgh to Montclair line is 1,342,544,448 kg. This is equal to 1,342,544.5 tonnes. This was obtained after adding the mass of all trains from Durban to Umlazi, Durban to Kelso, Durban to Crossmoor and Durban to West. Using this information and the total Wh/tonne above, the total energy recuperated is:

$52.39 \times 1,342,544.50 = 70,335,906.3 \text{ Wh} = 70,336 \text{ kWh}$

Montclair to Merebank

Montclair station is at kilometre point 3.336. From Montclair station the train accelerates to 70 km/h and use regenerative braking to stop at Merebank station. The slope is an average of 1 in 136 ascending. Table J.11 shows the energy recuperated.

Table J.11 Merebank station data

Gradient (1:n)	136
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.74
Wh/tonne	34.57

The total energy recuperated during regenerative braking from Montclair station to Merebank station is 34.57 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Montclair to Merebank line is 1,219,700,736 kg. This is equal to 1,219,700.74 tonnes. This was obtained after adding the mass of all trains from Durban to Umlazi, Durban to Kelso and Durban to Crossmoor. Using this information and the total Wh/tonne above, the total energy recuperated is:

$34.57 \times 1,219,700.74 = 42,165,054.4$ Wh $= 42,165.05$ kWh

Merebank to Reunion

Merebank station is at kilometre point 5.840. From Merebank station the train accelerates to 90 km/h and uses regenerative braking to stop at Reunion station. The slope is 1 in 96 descending. Table J.12 shows the energy recuperated.

Table J.12 Reunion station data

Gradient (1:n)	96
Initial velocity (km/h)	90
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.373
% Gradient	1.04
Wh/tonne	72.50

The total energy recuperated during regenerative braking from Merebank station to Reunion station is 72.50 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Merebank to Reunion line is 1,007,325,696 kg. This is equal to 1,007,325.7 tonnes. This was obtained after adding the mass of all trains from Durban to Umlazi and Durban to Kelso. Using this information and the total Wh/tonne above, the total energy recuperated is:

$72.50 \times 1,007,325.7 = 73,031,112.96 \text{ Wh} = 73,031.11 \text{ kWh}$

Therefore the total energy recuperated Umgeni to Reunion is 409,170.95 kWh

J.2 Reunion to Umgeni

The curves, gradients and speeds are given in Table J.13.

Table J.13 Central Area curves, gradients and speeds - Reunion to Umgeni

Section	Curves		Gradient	Maximum speed (km/h)
	From km	To km		
Reunion station	8.559		+1:275	
Reunion - Merebank	8.566	8.365	+1:96	90
	8.365	8.163	+1:96	70
	7.902	7.459	-1:298	90
	7.279	7.158	+1:94	70
	7.158	6.916	+1:55	70
	6.715	6.232	-1:1544	70
Merebank station	5.840		-1:153	
Merebank - Montclair	5.528	5.065	-1:119	70
	4.746	4.041	0	70
	4.041	3.880	+1:182	70
	3.880	3.538	+1:712	70
Montclair station	3.336		+1:135	
Montclair - Clairwood	3.317	3.236	-1:388	70
	3.236	3.176	0	70
	3.176	2.975	-1:318	70
	2.975	2.794	0	70
	2.794	2.431	+1:982	70
	2.431	2.331	-1:229	70
Clairwood station	2.000		0	
Clairwood - Rossburgh	2.00	1.000	0	60
Rossburgh station	0.00		0	
Rossburgh station	7.46		0	
Rossburgh - Umbilo	6.968	6.768	-1:640	80
	6.768	6.412	-1:96	80
Umbilo station	6.41		+1:3359	
Umbilo - Congella	6.082	5.782	0	80
	5.782	5.278	-1:740	60
	5.278	5.159	-1:1466	60
	5.159	5.002	+1:330	60
Congela station	4.66		0	
Congella - Dalbridge	4.292	4.152	-1:248	60
	4.152	3.817	0	60
	3.817	3.692	+1:220	60
	3.692	3.627	0	60
	3.627	3.452	-1:320	60
Dalbridge station	3.3		0	
Dalbridge - Berea Road	2.832	2.582	+1:546	60
	2.582	2.418	+1:1600	50
	2.418	2.357	+1:1600	50

Dalbridge - Berea Road

	2.357	2.157	0	50
	2.157	1.957	+1:764	60
	1.957	1.863	+1:330	60
Berea Road station	1.8		+1:330	
Berea Road - Durban	1.747	1.567	+1:273.7	50
	1.567	1.379	+1:1053	50
	1.347	1.093	-1:379	50
Durban station	0.00		+1:110	
Moses Mabhida	1.500		0	
Umgeni station	3.26		0	

Reunion to Merebank

Reunion station is at kilometre point 8.559. From Reunion station, the train accelerates to 90 km/h and uses regenerative braking to reduce the speed to the required 70 km/h at point 7.279. The slope is 1 in 298 descending. Table J.14 shows the energy recuperated.

Table J.14 Reunion to Merebank data - first gradient data

Gradient (1:n)	298
Initial velocity (km/h)	90
Final velocity (km/h)	70
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.154
% Gradient	0.34
Wh/tonne	27.75

It then uses regenerative braking to stop at Merebank station. The slope is 1 in 1544 descending. Table J.15 shows the energy recuperated.

Table J.15 Merebank station data

Gradient (1:n)	1544
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.06
Wh/tonne	38.15

The total energy recuperated during regenerative braking from Reunion station to Merebank station to station is 65.90 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Reunion to Merebank line is 1,007,325,696 kg. This is equal to 1,007,325.7 tonnes. This was obtained after adding the mass of all trains from Umlazi to Durban and Kelso to Kelso. Using this information and the total Wh/tonne above, the total energy recuperated is:

$65.90 \times 1,007,325.7 = 66,382,763.63$ Wh $= 66,382.76$ kWh

Merebank to Montclair

Merebank station is at kilometre point 5.840. From Merebank station it accelerates to 70 km/h and uses regenerative braking to stop at Montclair station. The slope is 1 in 712 descending. Table J.16 shows the energy recuperated.

Table J.16 Montclair station data

Gradient (1:n)	712
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.14
Wh/tonne	38.49

The total energy recuperated during regenerative braking from Merebank station to Montclair station is 38.49 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Montclair to Merebank line is 1,219,700,736 kg. This is equal to 1,219,700.74 tonnes. This was obtained after adding the mass of all trains from Umlazi to Durban, Kelso to Durban and Crossmoor to Durban. Using this information and the total Wh/tonne above, the total energy recuperated is:

$38.49 \times 1,219,700.74 = 46,946,281.48$ Wh = $46,946.28$ kWh

Montclair to Clairwood

Montclair station is at kilometre point 3.336. From Montclair station it accelerates to 70 km/h and uses regenerative braking to stop at Clairwood station. The slope is zero. Table J.17 shows the energy recuperated.

Table J.17 Clairwood station data

Gradient (1:n)	0
Initial velocity (km/h)	70
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.219
% Gradient	0.14
Wh/tonne	37.86

Clairwood to Rossburgh

Clairwood station is at kilometre point 2.00. From Clairwood station it accelerates to 60 km/h and uses regenerative braking to stop at Rossburgh station. The slope is zero. Table J.18 shows energy recuperated.

Table J.18 Rossburgh station data

Gradient (1:n)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0
Wh/tonne	27.02

The total energy recuperated during regenerative braking from Montclair station to Rossburgh station is 64.88 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Montclair to Rossburgh line is 1,342,544,448 kg. This is equal to 1,342,544.5 tonnes. This was obtained after adding the mass of all trains from Umlazi to Durban, Kelso to Durban, Crossmoor to Durban and West to Durban. Using this information and the total Wh/tonne above, the total energy recuperated is:

$64.88 \times 1,342,544.50 = 87,104,287.16 \text{ Wh} = 87,104.29 \text{ kWh}$

Rossburgh to Umbilo

Rossburgh station is at kilometre point 7.46. From Rossburgh station, the train can only accelerate to a maximum speed of 60 km/h due to the short distance even though the maximum speed allowed is 80 km/h. The distance between Rossburgh and Umbilo stations is 1.05 km. The train uses regenerative braking in order to stop at Umbilo station. The slope is 1 in 96 descending. Table J.19 shows the energy recuperated.

Table J.19 Umbilo station data

Gradient (1:n)	0
Initial velocity (km/h)	96
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	1.04
Wh/tonne	30.34

Umbilo to Congela

Umbilo station is at kilometre point 6.410. From Umbilo station, the train accelerates to 60 km/h and uses regenerative braking to stop at Congela station. The slope is zero. Table J.20 shows the energy recuperated.

Table J.20 Congela station data

Gradient (1:*n*)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0
Wh/tonne	27.02

Congela to Dalbridge

Congela station is at kilometre point 4.660. The train accelerates to 60 km/h and uses regenerative braking to maintain this speed between kilometre point 3.627 and 3.452. The slope is 1 in 320 descending. Table J.21 shows that no energy is recuperated.

Table J.21 Congela to Dalbridge data - first gradient

Distance (km)	0.175
Initial velocity (km/h)	60
Regenerative braking duration (s)	10.50
% Gradient	0.31
F_t (N/tonne)	-19.62
Energy recuperated (Wh/tonne)	0.72 (used)

The train then uses regenerative braking to stop at Dalbridge station. The slope is zero. Table J.22 shows the energy recuperated.

Table J.22 Dalbridge station data

Gradient (1:*n*)	0
Initial velocity (km/h)	60
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.156
% Gradient	0
Wh/tonne	27.02

Dalbridge to Berea Road

Dalbridge station is at kilometre point 3.300. From Dalbridge station, the train can only reach 50 km/h due to the short distance and the train uses regenerative braking to stop at Berea Road station. The slope is an average 1 in 547 ascending. Table J.23 shows the energy recuperated.

Table J.23 Berea Road station data

Gradient (1:n)	547
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.18
Wh/tonne	17.46

Berea Road to Durban

Berea road station is at kilometre point 1.800. From Berea station, the train accelerates to 50 km/h and uses regenerative braking to maintain this speed between kilometre point 1.347 and 1.093 on a descending slope of 1 in 379. Table J.24 shows that no energy is recuperated.

Table J.24 Berea Road to Durban data - first gradient

Distance (km)	0.254
Initial velocity (km/h)	50
Regenerative braking duration (s)	18.29
% Gradient	0.26
F_t (N/tonne)	-24.52
Energy recuperated (Wh/tonne)	1.3 (used)

It then uses regenerative braking to stop at Durban station. The slope is 1 in 110 ascending. Table J.25 shows the energy recuperated.

Table J.25 Durban station data

Gradient (1:*n*)	110
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.91
Wh/tonne	15.93

The total energy recuperated during regenerative braking from Rossburgh station to Durban station is 117.77 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Rossburgh to Durban line is 1,650,436,528 kg. This is equal to 1,650,436.5 tonnes. This was obtained after adding the mass of all trains from Umlazi to Durban, Kelso to Durban, Cato Ridge to Durban, Pinetown to Durban, Crossmoor to Durban and West to Durban. Using this information and the total Wh/tonne above, the total energy recuperated is:

$117.77 \times 1,650,436.50 = 194,371,906.61$ Wh $= 194,371.91$ kWh

Durban to Moses Mabhida

Durban station is at kilometre point 0.000. The train accelerates to 50 km/h and uses regenerative braking to stop at Moses Mabhida station. The slope is zero. Table J.26 shows the energy recuperated.

Table J.26 Moses Mabhida station data

Gradient (1:*n*)	0
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.0
Wh/tonne	17.84

Moses Mabhida to Umgeni

Moses Mabhida is at kilometre point 1.500. From Moses Mabhida, the train accelerates to 50 km/h and uses regenerative braking to stop at Umgeni station. The slope is zero. Table J.27 shows the energy recuperated.

Table J.27 Umgeni station data

Gradient (1:n)	110
Initial velocity (km/h)	50
Final velocity (km/h)	19
Acceleration (m/s^2)	-0.8
Braking distance (km)	0.103
% Gradient	0.91
Wh/tonne	17.84

The total energy recuperated during regenerative braking from Durban station to Umgeni station is 35.68 Wh/tonne. From Table 3.13, the mass of all trains with passengers on the Durban to Umgeni line is 810,083,904 kg. This is equal to 810,083.9 tonnes. This was obtained after adding the mass of all trains from Durban to KwaMashu and trains from Durban to Stanger. Using this information and the total Wh/tonne above, the total energy recuperated is:

$35.68 \times 810,083.9 = 28,903,793.6 \text{ Wh} = 28,903.79 \text{ kWh}$

Therefore the energy recuperated from Reunion to Umgeni is 423,709.03 kWh.

The total energy recuperated between Reunion and Umgeni is 832,879.98 kWh. This was obtained after adding the energy recuperated by trains moving in both directions between Umgeni and Reunion.

Appendix K

Rand Value of Regenerative Braking

The total for the whole year is R23,028,102.40 as given in Fig. K.4.

APRIL	Energy recuperated per month (kWh)	Peak						Standard					
		Energy Consumption	Old Tariff	Cost	Energy Consumption	New Tariff	Cost	Energy Consumption	Old Tariff	Cost	Energy Consumption	New Tariff	Cost
	2628732.00	262 873	0.8735	R 229 619.74	262 873	0.9192	R 241 633.05	578 321	0.6008	R 347 455.28	578 321	0.6322	R 365 614.56

APRIL		Off Peak						Totals
		Energy Consumption	Old Tariff	Cost	Energy Consumption	New Tariff	Cost	
		473 172	0.381	R 180 278.44	473 172	0.4009	R 189 694.56	R 1 554 295.63

MAY	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

JUNE	Energy recuperated per month (kWh)	Peak						Standard					
		Energy Consumption(LS)	Tariff (LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)	Energy Consumption(LS)	Tariff (LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)
	2628732.00	262 873	0.9192	R 241 633.05	262 873	2.8187	R 740 960.69	578 321	0.6322	R 365 614.56	578 321	0.8536	R 493 654.84

JUNE		Off Peak						Totals
		Energy Consumption(LS)	Tariff (LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)	
		473 172	0.4009	R 189 694.56	473172	0.4632	R 219 173.16	R 2 250 730.85

Figure K.1 April to June.

JULY										
Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
2628732.00	525 746	2.8187	R 1 481 921.38	1 156 642	0.8536	R 987 309.68	946 344	0.4632	R 438 346.32	R 2 907 577.38

AUGUST										
Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
2628732.00	525 746	2.8187	R 1 481 921.38	1 156 642	0.8536	R 987 309.68	946 344	0.4632	R 438 346.32	R 2 907 577.38

SEPTEMBER												
Energy recuperated per month (kWh)	Peak						Standard					
	Energy Consumption(LS)	Tariff(LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)	Energy Consumption (LS	Tariff (LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)
2628732.00	262 873	0.9192	R 241 633.05	262 873	2.8187	R 740 960.69	578 321	0.6322	R 365 614.56	578 321	0.8536	R 493 654.84
	Off Peak						Totals					
	Energy Consumption (LS)	Tariff (LS)	Cost (LS)	Energy Consumption (HS)	Tariff (HS)	Cost (HS)						
	473 172	0.4009	R 189 694.56	473 172	0.4632	R 219 173.16	R 2 250 730.85					

Figure K.2 April to June.

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
OCTOBER	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
NOVEMBER	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			Totals
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	
DECEMBER	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

Figure K.3 April to June.

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Totals
JANUARY	2628732.00	525746.40	0.92	483266.09	1156642.08	0.63	731229.12	946343.52	0.40	379389.12	R 1 593 884.33

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Totals
FEBRUARY	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

	Energy recuperated per month (kWh)	Peak			Standard			Off Peak			
		Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Energy Consumption	Tariff	Cost	Totals
MARCH	2628732.00	525 746	0.9192	R 483 266.09	1 156 642	0.6322	R 731 229.12	946 344	0.4009	R 379 389.12	R 1 593 884.33

Total energy recuperated per annum	R 23 028 102.40

Figure K.4 April to June.

Appendix L

Net present value (NPV)

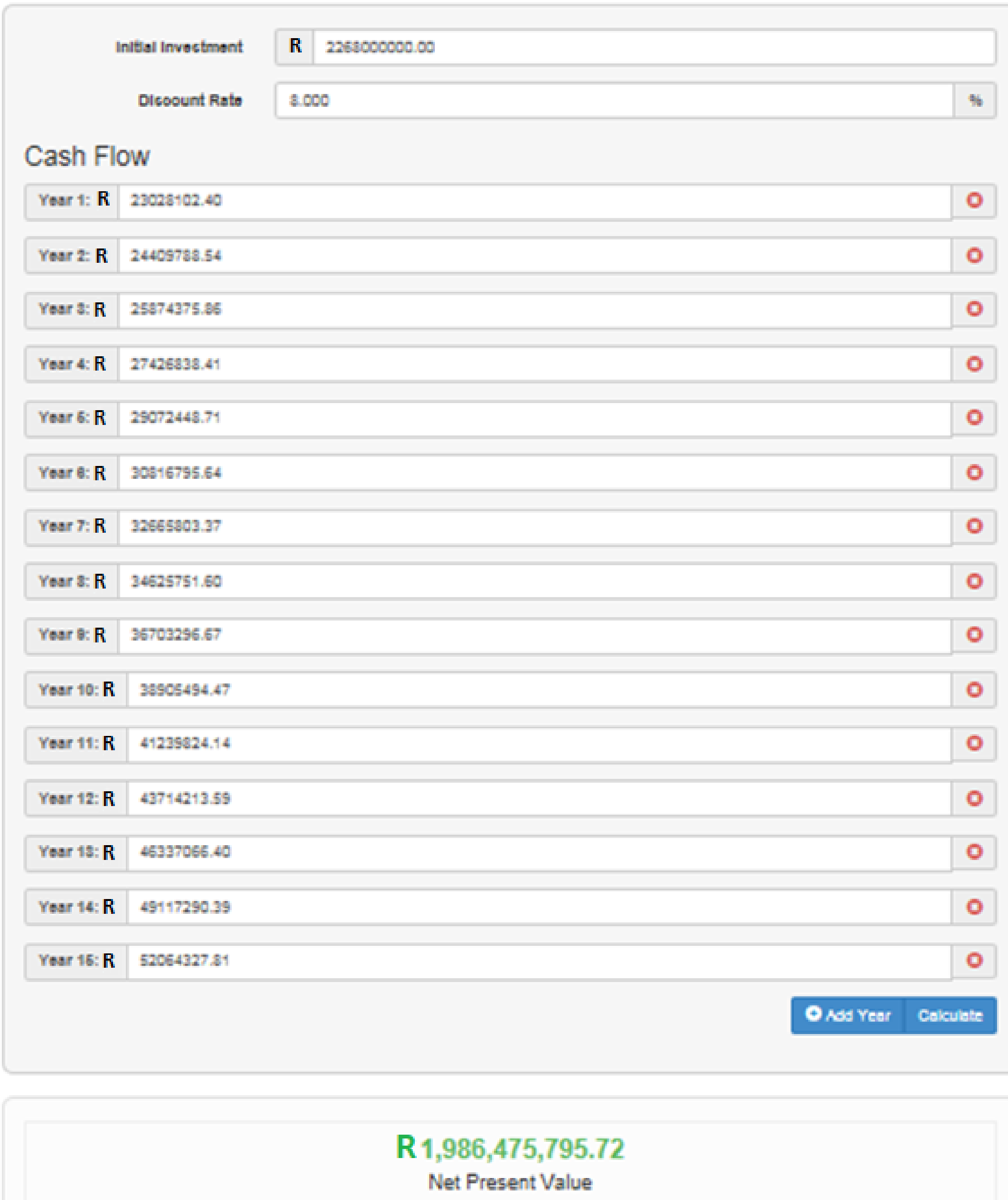

Figure L.1 Net present value.