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QUANTIFYING THE ECONOMIC BENEFITS OF GAUGE CHANGES ON THE SOUTH AFRICAN CORE RAILWAY NETWORK

CP DEMMEREZ DE CHARMOY

A dissertation submitted in partial fulfilment of the requirements for the degree of

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DISSERTATION SUMMARY

QUANTIFYING THE ECONOMIC BENEFITS OF GAUGE CHANGES ON THE SOUTH AFRICAN CORE RAILWAY NETWORK

CP DEMMEREZ DE CHARMOY

Supervisor:	Professor P.J. Gräbe
Department:	Civil Engineering
University:	University of Pretoria
Degree:	Master of Engineering (Transportation engineering)

In its white paper, the Department of Transport proposes a future South African core railway network which requires the conversion and construction of over 8,500 km of standard gauge railway track by 2050. The scale of the project would undeniably have a large cost attached to it which needs to be well understood before any of the construction takes place. Numerous studies regarding railway gauge have been conducted in South Africa, however, no single paper has addressed the issue of which specific railway corridors could *economically* benefit from a standard gauge intervention.

The purpose of the study was to identify which corridors in the South African core network could potentially benefit from a gauge change intervention. These identified corridors were then economically evaluated to determine which of the corridors would outperform the base case which was set as the Market Demand Strategy (MDS) plan. The three main gauge interventions which evaluated includes the direct conversion from narrow to standard gauge, the addition of a third rail to a narrow gauge line and the construction of a ring-fenced standard gauge line adjacent to a narrow gauge corridor. Lastly, simulations were carried out on the corridors which outperformed the base case, to establish how the operations of the corridor would be affected. Agent based simulation was conducted to understand the effects of the gauge changes performed on corridors which met the described criteria.

The conclusions of the study indicated that all of the corridors in the South African core network should follow the plans proposed in the MDS to achieve the maximum return for the analysis period, except for the Natal corridor. It was identified that the Natal corridor would benefit most from a standard gauge

single line which would run concurrently with the narrow gauge corridor transporting containers and other general freight. The results of the study did not directly correlate with Department of Transport’s white paper gauge change proposals. Many of the gauge conversions proposed by the white paper could be highly uneconomical and may require large government subsidies should they be undertaken. A thorough understanding of the financial implications of performing large scale gauge changes is required before any construction should take place. This study should be seen as a steppingstone towards this understanding.

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α	significance level for a t-distribution
$\bar{x}$	sample mean
n	sample size
σ	sample standard deviation
$t_{(1-\alpha,n-1)}$	t from students t-distribution for a stated level of confidence 1 – α and sample size, n
SE	standard error of the mean, $\frac{\sigma}{\sqrt{n}}$
$	United States of America Dollar
R	South African Rand
k$/m	kilo Dollars per meter
km/h	kilometres per hour
kV	kilovolts
kW	kilowatts
km	kilometres
m	meters
$\mathrm{m/s^2}$	acceleration
mt	million tonnes
mtpa	million tonnes per annum
P	present worth
F	future worth
i_m	minimum attractive rate of return
i_{ir}	interest rate
i_d	discount rate
i_r	inflation rate
r	average rate per tonne
t_{total}	total number of tonnes transported
n	duration of analysis

A	annualised worth
t	tonnes
min Z	error reduction term
R	South African Rand
P	calibrated system parameters
P^a	priori system parameters
I	calibrated system inputs
I^a	priori system inputs
Y_{k+1}	yard sequence
Y^{sim}	simulated measurements
Y^{obs}	observed measurements
w_i	weighting capturing the importance and accuracy of each component
$S(P^a, I^a)$	simulation model that maps inputs corresponding measurements
$Y_{n_s}^{sim}$	simulated measurements at a space-time point
$Y_{n_s}^{obs}$	observed measurements at a space-time point
n_s	space-time point
Y_i	output of interest related to the ith measure of performance
R_i	Minimum number of replications required to estimate the mean of Y_i with tolerance d_i
$s(Y_i)$	sample standard deviation of Y_i
$t_{\alpha/2}$	critical value of the t-distribution at significance level α
X	used railway line capacity,
Y	operational capacity (65 % of theoretical capacity)
V	velocity in km/h
v	velocity in m/s

R_v	vertical curve radius in m
L_m	locomotive mass
L_n	number of locomotives
W	axle load in tonnes
W_n	number of wagons
m_t	train mass excluding the locomotives
$m_{t\ total}$	total train mass
F_g	gravitation acceleration
$f_{d\ total}$	downhill force
f_d	downhill push per tonne
f_{dt}	net downhill force per tonne
f_{BE}	total breaking effort
f_r	friction breaking
f_{rt}	rolling resistance per tonne
Q	heat input into wheels
Q_w	heat load per wheel
TE_{max}	maximum continuous tractive effort
TE	tractive effort
T_{exp}	throughput envisaged
T_w	throughput per wagon per annum
T_L	throughput per locomotive per annum
$W_{required}$	total number of wagons required

W_t	trips per wagon per annum
Ψ	ruling grade

LIST OF ABBREVIATIONS

GDP	gross domestic product
AC	alternating current
CTC	centralised traffic control
CAPEX	capital expenditure
DC	direct current
IRR	internal rate of return
MARR	minimum attractive rate of return
MDS	market demand strategy
OHTE	overhead traction equipment
ERR	external rate of return
GRR	growth rate of return
RMSPE	root mean square percentage error
TCS	train connecting services
TFR	Transnet Freight Rail
LTPF	long term planning framework
PW	present worth
B/C	benefit/cost ratio

1 INTRODUCTION

1.1 BACKGROUND

South Africa’s rail network consists of 22,387 route-km or 30,400 track-km of which all is narrow gauge with the only exception being the 80 km Gautrain line which is standard gauge (Department of Transport, 2017). South Africa’s rail network has been unable to take advantage on rail’s inherent benefits because of the early South African government’s decision to construct the rail network in narrow gauge. Rail’s success is built upon its three genetic technologies which includes bearing, guiding and coupling (van der Meulen, 2010). By utilising narrow gauge, and not standard gauge, the South African rail network loses out on many benefits. According to the Department of Transport (2017) South Africa can operate long heavy haul trains however, South Africa is unable to take advantage of speed and axle load in the same way standard gauge systems are able to.

South Africa’s freight trains are not able to transport double stacked containers because the core network’s corridors are entirely narrow gauge. If selected lines are changed to standard gauge freight haul, using rail, would become more competitive when compared to road truck transport. Marsay (2005) indicated that the Natal corridor was dominated by road truck transport with rail only having 16 % of the corridors market share. The Department of Transport (2017) indicates that in ensuing 12 years, rail has slumped to a 90/10 split between road and rail on the Natal corridor.

If standard gauge options are implemented in the future, for freight carrying purposes, double stacking of containers would be possible resulting in the same number of trains operating on a line with approximately double the volume transported per trip therefore, maximizing line capacity.

The core network is approximately 60 % of the network and the remaining 9,000 km are classified as “branch lines” (Transnet, 2012). The main corridors which typically carry general freight are rated for 20 tonnes axle loading while the Ore line operates at 30 tonnes axle loading and the Coal line at 26 tonnes axle loading. Standard gauge rail countries are able to operate well above the 30 tonne axle loading threshold at the same travel speeds (Martland, 2013).

Numerous studies regarding railway gauge have been conducted within South Africa however, no single paper has addressed the issue of which specific railway corridors could benefit from standard gauge interventions.

1.2 OBJECTIVES OF THE STUDY

The objectives of the study are summarised as follows:

- To establish which corridors could potentially benefit from a standard gauge intervention;
- To identify what type of standard gauge intervention would be most economically beneficial on the identified corridors, such as adding a third rail, constructing a standard gauge line parallel to the narrow gauge corridor or completely changing the line from narrow gauge to standard gauge, and
- For the intervention identified, to understand how this will influence the operations on the corridor through the analysis of the intervention by means of simulation.

1.3 SCOPE OF THE STUDY

The study entails the evaluation of the core network with information made available by Transnet Freight Rail. The study focuses on identifying corridors which could potentially benefit from some form of standard gauge intervention and not the optimisation of the narrow gauge network. The study is a starting point for a more detailed future feasibility study, should the alternatives identified be seen as viable options by key role players in industry. The cost model used has limitations due to infrastructure costs having to be estimated from similar construction projects undertaken around the world, the actual number of locomotives and wagons to be utilised would vary depending on how operations are intended on being run and the disruption to the normal operations caused by the construction will also vary and required estimation. Limited simulation modelling was used due to the high need for calibration and verification with real world information that was difficult to obtain by means other than literature. The study looked at both heavy haul and mixed freight corridors that are part of the South African core network.

1.4 METHODOLOGY

The methodology can broadly be divided into two main sections which include:

1. The identification of corridors which could potentially benefit from standard gauge interventions. This required the analysis of data regarding the volumes of commodities moved along the various corridors. The analysis of the data focusses on highlighting

which routes carry enough volume currently and will be able to carry enough volume in the future to be able to pay off the capital investment associated with the various standard gauge interventions. A method of identification of these corridors is established as well as a criterion for indicating whether a corridor operates efficiently enough or not, to warrant a standard gauge intervention. The analysis is performed on Microsoft Excel due to the software's versatility and complemented by Python for more specific large data analysis.

2. The corridors identified are then evaluated with more detailed information such as line section volumes to allow for a good comparison between the various standard gauge alternatives. The detailed data on the various corridors along with the comparison of the various interventions then lead to the selection of the best alternative for each of the corridors. A sensitivity analysis is performed in order to observe how changing freight growth rate conditions would affect the success of the investment and whether it will be able to remain profitable in variable economic conditions. The effect on the rest of the corridor of the alternative selected is evaluated using simulation. AnyLogic simulation software is used for detailed simulation of the standard gauge intervention. AnyLogic's strength lies in its ability to perform simulations which incorporate system dynamics, agent based modelling and discrete event modelling on one platform at a microsimulation level.

1.5 ORGANISATION OF THE REPORT

The report consists of the following chapters:

- Chapter 1 serves as the introduction to the dissertation, outlining the background, objectives, scope, methodology and organisation of the research project.
- Chapter 2 contains a discussion of literature related to railway gauge and current governmental reports surrounding the gauge topic. The condition and future plans for the South African core network are summarised in the chapter along with previous investigations conducted on the topic of railway gauge.
- Chapter 3 provides the detailed process of corridor selection for gauge evaluation through the use of reports made available by Transnet Freight Rail. It also describes the manner in which alternatives were compared and evaluated before finally describing the manner in which simulation was used to model the various interventions selected.

- Chapter 4 covers the results of the analysis process and includes both the selection of the various corridors for consideration and the economic evaluation of each of the standard gauge alternatives. The results of the simulations of alternatives are displayed and discussed.
- Chapter 5 concludes with a summary of the addressed research objectives as stated in Chapter 1. Recommendations on future research activities that can augment and elaborate on the results of the research are summarised. The results of the research are also compared with the results of the study conducted by the Department of Transport (2017) in the National Rail Policy. The National Rail Policy seeks to reposition rail as the backbone of the country's freight transport industry.

2 LITERATURE REVIEW

This chapter provides a literature review which will supplement the study by reviewing various concepts and relevant research. The chapter reviews the South African railway network and considers the government's decision to select narrow gauge in the 1880s. South Africa's economic and environmental future is then reviewed before an overview of the state of the core railway network is reported.

The main railway corridors are discussed and the future of the core network is assessed. Thereafter, the infrastructure costs and methods of long-term project evaluations are be reviewed. Lastly, simulation methods and techniques are assessed for railway corridors.

2.1 BACKGROUND OF RAILWAY GAUGE IN SOUTH AFRICA

Railways played a key role in the development of South Africa through the 20th century and was a key driver of growth within the country. The following subchapter discusses the gauge selection decision within South Africa, with gauge being the distance between the inner sides of two parallel rails (Transnet, 2016).

2.1.1 The First Railway Line

The earliest railway construction took place in Durban and Cape Town with Durban completing its 3 km section of line first in 1860 (Transnet, 2010). In the first three years of operation, the line conveyed 20,000 tonnes of imports and close to 5,000 tonnes of exports before expansion began in 1865. This line was constructed as a standard gauge (1435 mm) railway line and it was privately owned. However, in 1875 the railways were transferred to the state and a decision was made to build the following expansion from Durban to Pietermaritzburg on narrow gauge due to the mountainous topography of the interior (Cottrel, 2010).

2.1.2 The Expansion of the Railway Network

In 1881, following the Boer's victory over the British at Majuba, Paul Kruger was made president and began construction of the Pretoria to Delagoa Bay narrow gauge railway line. This required the construction of bridges and tunnels in an untamed lowveld. The line was completed on New Year's Day 1895 (Transnet, 2010).

The Durban to Johannesburg railway line was completed in late 1895 which has over time lead to Durban becoming the busiest port in Africa and home to the largest container terminal in the Southern Hemisphere (Cottrel, 2010).

In 1910 the individual railway authorities signed an agreement which has led to the formation of what is today Transnet. 1976 and 1977 were dates which signified the completion of the Coal line to Richards Bay harbour and the completion of the Sishen to Saldanha Ore line respectively (Transnet, 2010).

2.2 RAILWAY'S ROLE IN SOUTH AFRICA'S ECONOMIC AND ENVIRONMENTAL FUTURE

The unstable political climate post 2010 within South Africa caused disinterest from global investors and a lack of Gross Domestic Product (GDP) growth. Since 2010, South Africa's GDP growth has hovered around the 1.5 % per annum mark (Transnet, 2016). Transnet (2016) anticipate that over the period from 2015 to 2045, South Africa is likely to experience forecasted growth rates per annum ranging from 2.1 % to 5 %.

These growth rates can be expected due to the Sub-Saharan economy being set to remain as one of the fastest growing economies in the world (Kambou, 2018). The Department of Environmental Affairs (2014) states that rail transport has the potential, under the correct circumstances, to provide a cost-effective freight transport option, creating a more efficient economy, providing access for freight and passenger movements and impacting an environmentally sustainable transport solution.

2.2.1 Predicted Growth Rates and Influence of Ports

The National Planning Commission (2012) aims to double the average economic growth rate to 5.4 % per annum for the period from 2012 to 2030, however, this would require fixed investment in economic infrastrucutre to increase from 20 % to 30 %. Local and foreign financing would be required to materialise and this is compounded by South Africa's inadequate savings ratio of 15 % of GDP. Eskom's delay in expanding power generation at Medupi and Kusile power stations has not assisted economic growth (Transnet, 2016).

The ports along the East Coast of South Africa provide connections to the northern countries in Africa such as Botswana, Zimbabwe, Zambia and the Congo through the narrow gauge rail network and the expansive road network. These ports do not experience much competition from Mozambique, mainly due to the lack of an effective rail system connecting the ports to the city centres (Transnet, 2016).

Approximately 60 % of Transnet's revenue is generated from the Coal and Iron ore lines (Transnet, 2018). The future of these two commodities should be well understood before any major upgrades are performed on the Coal and Iron ore export lines.

The future of coal is largely dominated by China and India who make up a major portion of the coal use in the world (MIT, 2007). These two countries will have the largest impact on the coal industry and may be affected by future environmental regulations due to coal's large CO_2 output and mercury issues. Any changes made to the Coal export line should be linked to such global issues.

Iron ore is used in the production of steel and iron. Tuck et al. (2017) illustrate that iron ore consumption has tripled during the period from 2000 to 2015. Iron ore usage is predicted to slow down in the future due to improved usage and recycling, however, this will be driven by China's consupmtion of the commodity (Creamer, 2017).

2.2.2 Influence of South Africa's Road Network on Modern Transportation

Railways within South Africa grew rapidly between 1896 and 1930, however, post 1930 the service required regulation and legality. Post 1930 pressure began to develop from the motor truck industry which is a syndicate of privately-owned enterprises (Janse Van Rensburg, 1996).

The combined effects of the De Villiers report (South African Transport Services, 1986) which suggested no new rail investments but to rather utilise the existing assets, and the deregulation of road transport in 1988, pushed large portions of the rail industry into decline. The lack of equitable pricing between road and rail along with the institutional bias towards road has led to road transportation's advancement in gaining market share (Department of Transport, 2017). Trains are only able to operate on one-dimensional longitudinal routes in forward or backward directions, whilst roads can transport goods on a large network with good mobility (Marinov et al., 2013).

The South African Transport Services (1986) and the Department of Transport (2017) stated that the only way in which railways could operate is through taking advantage of rail's inherent benefits. The Rail Road Association (2008) presented a position paper on railway gauge, discussing how narrow gauge has been disadvantaged due to globalisation and the surge in the use of standard gauge by developed countries.

Standard gauge rail is widely used and for this reason institutions have invested time and money into the advancement and development of standard gauge locomotives, wagons and coaches, to be more efficient during their lifetimes.

Narrow gauge does not receive this amount of research and special orders must be made when locomotives are required. The low supply induces inflated costs and because of the narrower gauge, smaller and weaker engines are installed into these locomotives, rendering them less effective than their standard gauge counterparts. In summary, a narrow gauge locomotive costs more than a standard gauge locomotive and is less efficient (Department of Transport, 2009).

2.2.3 Environmental Impact

Rail is viewed as a cleaner method of transporting freight and incurs lower externality costs (Havenga et al., 2012). Van Wee et al. (2005) indicates that on average, rail using electric traction, emits 2.75 times less CO_2 and N_2O than road transport per tonne kilometer. From an environmental standpoint, rail is the more efficient mode of transport due to the low friction coefficient of the steel on steel contact.

2.3 THE CORE NETWORK

The South African core railway network consists of 60 % of the entire network with the remaining 9000 km classified as “branch lines” (Transnet, 2016). The main lines, which typically carry general freight, are rated for 20 tonnes axle loading while the Ore line operates at 30 tonnes and the Coal line at 26 tonnes axle loading.

2.3.1 Perway Condition

The perway is referred to as a section of railway track with its numerous components (Mc Naught, 2015). Transnet, in more recent years, has put a large focus on maximising available infrastructure rather than building expensive new railway lines. Figure 2-1 displays the perway condition of the rail network in South Africa and illustrates the need for maintenance operations.

Figure 2-1 shows the challenges faced by Transnet, with most of the core railway network categorised to be in the average condition bracket. About 1500 km of the network are in the poor state. Good would indicate that the line is fully operational. Acceptable or average indicates that the required operational capacity is achievable and red means that less than 20 % of the infrastructure’s life is remaining (Transnet, 2012).

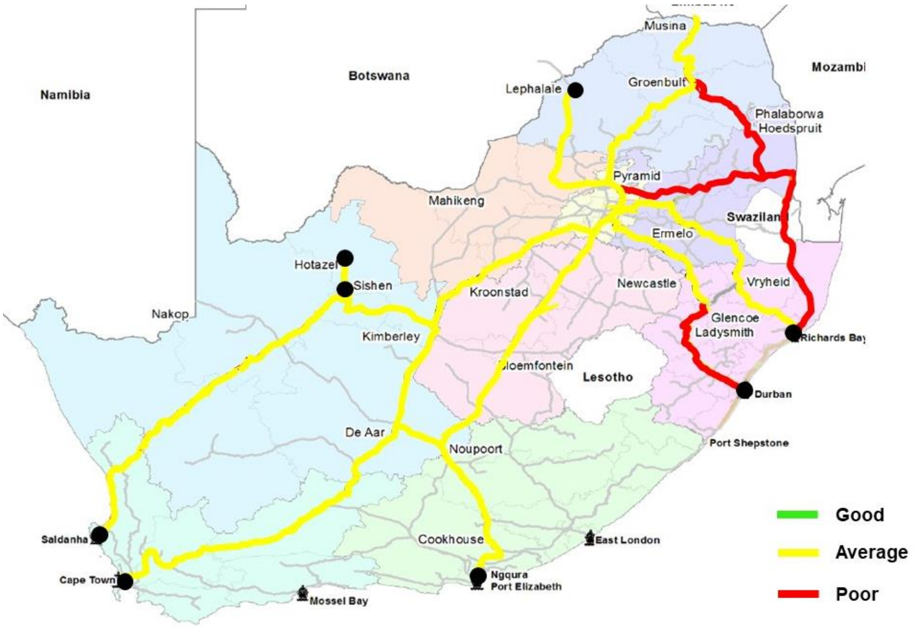


Figure 2-1: Perway condition (Transnet, 2016)

2.3.2 Railway Line Utilisation

Figure 2-2 displays the network utilisation during the year 2016. Much of the network lies in the moderate traffic operational section which indicates that there is adequate capacity available on the railway network to run more trains. The poor utilisation of the network combined with the low traffic volumes are cause for concern.

Line capacity can be broken down into theoretical, operational, practical and used capacity. Operational capacity is capacity in the form of train slots available for trains carrying freight to pass through the system, this is typically 65 % of the theoretical capacity with maintenance and operational allowances taking up the other 35 % (Transnet, 2016). Practical capacity is the operational capacity minus the condition-based allowances, such as speed restrictions, where upgrades can improve this factor. Used capacity is the actual capacity used on the line. Burdett & Kozan (2006) compiled a method of estimating absolute traffic capacity using bottleneck theory for a wide range of operational conditions.

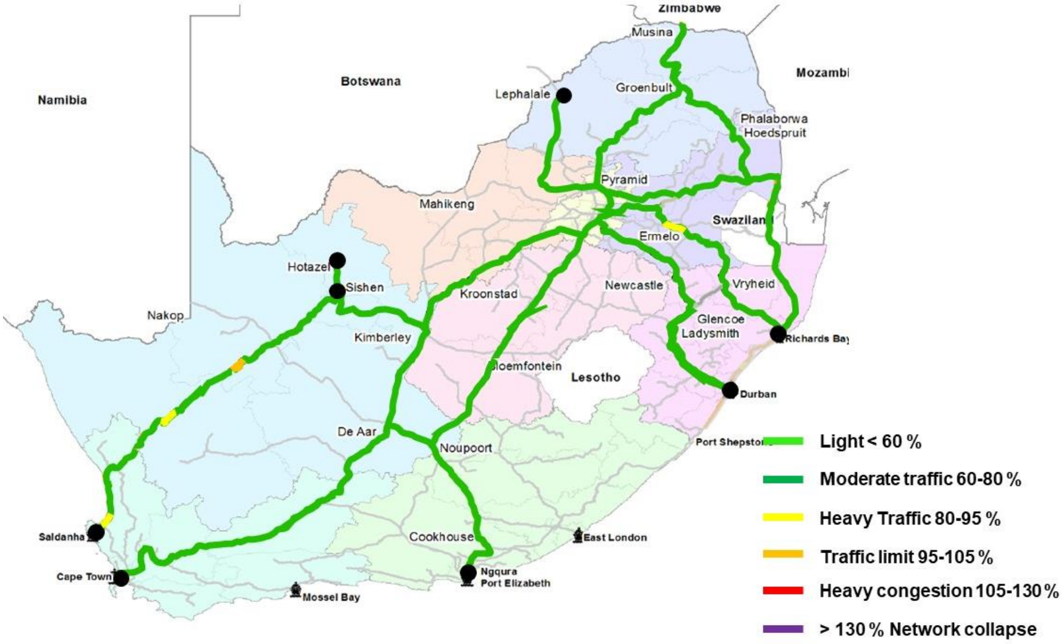


Figure 2-2: Railway line utilisation (Transnet, 2016)

Transnet (2016) expect the core network to approach complete network collapse by 2046 should no investments be made towards line and capacity upgrades.

2.4 KEY CORRIDORS IN SOUTH AFRICA

Before standard gauge options can be considered, a thorough overview of the key railway corridors in South Africa is provided. The core network, operated by Transnet, is the main carrier of commodities between the various inland centres and mines to the coastal ports. Transnet (2016) indicate that the core network consists of 18 sections and can be categorised into the following four systems:

- Iron Ore and Manganese System;
- Coal System;
- North-Eastern System, and
- Intermodal and General Freight System.

2.4.1 The Natal Corridor

The Natal corridor is the double line which runs from Booth, Durban to Rietvallei, Johannesburg which is approximately 695 km in length. The line has an axle loading of 20 tonnes, the line operates using 3kV DC electrification which is the old system of electrification and uses the Centralised Traffic Control (CTC) (Transnet, 2016). The line is mostly double line except for the section between Union and Glenroy stations.

This line transports 21.6 million tonnes per annum of general freight to the port and 4.7 million tonnes per annum from the port (Transnet, 2017). The cumulative amount is expected to grow to 50.49 million tonnes per annum in 2030 and 73.44 million tonnes per annum in 2045. The line is only able to operate 50 wagon trains and a 150-wagon compilation yard in Durban still needs to be identified (Transnet, 2012).

The current demand shows a theoretical 33 trains per day and by 2044 at least 184 trains per day – an impossible scenario - will need to run to meet the demand (Transnet, 2012). Currently, sections of the line operate at a speed restriction of 50 km/h due to steep gradients, tight curves and worsening perway condition. Transnet (2016) is of the opinion that the only feasible long-term solution is if longer trains are run on the line however, the Department of Transport (2017) argues that double stacked container trains are the future of container freight rail transport.

Figure 2-3 displays the Natal Corridor linking the Gauteng region with the port in Durban. The line also extends from Richards Bay to Port Shepstone, however, this line does not receive much traffic.

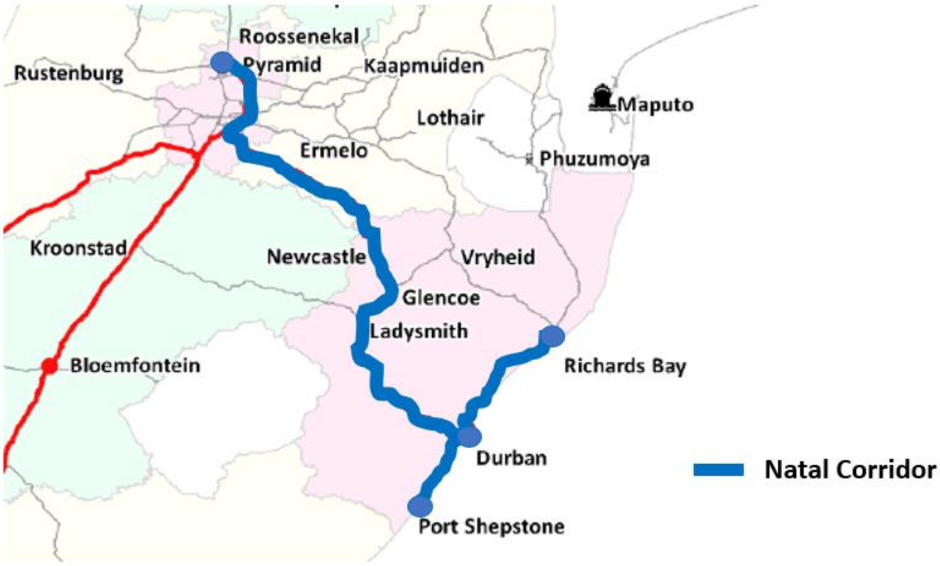


Figure 2-3: Layout of the Natal Corridor (Transnet, 2016)

2.4.2 The North-Eastern System

The system operating in the lowveld that connects the South African system to the Mozambican, Zimbabwean and Swazi networks is known as the North-Eastern System. This does not include the section of the line operating between Ermelo and Richards Bay.

The routes from Gauteng to Musina and Komatipoort are the main routes to Zimbabwe and Mozambique respectively. The routes carry mainly intermodal and general freight traffic (Transnet, 2016). Musina to Pyramid contains both single and double-line sections and can carry 20 tonne per axle loads. Groenbult to Kaapmuiden are 3 kV DC and non-electrified sections of track. The line can operate 20 tonnes per axle loading and has main exports of Magnetite and Phosphates.

Greenview to Komatipoort is a single-line section and is electrified with 3 kV DC. The line is able to carry axle loads of 20 tonnes and links Mozambique and Richards Bay via Swaziland (Transnet, 2016). Komatipoort to Richards Bay is considered a general freight, single-line and has an axle load capacity of 20 tonnes. 75 wagon trains are able to operate on this lane.

Figure 2-4 displays the North-Eastern System and how it connects the eastern sections of South Africa to the eastern neighbouring countries. The dotted line propagating from Lothair indicates that the section is under construction.

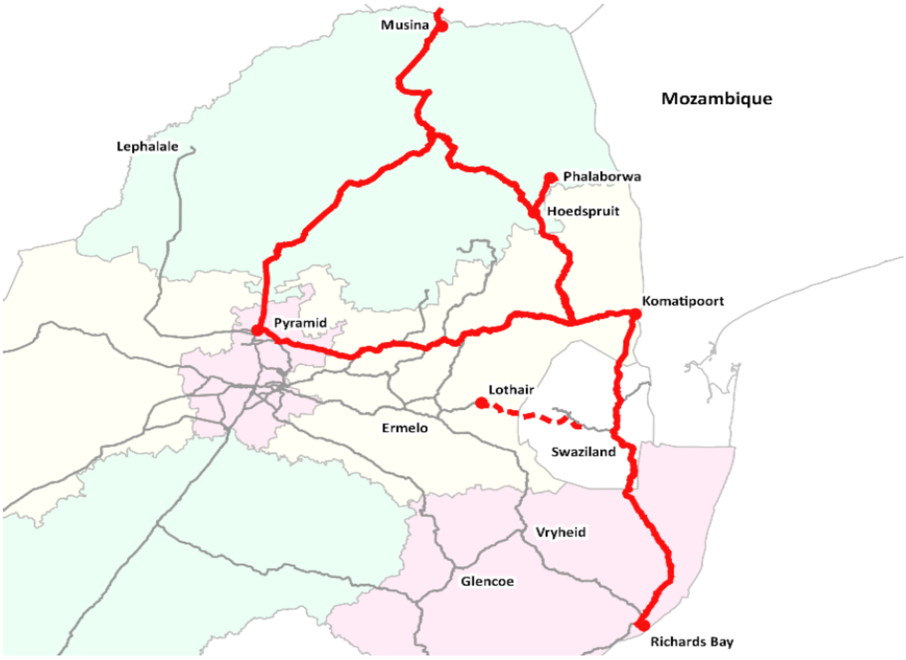


Figure 2-4: Layout of the North-Eastern System (Transnet, 2016)

2.4.3 The Coal line

The corridor which transports coal from Ermelo to Richards Bay is referred to as the Coal line. The line is considered to be a heavy haul operation with 26 tonne axle loading limits for the trains. Transnet (2016) indicates that approximately 20 % of the commodities transported on the Coal line are considered general freight.

The Coal line is used to transport on average 85 million tonnes per annum of coal from 44 different coal mines in the Mpumalanga and northern regions. The route length is 580 km with 25 kV AC traction and is frequented by 16 coal export trains a day consisting of 200 wagons each (Transnet, 2016).

The line capacity is limited by a single-track section through the Overvaal tunnel, however, a project has been initiated to construct another tunnel to relieve the capacity constraints on the line (Transnet, 2016).

Figure 2-5 displays the Coal line running from Lephalale to Richards Bay. The main section of the corridor is between Ermelo and Richards Bay since it carries the bulk of the traffic.

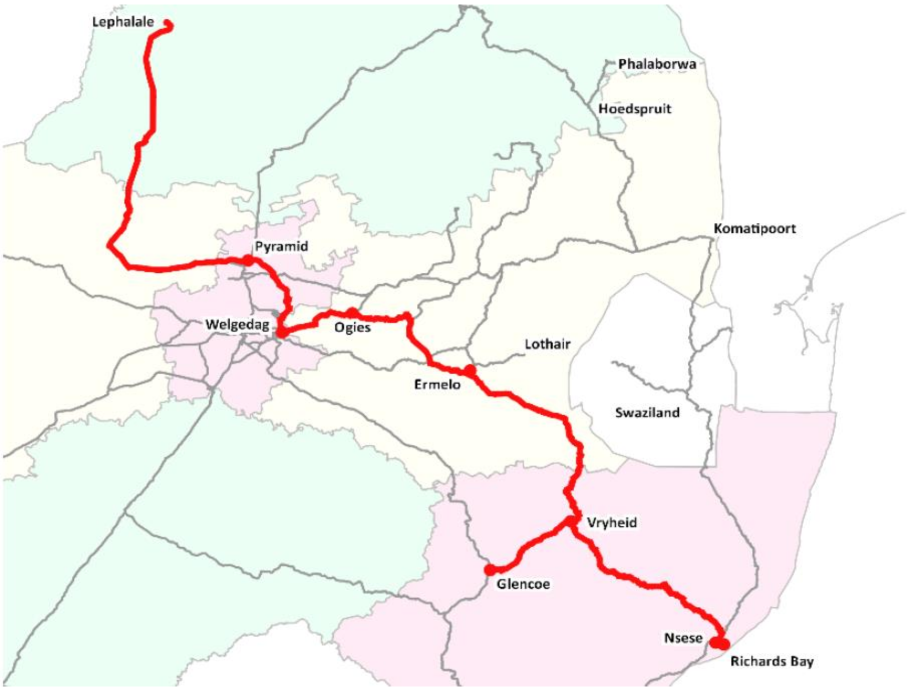


Figure 2-5: The Coal line (Transnet, 2016)

2.4.4 The Iron ore line

The corridor operating between Sishen and Saldanha carries the heaviest per axle tonnage in South Africa which is 30 tonnes per axle. The line is 861 km long, single railway line and is electrified with 50 kV AC traction. A maximum gradient of 1:250 allows for 342-wagon trains to transport iron ore daily (Transnet, 2016).

The corridor currently transports 60 million tonnes per annum and this amount is set to increase to 73 million tonnes per annum by 2046 according to Transnet (2016). The corridor is able to transport 38 trains per week with this number set to increase following proposed upgrades in the Long Term Planning Framework (LTPF).

Figure 2-5 displays the Iron Ore Corridor between Sishen and Saldanha. The other railway line visible in Figure 2-5 runs from Hotazel to Port Elizabeth and is mainly used to transport manganese, however, it is also used for general freight.

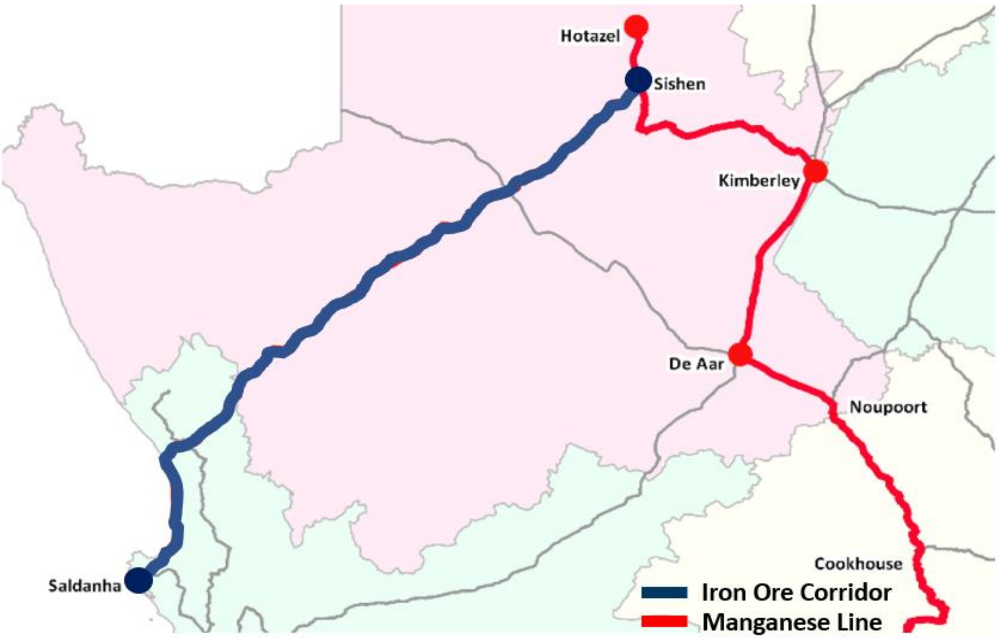


Figure 2-6: The Iron Ore Corridor (Transnet, 2016)

2.4.5 The Gauteng to Cape Town System

The corridor between Gauteng and Cape Town is largely one-directional in terms of commodity flow and is restricted by the single-track section between Kimberley and De Aar. The line, on average, transports 2.5 million tonnes per annum of various commodities such as maize, containers and coal mining products (Transnet, 2016).

The line is electrified with 3 kV DC between Bloemfontein and Gauteng but is operated using diesel locomotives south of Bloemfontein. The corridor is set to grow in time, with more containers being expected to be transported to the port in Cape Town as well as a gradual increase in other commodities (Transnet, 2016).

Figure 2-7 presents the Cape Town to Gauteng rail corridor. The corridor joins the Gauteng Freight Ring in the South-East of Gauteng and continues in this direction towards the Western Cape. The line also allows for two possible options of reaching De Aar. This is typically dependant on the commodity being transported and the stops made during the journey.

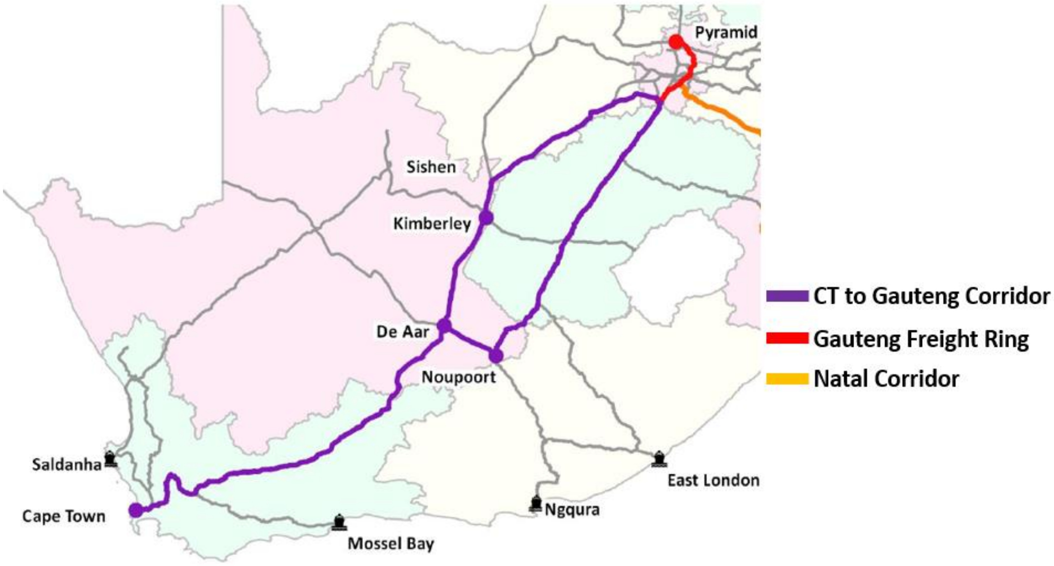


Figure 2-7: The Gauteng–Cape Town Corridor (Transnet, 2016)

2.5 POSSIBLE FUTURE OF THE CORE NETWORK

The core network is well setup to serve South Africa’s export and import needs, but it is the efficiency at which the system operates which is the cause for concern. This sub-section will discuss proposals put forward regarding the future of the core railway network and evaluate rail projects in Africa and globally.

2.5.1 Outcomes of the National Rail Policy

The Department of Transport (2017) proposed a future core network which incorporates standard gauge railway lines which will need to be constructed. This would require a large amount of capital investment, however, it may relieve stress on

South Africa's road network which currently carries the bulk of the freight in the country.

The National Rail Policy's (NRP) vision is for rail to be a competitive, safe, sustainable and affordable transport mode that will become the backbone of the country's freight logistics while strengthening South Africa's economic growth and social development by 2050.

The NRP seeks to do this through the halting of rail's decline by implementing a master plan, funding all projects related to the plan and beginning a rolling plan within five years of the NRP becoming an act and completing the plan before 2050. It further aims to reduce business costs and implement governance to encourage investment through concessions and lessees.

The NRP is driven by taking advantage of rail's inherent benefits which is maximised through the use of standard gauge railway.

Figure 2-8 displays what the future may look like for the South African core railway network as presented by Van der Meulen (2010). The network provided is similar to the one presented by the Department of Transport (2017) in the NRP. The network consists of 5,200 km of track of which 744 km are high speed rail (in excess of 270 km/h), 2,691 km are freight orienated and 900 km are passenger orientated. The Sishen-Saldanha line would remain narrow gauge and so would the Beit Bridge-Durban line.

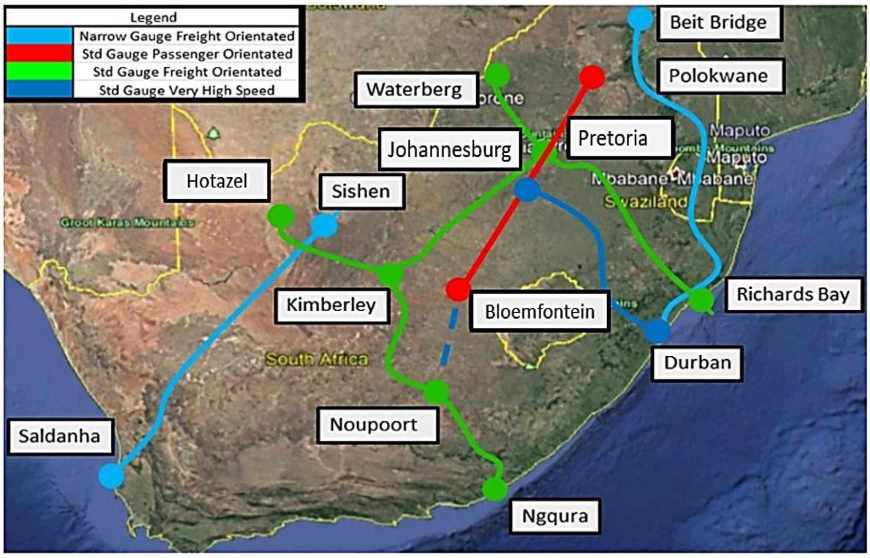


Figure 2-8: An essential South African railway network (adapted from Van der Meulen (2010))

Narrow gauge railway lines have isolated South Africa from rail's strides in speed and the more recent rail revitalisation (Department of Transport, 2017). Implementing standard gauge systems into the network would enable South Africa to take advantage of rail's inherent benefits which are hindered by narrow gauge railway operations. The NRP would allow South Africa to efficiently transport passengers and freight, however, the issue of payback for the investment or the financial implications were not covered in the paper.

2.5.2 Implementation of the Market Demand Strategies Objectives

Transnet (2012) compiled the Market Demand Strategy (MDS) to curb the loss of freight transportation market share to road and to meet future commodity demands South Africa is set to experience. The MDS should lead to a modal shift from road to rail (Creamer, 2014).

The MDS planned to invest R 336 billion into a capital investment programme. This would enable economic growth through the construction of rail, ports and pipeline infrastructure (Transnet, 2012). The MDS would take South Africa to 350 million tonnes in the year 2020 and move Transnet into the top five countries in South Africa with respect to revenue (Transnet, 2012). The MDS plans have been guided by the Long-Term Planning Framework (LTPF) which was compiled by Transnet (2016).

Transnet began the transition from the MDS to the Transnet 4.0 Strategy in 2018 which focuses on improved operating models, geographic expansion and market and customer development (Transnet, 2018). This 4.0 Strategy is intended to be supported by digital technologies to improve decision-making. This came after Transnet had already spent R 200 billion in achieving the MDS goals.

2.5.3 Global and African Railway Projects

The Department of Transport (2017) uses numerous examples from around the world to illustrate the global trend emerging, which is narrow gauge railway line conversions to standard gauge or the complete removal of narrow gauge lines. In 2007 the African Union stated that interoperability within the Africa continent shall be done through the use of standard gauge railway in the construction of new railway lines due to standard gauge rail's benefits when compared to narrow gauge (Department of Transport, 2009).

China has begun converting narrow gauge lines to standard gauge on a large scale. Within the African continent, Kenya completed their first standard gauge railway line along with Ethiopia, Ghana and Nigeria. The picture is clear, no country is building their 2050 transport layout on a narrow gauge railway backbone.

Kenya's dilapidated railway system with 100 year old technology resulted in freight trains travelling at 22 km/h and passenger trains at 40 km/h. Large Chinese investment of $ 3 billion led to the construction of a 3,100 km standard gauge railway which is set to be completed by 2025 (Irandu, 2017). Within South Africa the Gautrain Rapid Rail Link was constructed and operates effectively on a standard gauge railway system. The R 30 billion, 80 km double line railway was constructed between 2006 and 2011 (Marsay, 2018). Australia considered a narrow gauge country, completed construction of a large standard gauge network in 1995 which connected the major capitals within Australia (Department of Transport, 2009).

Japan began the railway renaissance with the introduction of high-speed trains. This was followed by heavy haul operations in 1972, heavy intermodal in 1980 and urban rapid transit in the late 1980s (Department of Transport, 2009). Both Van der Meulen (2010) and the Department of Transport (2017) concur that the railway industry is driven by increasing speed, escalating axle load and extending train lengths. Standard gauge railway trumps narrow gauge railway in all these sectors and as a result, African countries have begun their conversion to standard gauge railway.

Spain decided to convert its broad gauge network to standard gauge over a 40-year period in order to limit capital expenditure each year (Rail Road Association, 2008). Japan's narrow gauge network remains the backbone of their railway operation and the narrow gauge passenger trains carry more passengers than the high-speed standard gauge passenger line constructed in 1964 (Department of Transport, 2017). Japan's use of narrow gauge gives rise to the argument that narrow gauge railway can be successful in a world dominated by standard gauge.

2.5.4 NATMAP 2050 Report Findings

The Department of Transport (2009) compiled the NATMAP 2050 report which evaluated South Africa's railway network and a few options available to the country regarding railway gauge. The report provided the following recommendations:

- A long-term masterplan should be compiled which optimally uses standard gauge interventions with the master plan's network to be much smaller than the current core network;

- The masterplan should be viewed as a step-by-step mitigation strategy to introduce standard gauge railway with only viable and economically feasible standard gauge options constructed;
- The large-scale conversion of narrow to standard gauge is not economically feasible, therefore, the current core network should be used to its maximum potential but is should be understood that it may shrink with time as other transport modes increase in competitiveness and as the standard gauge network grows;
- View gauge conversion as a strategic approach to improving operations and see dual gauge overlaps between neighbouring countries as results of the strategy, and
- Apply the African Union's standard gauge resolution to new railway lines where it makes economic sense.

The report investigated the costs and implications of constructing the ensuing projects; a high speed passenger railway line between Johannesburg and Durban, similar to the TGV in France, a passenger railway line along the Moloto corridor where narrow and standard gauge options were compared, converting the entire network to standard gauge and lastly, a notional study was conducted in order to view the differences between narrow and standard gauge projects in the heavy haul context (Department of Transport, 2009).

The results of the notional heavy haul line indicate that standard gauge railway is more expensive to construct however, cheaper rolling stock and superior operations result in standard gauge railway being 5.9 % cheaper than a narrow gauge railway line (Department of Transport, 2009). It was also noted that the maintenance costs per kilometre are similar for the following reasons: a standard gauge sleeper provides a wider footprint, but will carry larger axle loads in this scenario, therefore, maintenance costs approach R 270,000 per km per annum for both gauges (Department of Transport, 2009).

The Department of Transport's (2009) perspective on the advantages of standard over narrow gauge are as follows:

- Standard gauge rail is ~32 % wider than narrow gauge which allows trains to have greater stability and are also able to travel at greater speeds on the track,

- The ~32 % greater stability of standard gauge rail allows the maximum permissible centre of gravity to be ~32 % higher which enables double stacking of container freight to be performed,
- The wider standard gauge allows for taller and wider vehicle profiles than narrow gauge. Although it is possible to build similar sized narrow gauge vehicles, existing structures would not allow for this since they were built to the original narrow gauge railway line standards,
- The majority of the global research and development is performed in standard gauge countries such as China and The United States of America making standard gauge more competitive,
- Standard gauge locomotives are cheaper per kN of force that they deliver when compared to narrow gauge ones, and
- Formation stresses are reduced in standard gauge railways due to a longer sleeper being used which increases the bearing area of the sleeper.

2.6 RAILWAY INFRASTRUCTURE AND ROLLING STOCK COSTS

Railway infrastructure has a high cost attached to it due to the need for accurate track alignment, smooth geometry and manageable gradients for the trains operating the line. This may require tunnelling in steep topographies or bridge construction to traverse rivers and deep valleys. Lombard (2017) indicates that design parameters such as ruling grade, gauge, locomotive type, curve radii and axle loading will affect the long-term economic life of a railway project. Locomotives are unique pieces of machinery and are bought in large numbers by railway operators and must be coupled to various wagon types.

2.6.1 Bridge, Tunnel and Track Structure Costs

Railways are built incorporating the physical track, bridges to cross rivers and tunnels to avoid steep terrain. The construction of these structures is some of the most expensive in the transportation infrastructure industry.

The construction of a standard gauge network or line would lead to breaks-of-gauge within South Africa and the neighbouring countries. The Department of Transport (2009) indicates that the following solutions are available for use in the break-of-gauge conundrum:

- Transhipment;
- Bogie changing;
- Variable gauge wheel sets, and
- Dual gauge track.

The determination of the cost per kilometre to construct a tunnel was also obtained from literature where various tunnelling projects were compared in order to determine the cost per m of a tunnelling project as a function of the bore diameter (Rostami et al., 2013). Figure 2-9 illustrates the unit cost in k$/m of tunnel as a function of bore diameter for different subway tunnel types.

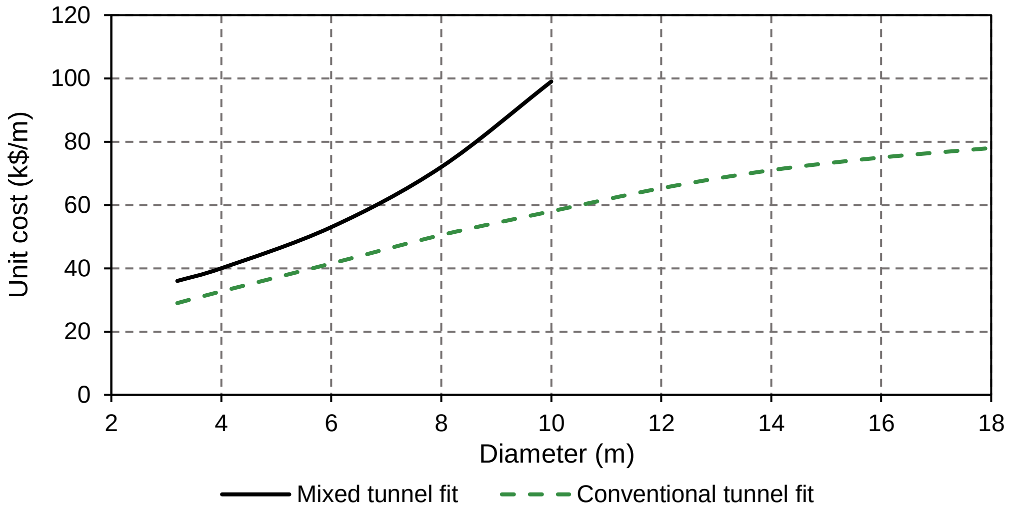


Figure 2-9: Unit cost vs. diameter for conventional and mixed ground subway tunnels (redrawn from Rostami et al. (2013))

Transnet (2017) published the costs of constructing a recent project between Ermelo and Majuba. The Department of Transport (2009) and Lombard (2017) indicate that the cost to construct a standard gauge railway track is in the range of 7 % more than constructing a narrow gauge railway track. Hadi et al. (2016) conducted a study reviewing the cost to construct railway bridges. This amount per m of railway bridge is approximately double the cost of conventional railway track per m.

2.6.2 Rolling Stock Costs

Rolling stock varies based on the intended function of the equipment. The order value and size will also affect the discount rate offered by the producer.

Railway Gazette (2018) provides recent rolling stock purchases and indicates that rolling stock prices vary from country to country depending on the rolling stock's purpose. Recent South African locomotives have been estimated to cost R 41 million for an electric and R 32 million for a diesel locomotive (Creamer, 2014).

Wagons have many contrasting functions depending on the commodity they are transporting therefore, their prices can vary from one another. The simpler wagons used by Transnet cost R 1.2 million and the more sophisticated wagons cost R 2.5 million per unit. A simpler wagon would be a flatbed, used in container operations and a more sophisticated wagon would be a tanker or gondola tipper coal wagon (Transnet, 2018). The type of a gauge a wagon will operate on does not have a major influence on the wagon's price (Lombard, 2017).

2.6.3 Railway Operating Costs

The operating costs are variable and dependant on the line density, line utilisation and tonnes moved on the line. Harris (1977) developed a relationship between operational cost and density on a line which displayed that the greater the density the lower the operating costs. This relationship can be used to determine operating costs as line utilisation increases with time due to increasing demand.

Havenga et al. (2012) utilised this relationship postulated by Harris (1977) to determine operating costs of rail operations in order to identify the cost differences between motor and rail trasnport. Havenga et al. (2012) was also able to establish the externality costs associated with each of the transport modes.

2.6.4 Railway Revenue Calculation

In the railway industry, revenue is generated through the transportation of commodities on railway networks. Transnet (2018) stated that a commodity volume growth of 3.3 % was obtained despite a low GDP growth and lower than predicted commodity prices.

The year 2018 saw Transnet accumulate R 43,709 million in revenue from the following sectors:

- General freight generating R 23,586 million;
- Export coal generating R 12,022 million;
- Iron ore export generated R 6,314 million, and
- Other commodities generated R 1,788 million.

Transnet (2018) indicates that the Coal line and the Iron ore line generates R 0.279 per tonne-kilometre and R 0.122 per tonne-kilometre respectively. The rate to transport one tonne of a commodity collected from TFR in 2017 indicates that TFR generates on average R174.95 per tonne of freight transported , however, this value changes depending on the type of freight transported and the origin and destination of the order (Transnet, 2017). For the 2018 fiscal year, Transnet was able to increase the average rate to R 186.75 per tonne which was attributed to an increase in the average Consumer Price Index (CPI).

2.7 INFRASTRUCTURE ALTERNATIVE EVALUATION METHODS

Various techniques for comparing infrastructure projects exist. It is therefore important to evaluate the relevant techniques. Each method will have its own limitations and benefits over the others. It is likely that a combination of the various methods will be most effective for the purposes of this research.

Rostami et al. (2013) indicate that construction projects have a high level of risk attached to them due to unforeseen conditions in the natural environment. This is therefore the main reason for the use of high contingency factors on top of the estimated construction costs. Choosing the best alternative may simply be a matter of determining which alternative best meets the selection criterion (Newnan et al., 2004).

Remer & Nieto (1995) presented 25 different methods to evaluate economic desirability in projects. These 25 methods were categorised into the following 5 types:

- Net present value methods;
- Rate of return methods;
- Ratio methods;
- Payback methods, and
- Accounting methods.

Payback methods and accounting methods were not utilised for this study and have not been discussed further. Remer & Nieto (1995) defined economic evaluation steps to be followed for project evaluation. The economic evaluation steps allow for a project to be fairly evaluated given the other alternatives presented for a project.

Table 2-1 serves as a summary of economic terms and factors used for evaluation. Money has a time value (Merino, 1993). This implies that the same sum of money in 1995 will not have the same value in 2015 due to economic growth, inflation and other similar factors.

Table 2-1: Summary of economic evaluation factors (adapted from Remer & Nieto (1995))

Factor name	***Formula***	***Notation***	***Solves for***	***Given***
Single-payment, present worth	$P = F[\frac{1}{(1+i)^n}]$	$(P/F, i\,\%, n)$	Present worth	Future worth
Single-payment, compound amount	$F = P(1+i)^n$	$(F/P, i\,\%, n)$	Future worth	Present worth

Remer & Nieto (1995) indicate that when using any project evaluation method, there are three analysis-period situations which could be considered which include:

1. The useful life of each alternative equals the analysis period;
2. The alternatives have differing useful lives from the analysis period, and
3. Analysing the project with an infinite analysis period.

2.7.1 Net Present Value Methods

Net present value methods include present worth, future worth, annual worth and capitalised worth. The most popular evaluation methods used are the net present value criterion methods, the internal rate of return method, the external rate of return method, return on investment method, benefit/cost method and payback period method. However, a shift in the 1990s from the use of internal rate of return method to present value criterion methods was noted (Remer & Nieto, 1995).

The net present value criterion can be broken up into four subtopics which includes present worth method, future worth method, annual worth method and the capitalised worth method (Remer & Nieto, 1995). The present worth method evaluates a project over a given period and relates the total cost to one present date equivalent value (Žižlavský, 2014). The future worth method alternatively, resolves the cash flow of a project to one cash flow at a future date.

An assumption made by the net present value methods is whenever using any of the equivalence methods is that all cash flows received from a project are reinvested at the same fixed rate used to calculate the equivalent worth's (Blank & Tarquin, 1989). This rate is typically referred to as the Minimum Attractive Rate of Return (MARR).

2.7.2 Rate of Return Methods

The rate of return methods include the Internal Rate of Return (IRR) method, the External Rate of Return (ERR) method and the Growth Rate of Return (GRR) method. The IRR method will be further discussed.

IRR is a measure of investment worth which calculates the interest rate for which the present worth of a project equals zero with the term internal indicating the it only considers internal factors unlike the MARR (Park & Sharp-Bette, 1990). The criteria for accepting or rejecting a project depends on the MARR despite the MARR not being incorporated in the calculations. If the calculated IRR or discount rate, i_d, is greater than the MARR, i_m, the project is acceptable, if the IRR equals the MARR, the investor remains indifferent and if the IRR is less than the MARR the project is rejected (Remer & Nieto, 1995). The MARR is typically specified by the client.

2.7.3 Ratio Methods

Ratio methods can be broken down into six methods which include cost effectiveness, savings-to-investment ratio, profit-to-investment ratio, benefit/cost ratio, return on investment and premium worth percentage. Only the benefit/cost ratio shall be elaborated on in this sub-section.

The benefit/cost ratio method was introduced in the 1930s in order to evaluate various project proposals (Au & Au, 1992). As long as a monetary value can be attached to the benefits, the method provides simple results. A project is viewed negatively if the proposed project results in a reduction of the benefits or similarly, if the ratio is less than 1 (Remer & Nieto, 1995).

2.8 THE SIMULATION OF RAILWAYS

Simulation is the imitation of the operation of the real-world process or system over time therefore it generates artificial history of a system (Banks et al., 2005). The observation of that artificial history is used to infer on the operating characteristics of the real system.

Simulation can incorporate system dynamics, discrete event modelling as well as agent-based modelling. System dynamics evaluates the dynamic behaviour of various systems such as mechanical, fluid or thermal entities which are described by differential equations (Lobontiu, 2010). A discrete system involves the change of state only at discrete points in time which are called events, whose chronological sequence describes the behaviour of that system (Ostermann et al., 2010). Agent-based modelling is comprised of interacting autonomous agents where an agent is any type of independent component or element (Macal & North, 2006).

Marinov et al. (2013) indicate that rail operations are broken up into dynamic and static resources. Static resources include the track structure, signals, platforms, buildings, catenary and bridges while dynamic resources include all moving assets such as passenger and freight wagons, train sets, locomotives and maintenance machines.

Simulations are performed at different levels of detail which includes microscopic, mesoscopic, and macroscopic models. As the model increases in size, the amount of model detail will be reduced however, largescale microsimulation is beginning to be implemented as more advances in computer hardware are made (Alvarez & Alonso, 2018).

2.8.1 Simulation Setup Methodology

Train movement on a double track can be related to car movement on a two-lane freeway however, trains experience delays due to junctions and crossings which can hold up other trains on the network (Dessouky & Leachman, 1995). The reduction of this delay is the optimisation of the operation of the network.

Dessouky & Leachman (1995) state that a method of analysing delay on a network is using a G/D/1 Queue. It unfortunately was limited by the fact that it analysed the track independently and did not consider the rest of the network's interaction.

Rail networks are usually made of a combination of double and single-track railway lines. Marinov & Viegas (2011) utilised work centres and storage areas to build up a simulation rail network model. The work centres replicated the operation process of freight trains and was characterised with inbound traffic, service patterns and outbound traffic. The storage areas consisted of attributes used to replicate where the freight trains were held while waiting to be processed on various sections of the rail network.

Dessouky & Leachman (1995) state that the characteristics and assumptions of a double-track rail network model are as follows:

1. Each train has a unique route which uses a certain section of a network;
2. The headway from the front of one train to the back of a leading train is one train length;

3. Trains travelling on a rail network have varying lengths and acceleration rates, and
4. The maximum speed of a train depends on the track section.

The assumptions govern the simulation model setup and lead to a realistic evaluation of a railway corridor or network through the addition of randomness.

Yang et al. (2014) utilised AnyLogic to conduct a study on a railway station in China. The use of the pedestrain, enterprise and rail yard libraries allowed for a complex system to be designed were, peak and off-peak situations could be simulated and analysed.

Marinov & Viegas (2011) indicate that time-dependant distributions are useful for modelling systems that do not reach a steady state, such as freight trains running on a schedule. When initating a model it is important to note that there is a transient period where the model does not have entities in certain states due to the model starting in an intially empty state. Marino & Viegas (2011) state that a warm-up period is required to avoid bias in the results as a result of this intially empty system.

2.8.2 Simulation Model Calibration and Validation

Simulation models vary in detail therefore, the amount of data inputs vary proportionately. Data inputs may be static such as geometry or dynamic, namely demand or orders. Data inputs can either be measure directly or if the inputs are unknown, they will need to be calibrated (Koutsopoulos & Wang, 2007).

Koutsopoulos & Wang (2006) proposed a systematic approach to the calibration of rail simulation models and indicated that simulation models can benefit from track occupancy data.

Koutsopoulos & Wang (2007) state that the application of rail simulation models requires the following steps:

- Input data preparation and calibration of unknown inputs and model parameters;
- Validation;
- Evaluation methodologies and scenarios, and
- Output analysis and interpretation of results.

Jobanputra & Vanderschuren (2012) utilised a confidence interval, with a 90 % confidence level, to ensure the model outputs fell within an acceptable range. Koutsopoulos & Wang (2006) considered the calibration process to be an optimisation exercise with the objective of reducing the error difference between the simulated and observed values. Hourdakis et al. (2003) used a heuristic search optimisation method to calibrate a microscopic simulation model. The network volume was used as the single parameter for calibration of the model and a Root Mean Square Percentage Error (RMSPE) was used to calculate the difference between the observed and simulated values which was similarly used by Balakrishna et al. (2007). Kim et al. (2005) calibrated a microsimulation model using the network travel time and optimised the procedure with the use of a genetic algorithm. The Mean Absolute Error Ratio (MAER) was used to evaluate the differences between the simulated and observed values. Balakrishna et al. (2007) utilised volumes counts during multi-criteria parameter calibration of a microscopic simulation model.

Validation refers to the process of examining the extent to which a simulation model reproduces reality (Toledo & Koutsopoulos, 2004). This would be best performed when the real and simulated systems are fed identical inputs however, this is not possible. Validation is typically based on a set of performance measures that are statically relevant to the study such as time in a yard or headway distributions. Validation can be performed either visually or statistically where visually would be through the analysis of plots. Statistical approaches use summary statistics or goodness-of-fit measures.

Simulation models output requires proper analysis therefore, measures of performance should be calculated from several independent replications (Koutsopoulos & Wang, 2006). A single run may lead to an erroneous conclusion especially if the underlying distribution has a large variance (Law & Kelton, 2000).

Figure 2-10 displays a simulation models architecture postulated by Koutsopoulos & Wang (2007) that displays a simulation models inputs, scenarios, operating strategies and outputs. The main inputs have been summarised in the figure with each input having a further set of inputs and parameters required such as various the rolling stock characteristics or depot spacing. The operational strategies represent the real-time control operations aiming at service restoration. The simulation outputs a large set of performance measures relating to the simulation operations.

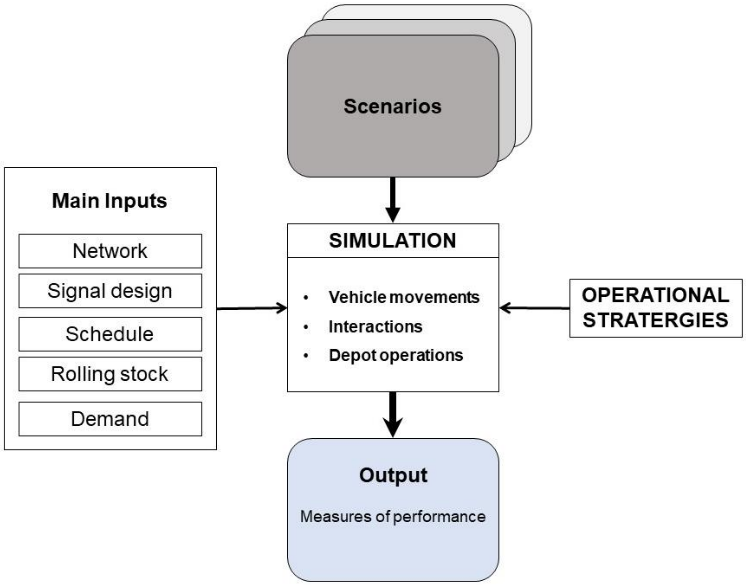


Figure 2-10: Architecture of a simulation model (redrawn from Koutsopoulos & Wang (2007))

Optimisation of a railway system involves the optimisation of an objective function. Heuristic methods were used by Song & Irving (2001) and Mazzarello & Ottaviani (2007).

2.8.3 Yard Simulation

Freight rail terminals receive trains, regroup or classify railcars and construct outbound trains (Lin & Cheng, 2011). Terminals have two forms which include hump yards, which use gravity to sort railcars, and flat switching yards. Lin & Cheng (2009) developed a yard simulation framework with the purpose of optimising yard operations.

Typically rail freight operators practice either improvised operations or scheduled operations. They are the general philosophies of railroad operation (Pachl & White, 2003). Improvised operation entails only running a train when there are enough wagons to make up a full train however, this does not lead to good customer satisfaction. Scheduled operation requires freight trains to be as reliable as passenger trains however, trains may be forced to run at reduced formations (Marinov & Viegas, 2011). Depending on the line and the commodity being transported this will vary.

Classification yards are highly complex however, the simulation of terminal models can assist in identifying bottlenecks, car delays and process improvement (Lin & Cheng, 2009).

Lin et al. (2012) utilised a set of functions to define train movements along a corridor and applied an energy function to optimise the cost savings. One of the main objectives of the functions was to use the yards available which resulted in the least amount of train reshuffling. The optimisation of this operation led to large time savings which were converted into cost savings.

Muñuzuri et al. (2016) states that the movement of trains within an intermodal terminal can be a complex planning problem that can lead to bottlenecking and suboptimal solutions. A back tracking algorithm was used to allocate destination sections to inbound trains as well as to outbound trains in cases were there was more than one access point to the terminal's network.

In rail transportation, a commodity may have to pass through many yards before it reaches its final destination. For this reason, car blocking is used whereby groups of cars are classified together to avoid awkward train reclassification in the yards preceding the final destination of the car block (Yaghini & Akhavan, 2012).

2.8.4 Corridor Simulation

A corridor is made up of track sections, yards and junctions with the aim of delivering commodities from and origin to a destination. Dessouky & Leachman (1995) indicate that a good method of evaluating railway alternatives is through the use of simulation which focusses on the difference in total delay accumualted in an alternative and a proposed status quo alternative.

Transporting goods along a corridor will involve stopping at various stations in order to make deliveries. Lin et al. (2012) indicates that this process can become very complex along a corridor due to the issue of Train Connecting Services (TCS).

Keaton (1989) used Lagrange relaxtion in solving large network problems despite restricting the number of routes of each demand to only one. Thomet (1971) addressed the TCS issue through the development of a cancellation procedure which gradually replaced direct shipments with a series of intermediate train connections with the purpose of minimising operation and delay costs. Crainic & Rousseau (1986) used a heuristic method to solve a network that considered non-linear terms associated to congestion effects.

Sogin et al. (2013) indicated that the addition of passenger trains to single track freight railway lines can cause up to double the average delay depending on the traffic mix. Sogin et al. (2013) simulated a single line railway with sidings every 24 km and were able to transport up to 40 trains per day with 0 passenger train trips per day.

2.9 SUMMARY

The literature presented provides a summative overview on the topics of railway gauge in Africa, railway project costs, infrastructure evaluation methods and railway simulation methodologies. Section 2.1 described the early South African government’s decision to standardise narrow gauge due to the topography of the country’s landscape. Studies and reviews conducted by Cottrel (2010) and Transnet (2010) provided insights into how the network grew with time and highlighted key milestones in the 20th century.

Section 2.2 described the economic future of South Africa and the expected growth rates for the period between 2015 and 2045. The slow GDP growth post 2012 was evaluated and likely investment opportunities were discussed. The section also reviewed the economic effects road has had on the rail network and discussed the impacts of the deregulation of road transportation in 1988.

The core network of South Africa was evaluated in section 2.3 with the following being noted:

- Much of the core line requires maintenance interventions while the other areas are approaching the end of their design lives, and
- The network is underutilised with only moderate traffic being experienced by the major railway corridors.

Section 2.4 summarised the main corridors and systems operated by Transnet. The overview indicates that the Coal line and Iron ore line are operating effectively and efficiently however, the other systems evaluated require various upgrades in order to improve operations which has been noted by Transnet (2016).

Some of the ideas proposed by the Department of Transport (2017) were discussed in section 2.5. The NATMAP 2050 paper went into a large amount of detail regarding a plan that proposes the need for standard gauge railway line intervention. A timeline was also compiled that discussed when certain infrastructure should be constructed by and was supplemented by a map indicating the potential future of the core network.

The recommendations of the Department of Transport's (2009) NATMAP 2050 will be used to guide the study.

Section 2.6 assessed the infrastructure and rolling stock costs associated with railways. Rolling stock was found to be highly versatile with many different locomotives and wagons being used in the numerous transportation operations performed by railways. The section also established that infrastructure costs are dependent on many factors however, the literature reviewed was able to provide rates per kilometre of railway track, bridges and tunnels.

Section 2.7 reviewed the two-part papers presented by Remer & Nieto (1995) that discussed project evaluation methods. The relevant methods were discussed and reviewed so that the appropriate method of evaluating infrastructure projects could be utilised in the study.

Section 2.8 critiqued the various railway simulation modelling methodologies. Koutsopoulos & Wang (2007) presented methods to calibrate and validate models to ensure that models provide accurate and reliable results. It was also noted that a heuristic search method can be used in railway optimisation of a specified objective function. Lin & Cheng (2009) presented a paper which evaluated yard simulation challenges and developed a model to optimise rail yard operations. Lin et al. (2012) evaluated the issue of TCS and how to develop a model which optimised the operation of processing train orders along a corridor with the aim of reducing costs.

3 METHODOLOGY

This chapter discusses the method by which corridors were identified that could potentially benefit from standard gauge interventions. This includes the analysis of the commodity growth on the line over a period as well as its projected growth forecasts. The chapter progresses with the review and identification of the various relevant standard gauge intervention alternatives for each corridor.

The chapter also assesses how the project will be evaluated through the use of various economic evaluation methods that have been described by Remer & Nieto (1995). A method of determining the interventions' impacts on operations and the economic effects will be proposed. Information was made available by TFR for each of the railway corridors within South Africa through the LTPF and the MDS.

The chapter ends with the establishment of a method of simulating the various gauge intervention options which includes simulation modelling performed using AnyLogic. The method of validation and calibration of the model is also described, closely following the method presented by Koutsopoulos & Wang (2007).

Figure 3-1 displays the summary of the methodology for analysing a railway project. The procedure displayed was followed for the analysis of each of the corridors.

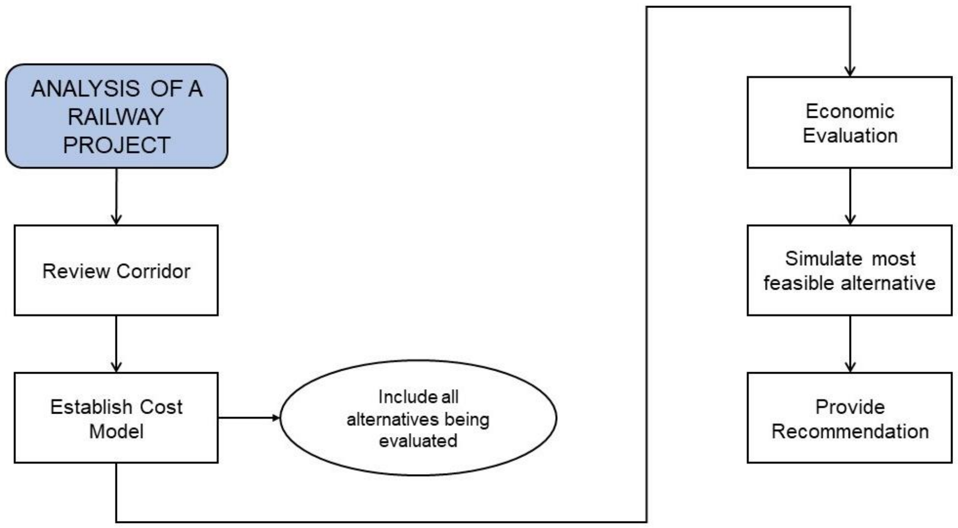


Figure 3-1: Summary of the methodology for analysing a railway project

3.1 IDENTIFICATION OF CORRIDORS FOR INTERVENTION

The South African core railway corridors carry the bulk of the commodity volumes of the rail system. For this study it is important to identify which lines, in the long and short-term, will best benefit from a standard gauge intervention. A method of evaluating a railway corridor was established which required various operational and predicted growth rate information. The following sub-sections indicate the reasoning for the inclusion of specific factors in the review of a railway corridor.

Figure 3-2 displays the principal factors used to determine how a corridor was performing and provided a general overview of the corridor. To effectively understand a railway corridor, the annual tonnage must be determined, the expected growth on the railway corridor and the condition of the corridor should then be evaluated before the capacity of the corridor is reviewed.

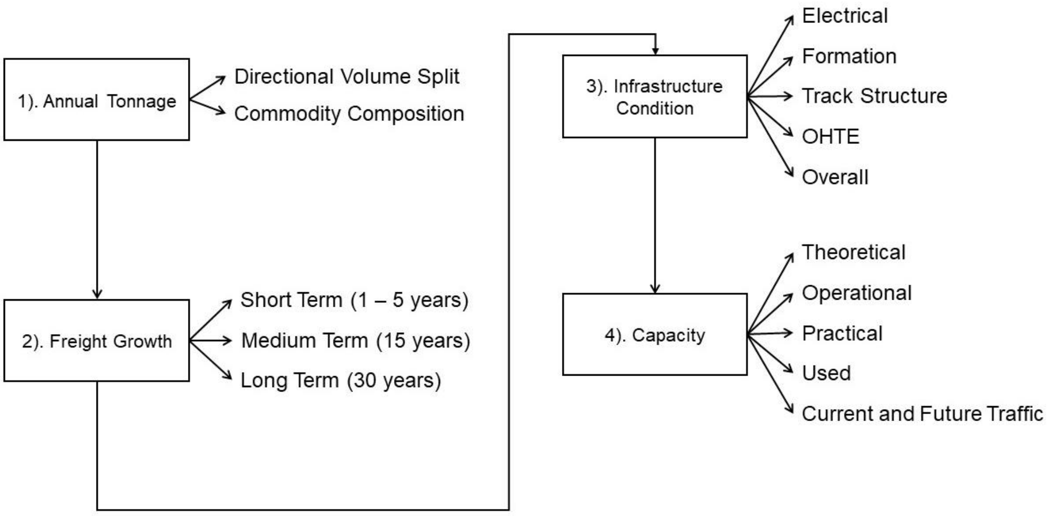


Figure 3-2: Method of reviewing a railway corridor

3.1.1 Annual Tonnage for a Corridor

Corridors which do not transport enough commodities will not be able to cover the costs of constructing new infrastructure. These corridors would require further investigation and would most likely proceed with the plans proposed in the MDS. The annual tonnage is the key driver of revenue generation along a corridor.

Figure 3-3 displays the present worth of hypothetical railway corridors to evaluate whether a corridor would have a positive or negative present worth if a narrow to standard gauge conversion was implemented. The calculation was influenced by the amount of tonnage transported per year for a 30-year analysis period on corridors of varying length. The present worth reduces as the line length increases due to increased capital expenditure of the associated infrastructure for the same amount of tonnage being transported. This allows corridors in the core network to be evaluated by comparing their expected tonnage transported per year and line length of the corridor with the information in the figure. The present worth could then be estimated from the figure. For example, a corridor that transports 50 mtpa and is 400 km in length would be expected to have a present worth of approximately R 200,000 million if it was converted to standard gauge.

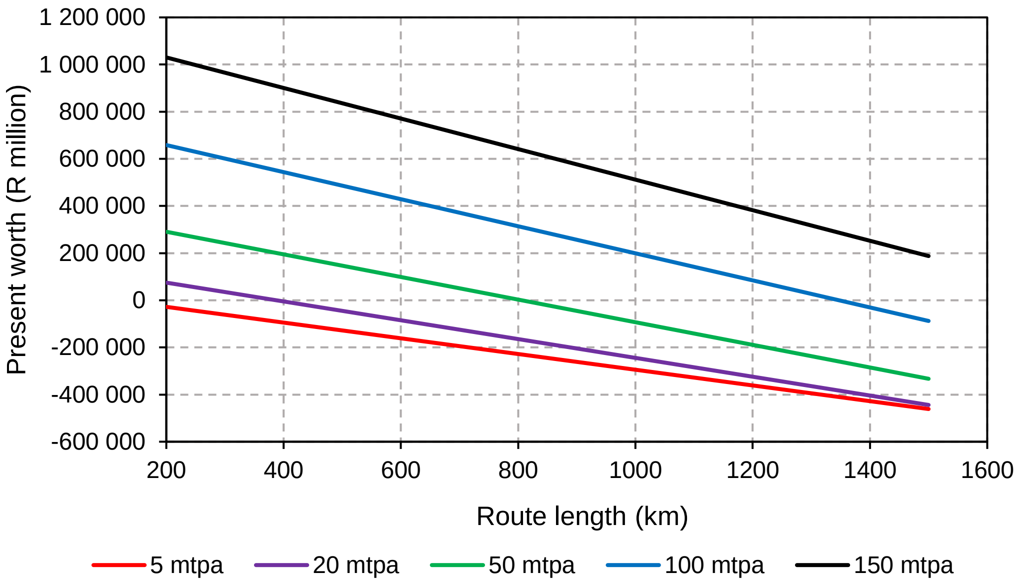


Figure 3-3: Narrow gauge to standard gauge conversion project evaluation for a 30 year analysis period and 2.5 % discount rate

Hudson et al. (1997) indicates that the discount rate is the interest rate less the inflation rate ultimately giving the true return of the investment.

3.1.2 Tonnage Growth

Transnet (2016) indicates that the key driver of freight growth is GDP and as a result stated that South Africa is likely to experience the following forecasted freight growth rates per annum:

- Likely scenario: 3.0 %;

- High scenario: 4.1 %, and
- Low scenario: 2.1 %.

These growth rates may vary from year to year depending on the economic situation within South Africa. It was therefore important to conduct a sensitivity analysis on the growth rates so that the best alternative was selected (Remer & Nieto, 1995). The growth rate of the freight volumes has a direct effect on the supply required to transport commodities. If enough supply is not made available, rail is likely to lose more market share to road transportation.

3.1.3 Infrastructure Condition

The condition of the infrastructure on a rail corridor is a good indicator of when maintenance or upgrades are likely to take place as well as to what level this will be required to be done at. From the review of the key corridors within South Africa it could be observed that there was old technology and aging infrastructure present in some of the corridors. This includes old communication systems, dated 3 kV DC electrification and formations in poor condition. Transnet (2016) provided a summary of the network condition which could be used to identify which lines would require maintenance or an upgrade.

The current established condition of a corridor, which may experience growth in the future, with poor infrastructure condition may add to the argument that the next step is to intervene using a standard gauge alternative. If major disruptions are set to take place on a line in any case, then it is worthwhile considering a standard gauge upgrade or conversion option.

3.1.4 Line Capacity

Corridors typically transport more freight in one direction compared to the other. The Ore and Coal lines are mainly used for exporting the two commodities respectively, however, the Natal corridor transports containers evenly in both directions (Transnet, 2016).

The practical capacity utilisation, which is 65 % of the theoretical capacity, could be used to assess how congested a corridor was and if it had capacity available to meet demand increases on the corridor over time (Transnet, 2016). The practical capacity utilisation was used to evaluate how long a line would be able to operate before upgrades are due.

3.2 ECONOMIC EVALUATION OF RAILWAY PROJECTS

The ultimate determining factor whether an alternative can be selected is the cost that is associated with the alternative compared to the base case. Transnet's (2016) MDS has already scheduled various upgrades and was evaluated as a base case for economic evaluation of the other alternatives. If any of the alternatives economically outperformed the base case, then they were deemed to be more beneficial than the base case. The most beneficial alternative standard gauge case was selected to be simulated.

The economic evaluation of each of the projects was conducted using the following procedure provided in Table 3-1 which was adapted from Remer & Nieto (1995):

Table 3-1: Economic evaluation steps for railway projects (adapted from Remer & Nieto (1995))

Step	*Description*
1	Define a set of railway investment projects for consideration for the corridor
2	Establish the analysis period for the economic study
3	Estimate the cash flow profile for each railway project
4	Specify the time value of money, discount rate
5	Examine the objective and establish criteria to measure effectiveness
6	Apply the relevant project evaluation technique(s)
7	Compare each project proposal for preliminary acceptance or rejection
8	Perform sensitivity analysis
9	Accept or reject a proposal on the basis of established criteria

3.2.1 Cost Model

To determine whether a line would benefit from a standard gauge intervention, an economic method of evaluation was used over the life of the project.

A base comparison case was selected (Stanford University, 2005). It was decided that the MDS plans proposed by Transnet should be used as the base for all analysis. All interventions were compared to the MDS investment plan to determine which investment would provide the greatest benefit. Benefits include increased profitability, increased line capacity to meet long term traffic demands, infrastructure condition improvements and improved rolling stock condition. However, the main criteria used was the comparison of the various project's profitability. For each analysis the number of tonnes transported was kept the same even if the standard gauge intervention allowed the corridor to be able to transport additional freight. A sensitivity analysis was conducted on the freight growth rate since there is a lot of uncertainty associated with the future freight demands of the country. It was used to observe whether a low freight growth rate would lead to a negative present worth for each of the analysis for the specific corridor.

Table 3-2 displays the assumptions made so that the magnitude of implementing a standard gauge intervention could be estimated.

Table 3-2: Assumptions made in economic calculations (Department of Transport (2009), Lombard (2017), UIC (2017) and Joubert et al. (2001))

Item	*Assumption*
Axle loads	Axle loads would vary depending on the alternative selected for the section.
Bridges	Bridges would not require any changes except for older narrower steel bridges. Allowance must be made for road-over-rail bridges.
Contingencies	All construction projects were assumed to have 10 % contingencies attached to them.
Curvature	For line upgrades, would remain as before but may change for new lines.
Double line centres	Double lines would remain at 4.00 m centres for line upgrades.
Earthworks	For upgrades, banks and formations would be widened on both sides and culverts would be extended.
Electrification	Standard gauge locomotives would require 25 kV AC electrification.
Horizontal clearance	For line upgrades would require widening since standard gauge track is 200 mm wider.
Horizontal curves	Horizontal curves were not made sharper than 500 m for standard gauge interventions. High speed rail requires a curve radius of between 2,500 m and 5,500 m.
Ruling grades	For line upgrades would remain as before. For new lines, the ruling grade was selected as 1:100. This allows for 38 wagons to be hauled per locomotive that output 4540 kW of power at 454 kN of continuous tractive effort. High speed passenger trains were restricted to maximum grades of 1:65 for mixed traffic instances.
Signalling	If a third rail was implemented, major upgrades would be required.
Line speed	Maximum speed would remain at 80 km/h for freight haul. High speed rail speed was set at 250 km/h and speed restrictions were implemented on tight curve sections.
Track centres in yards	Yard centres for upgrades would remain the same as currently for narrow gauge lines.
Tunnels	Increased vertical and horizontal clearances were required for tunnels if upgrades were proposed.
Vertical clearance	Vertical clearance would need to be adjusted if double stacking was considered on the line.
Vertical curve radius	Vertical curves are designed as a function of line speeds using $R_V = 0.39 \cdot V^2$, where V is in km/h. For line speeds of 250 km/h R_V ~ 25,000 m and for line speeds of 80 km/h R_V ~ 2,500 m. Speed restrictions could be implemented for high speed passenger trains.

Figure 3-4 describes the methodology used to setup the cost model, which was used to evaluate each of the alternatives for a corridor. The base case and the alternatives were all evaluated in the same manner to allow for simple comparison between all the cases.

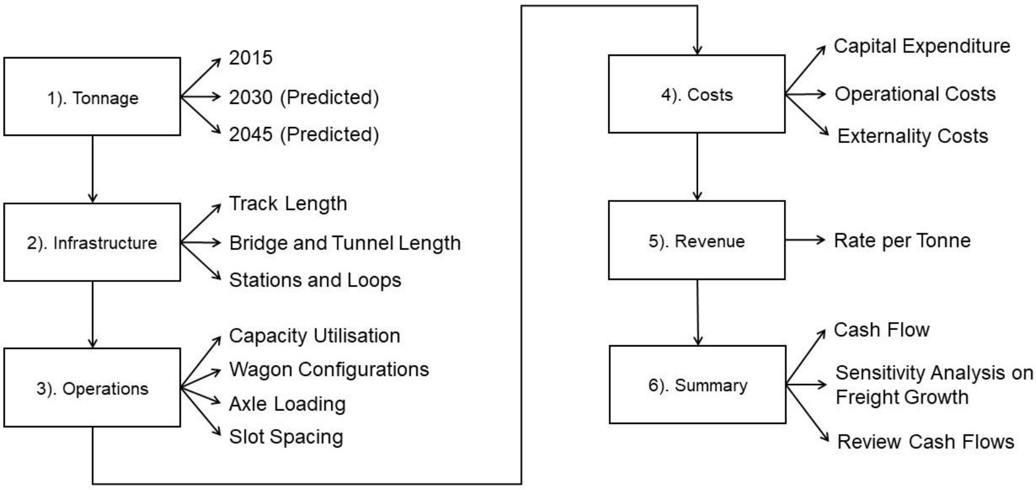


Figure 3-4: Cost model setup for evaluation of a railway investment

3.2.2 Revenue

Revenue could be determined with Equation 3.2 which incorporates the average rate per tonne, r, and the effect the discount rate will have on the future value using the future value formula (Remer & Nieto, 1995). The number of tonnes transported along the corridor, t_{total}, is then multiplied to obtain the revenue generated along the line. Stats SA (2019) indicates that South Africa has maintained an inflation rate of 4.5 % per annum since 2010 which was selected as the inflation rate, i_r. The interest rate, i_{ir}, was selected to be 7 % (South African Reserve Bank, 2019). The discount rate, i_d, is equal to the interest rate less the inflation rate and is considered to be the true return of an investment (Hudson et al., 1997).

$$Revenue = (r)(\,t_{total})(1 + i_d)^n \tag{3.2}$$

Where:

r = average rate per tonne (R/tonne)

i_d = discount rate, 2.5 %

n = analysis period in years

t_{total} = total number of tonnes transported during the analysis period

3.2.3 Costs

Costs were broken down into capital expenditure (CAPEX), operational and rolling stock costs. Maintenance was assumed to be equivalent for all operations which was the same assumption made by the Department of Transport (2009) and Lombard (2017). The capital expenditure costs consist of bridge, tunnel, track, control systems, communications and OHTE construction. Track, control system, communications and OHTE were all grouped under track.

Table 3-3 displays the infrastructure costs per kilometre that were used in determining the cost of the various alternatives. The cost of constructing the railway track was obtained from a recent project completed by Transnet (2017) and Lombard (2017). The cost of constructing a railway bridge was obtained from a study conducted on numerous bridge construction projects by Hadi et al. (2016). The study determined an average R per m to construct a bridge. The rate per m of tunnel is related to the tunnel's bore diameter. These rates were collected from a study conducted by Rostami et al. (2013). Table 3-3 indicates that standard gauge has a premium of R 3.8 million per kilometre over narrow gauge on a single line and R 7.6 million per kilometre on a double line.

Table 3-3: Infrastructure costs per kilometre (Transnet (2017), Lombard (2017), Rostami et al. (2013), Joubert et al. (2001) and Hadi et al. (2016))

Infrastructure type	*Rate (R million/km)*	
	Narrow gauge	*Standard gauge*
Single Track Ballast	62.0	65.8
Double Track Ballast	124.0	131.6
Bridge Single Track	73.8	83.9
Bridge Double Track	147.7	167.9
Tunnel Single Track	472.2	512.6
Tunnel Double Track	944.3	1,073.7

Figure 3-5 displays the relationship used to calculate the operational costs per track kilometer (Harris, 1977). The density is calculated by dividing the tonne track kilometers by the route kilometers.

Included in the operational costs was an externality cost that accounts for rail's impact on the environment. This factor calculated by Havenga (2012) and Department of Environmental Affairs (2014) came to R 0.0129/tonne-km. Vandoorne (2017) indicates that an increase in tonnage leads to increased uncertainty in the total life cycle costs of performing maintenace. For 200 million gross tonnes per annum a rate of R 19,000 /million gross tonne/km can be expected for maintenance activities.

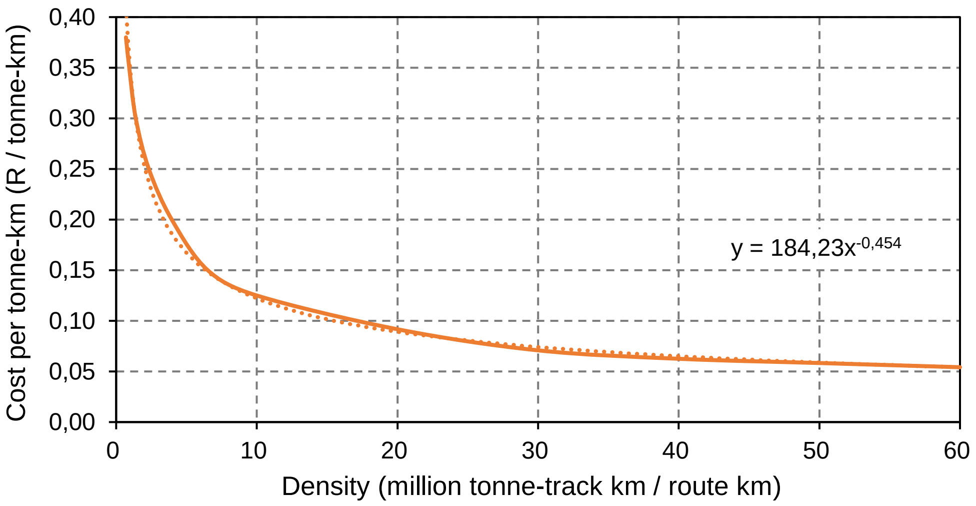


Figure 3-5: Intermodal density change on the Harris curve due to density-driven savings (redrawn from Harris (1977))

The operating costs obtained from Transnet's Integrated Report from 2017 for the Natal Corridor was used to verify the Harris relationship. Transnet (2017) indicated that their operating costs amounted to R 2,621 billion and the Harris relationship calculated the operating costs for the year to be R 2,764 billion which is a difference of 5.5 %.

Table 3-4 summarises the prices of diesel and electric locomotives. The prices of locomotives where collected from Transnet (2017), Railway Gazette (2018) and Creamer (2014). The average values of various electric and diesel locomotives were taken for both narrow and standard gauge purposes.

Table 3-4: Average locomotive prices (Railway Gazette (2018), Creamer (2014) and Lombard (2017))

Locomotive type	*Electric (R million/unit)*	*Diesel (R million/unit)*
Narrow gauge	41.0	32.0
Standard gauge	25.8	20.2

Table 3-5 summarises the costs of purchasing the two types of wagons. Transnet (2018) procured a large number of wagons with the prices of the two main wagons displayed in the table. Standard gauge and narrow gauge wagons could be bought for similar prices (Lombard (2017) and Transnet (2018)).

Table 3-5: Average wagon prices (Lombard (2017) and Transnet (2018))

	Container CR (R million/unit)	*Tanker (R million/unit)*
Wagons	1.2	2.5

Lombard (2017) indicates that the number of wagons per locomotive is a function of the ruling grade. Dutton (2014) states that to prevent heat damage to the wheels of a train, the heat input per wheel should not exceed 12 kW in South African conditions. The Tractive Effort (TE) of a locomotive can be determined from the locomotive's power curve.

Table 3-6 displays the method used to calculate the heat input per wheel for a train and a single locomotive with a mass, L_m. The wagon's axle load is defined by W, in tonnes. A ruling grade, of 1:Ψ was selected and the gravitational acceleration, F_g, was selected as 9.807 m/s^2.

Table 3-6: Determination of the heat input per wheel to determine the limiting number of wagons per locomotive (Dutton (2014) and Lombard (2017))

Parameter	*Unit*	*Comments & Explanations*
Number of Wagons - W_n	-	The number of wagons to be hauled by a locomotive
Train mass - m_t	Tonnes	$W_n \cdot W$
Net downhill force - f_d	kN	$TE = \frac{F_g}{\Psi}(L_n \cdot L_m + m_t) + m_t \cdot 0.1373(W)^{-0.754}$
Total braking effort - f_{BE}	kN	From braking curve for a speed
Friction braking for a speed - f_r	kN	$f_d - f_{BE}$
Heat input in wheels - Q	kW	$f_r \cdot v$
Heat load per wheel for a speed - Q_w	kW/Wheel	$\frac{Q}{8W_n} < 12$

Table 3-7 displays the method for determining the number of wagons and locomotives for a railway project (Lombard, 2017). The main influencers in the determination of the rolling stock are the envisaged throughput and ruling grade.

The ruling grade directly impacts the tractive effort calculations whilst the throughput envisaged affects the number of rolling stock required. In the table, the wagon payload is represented by W_p and the time operational and time per cycle from pit to port and back to the pit are denoted by T_{op} and T_{cycle} respectively. These calculations allow for the number of wagons and locomotives, for new projects, to be established using first principles.

Table 3-7: Determination of the number of wagons and locomotives for a railway project (Lombard, 2017)

Parameter	***Unit***	***Comments & Explanations***
Throughput envisaged - T_{exp}	mtpa	The maximum estimated tonnage to be transported along a line.
Ruling grade	1: Ψ	The steepest up or down slope a train will be required to traverse.
Rolling Stock		
Wagons per locomotive	-	$TE = \frac{F_g}{\Psi}(L_n \cdot L_m + m_t) + m_t \cdot 0.1373(W)^{-0.754}$
Throughput per cycle	tonnes	$W_n \cdot W_p$
Trips per wagon per annum - W_t	-	$\frac{T_{op}}{T_{cycle}}$
Wagon throughput per annum - T_w	tonnes	$W_p \cdot W_t$
Locomotive throughput per annum - T_L	mt	$W_n \cdot W_p \cdot T_w$
Wagons required	-	$\frac{T_{exp}}{T_w}$
Locomotives required	-	$\frac{T_{exp}}{T_L}$

3.2.4 Cost Model

Microsoft Excel was used to compile the cost model since the programme is versatile and allowed for additional information to be added to the calculations easily. The key factor which affected both costs and revenue was the annual tonnage transported on a corridor. The tonnage was restricted based on each corridor’s capacity. As the amount of annual tonnage was varied, so were the operating costs and the amount of revenue generated on the corridor. For each year between 2015 and 2045, the analysis period, a summary of the operating costs, CAPEX, revenue and line properties was generated for each of the alternatives evaluated on the corridor. From the summary, the profit could be determined and ultimately the IRR, B/C ratio and PW could be determined for the purpose of comparing the alternatives.

3.2.5 Alternatives

The alternatives which were considered and evaluated per section are broken up into narrow gauge, standard gauge and a combination of the two gauges. The narrow gauge alternative are the plans proposed by Transnet (2012) in the MDS which describes the planned upgrades per corridor.

Figure 3-6 displays a summary of the various alternatives which could be implemented on a railway corridor. The implications of performing these various interventions can be summarised as follows:

- Implementing the MDS would imply that that the corridor remains narrow gauge and that the corridor would receive the necessary upgrades as stated by the MDS;
- A dual gauge bogie eliminates the need to perform transhipment at transitions between narrow and standard gauge sections, however, the rolling stock is highly specialised;
- A third rail will entail large construction costs, however, both narrow and standard gauge trainsets could utilise the corridor,
- Bogie changing requires expensive cranes to lift wagons individually so that each bogie set can be changed manually,
- Transhipment requires loads to be transferred from one wagon to another at depots were breaks of gauge occur, and
- A ring fenced line implies that a standard gauge railway line could be built parallel to a narrow gauge corridor in order to increase corridor capacity and tonnage transported.

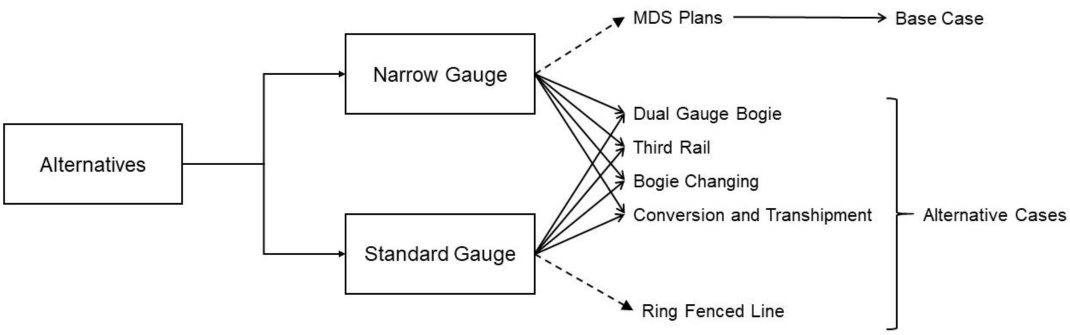


Figure 3-6: Alternatives for possible use in the cost analysis

The identification of the best alternative to implement per corridor was done through the analysis of the geographic location of the corridor and its position relative to other lines, the preliminary expected increase in volume transported annually and the required increase in line capacity to meet future demand.

An environmental benefit may exist if rail is selected over road to transport freight. A confidence interval can therefore be used to display these benefits. Van As (2015) states that the two-sided confidence interval, for a 100 (1 - α) per cent confidence interval, is given by:

$$\bar{x} \pm t_{(1-\alpha:n-1)} \cdot SE \qquad \textbf{(3.1)}$$

Where:

$\bar{x}$ = sample mean

$t_{(1-\alpha:n-1)}$ = the value of t from the students t-distribution for a stated level of confidence 1 – α and sample size, n.

SE = the standard error of the mean, $\frac{\sigma}{\sqrt{n}}$.

3.2.6 Cash Flow Calculations

For each alternative evaluated on a corridor, the following was calculated:

- Total cost including operational costs and CAPEX;
- Revenue generation per year, and
- Cash flow.

The cash flow was taken as the amount of revenue less the total costs per year before taxation, interest, amortisation and depreciation, thereby providing the net profit or cashflow (Hudson et al., 1997).

3.2.7 Economic Evaluation Techniques

The relevant and applicable evaluation techniques are required for evaluating railway projects to ensure the most accurate outcome is represented.

Present worth methods are useful by discounting all cashflows to a present date and displays the present consequence of a project. However, the method ignores project size (Remer & Nieto, 1995). The present worth method was used in conjunction with the benefit/cost ratio and IRR methods.

Figure 3-7 represents how the economic evaluation was conducted using the three economic evaluation methods. Each evaluation was performed in isolation and the cases were ranked from most to least profitable for each method. For mutually exclusive projects that resulted in discrepancies in determining the most profitable project, an incremental analysis was performed to determine the better investment (Blank & Tarquin, 1989).

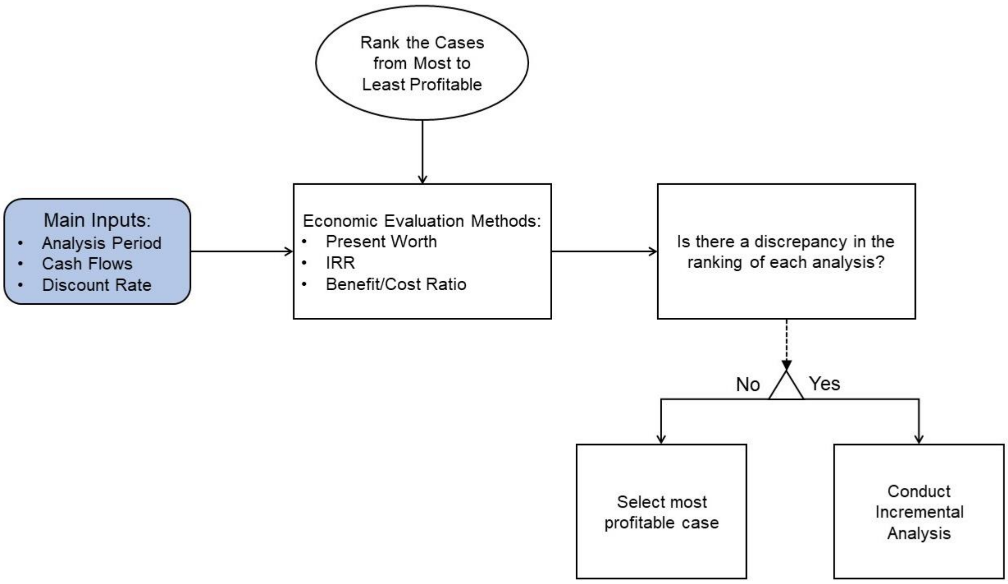


Figure 3-7: Method of evaluating a project economically

3.3 SIMULATION MODEL SETUP

A simulation was used to analyse the effects of performing a standard gauge intervention on a corridor. Simulation is an effective tool for imitating real-world processes over time and generating artificial history (Banks et al., 2005). Simulation was used to aid in obtaining a more optimal network through the analysis of line sections which caused bottlenecking. The number of sidings required per depot to prevent unnecessary queuing prior at the entrance of the rail depots was also able to be determined. Various simulation parameters could also be varied dynamically during the simulation such as changing the freight demand per day and the effect it had on the network per section as well as a whole.

This section seeks to provide the methodology for setting up a railway simulation utilising AnyLogic as well as providing the verification and calibration methods used to ensure accurate outputs.

3.3.1 Identification of Line Properties

To simulate the operation of a railway corridor, the properties of the corridor must be defined. This would range from the line type to the traction selected for the corridor to be evaluated.

Table 3-8 displays the parameters required to establish a simulation model. For optimisation of the model the wagon length, crossing loop length and crossing loop spacing were varied, however, this will be discussed further in Section 3.3.3.

Table 3-8: Properties required to compile a simulation model

Property	***Description***	***Units***
Axle loading	Axle loading rating for the line	tonnes/axle
Crossing loop length	Length of the crossing loop	km
Crossing loop spacing	Distance between crossing loops	km
Curve radius	Maximum curve radius	m
Freight mix	Distribution of commodity wagon types	-
Gradient	1: Ψ, where Ψ is the ruling gradient	-
Line length	Length of the line	km
Line speed	Maximum speed for the line	km/h
Line type	Single or double line	-
Number of stations	Stations between the end points of the line	-
Time in depot load/unload	Time to load or unload a set of wagons	hours
Traction	Diesel or electric	-
Train acceleration/deceleration	Rate the train accelerates or decelerates	m/s^2
Trains in system	Total number of trains in the system	-
Wagons per train	Number of wagons per train	-

Most of the simulation model was constructed using AnyLogic's rail library. The rail library contains two agent types, namely train types and rail car types, which form the main building blocks of an AnyLogic model. Table 3-9 displays the agents defined for the simulation and the space mark-up tools used to spatially create the model. In the simulation, a locomotive, open cars and box cars were created as agents as well as a specific train type which was a combination of the agents described.

Table 3-9: Agents and space mark-up tools utilised to setup the simulation model in AnyLogic

Element	***Type***	***Description***
Train Type	Agent	The agent defines the way in which a sequence of rail cars was coupled.

Element	***Type***	***Description***
Rail Car Type	Agent	Defines the types of rail cars used in the model, each with their own visual.
Railway Track	Railway Track	Forms the elements of a railway network. Gauge could be modified.
Position on Track	Position on track	Used as points to define exact positions on a railway track.
Railway Switch	Railway Switch	Used to join railway tracks at an intersection.

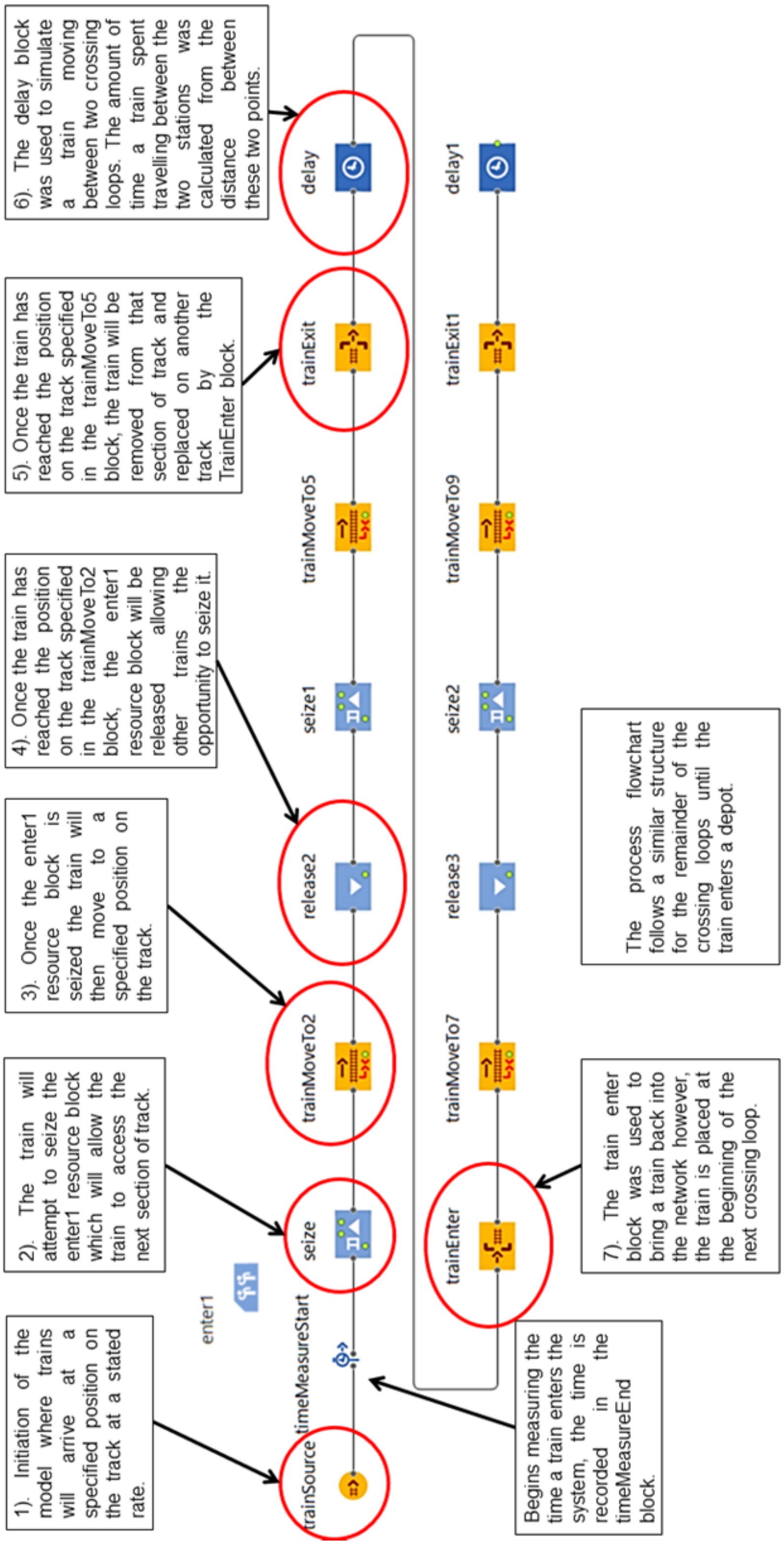
Table 3-10 displays the logic blocks utilised to build the simulation model in AnyLogic. A description of each of the logic blocks has been provided in the table. Each of the logic blocks contain parameters which can be varied to allow for the system to operate as desired by the modeller. These parameters vary depending on the logic block's purpose, for example a TrainSource block, which is linked to the Train agent, was used to define the train's number of wagons, speed, acceleration and deceleration.

Table 3-10: Description of logic blocks used in the AnyLogic simulation model

Logic block	***Description***	***Parameters***
TrainSource out	The train source block was used to start any railway process flow. Trains are placed on tracks and injected into the train process flowchart	Arrival time, Number of arrivals, Train size, Position on track, Speed, Acceleration and Deceleration
TrainMoveTo in out outHit	The only block that controls train movement. A train was only able to move while it was inside this block.	Direction, Route, Check for free space, Start options and Finish Options
TrainDispose in	The block removes the train from the model. In a closed system such as a railway corridor, this block was not used.	On enter [code]
TrainDecouple in out outDecoupled	A set number of cars are decoupled from an incoming train and creates a new train from those cars. This was used with a delay block to incorporate the time taken to decouple the cars.	Decouple and Number of cars to decouple
TrainCouple in1 out in2	Couples two trains and forms one train when the two ends of the train touch each other.	On enter [code] and On exit [code]
TrainExit in out	This block removes the train from the network and passes the train agent through a regular process flowchart, where it may experience delays or queues. The block was used with a delay block to simulate a train travelling along a straight section of track between two crossing loops.	-
TrainEnter in out	A train enter block was used to bring a train agent back into the network. It placed the train agent on a track.	Entry point, Position on track and Orientation on track

Delay in out	The delay block was used to delay agents for a certain amount of time. It was used to simulate a train running between two crossing loops once it was removed from the system using the train exit block.	Delay time, Capacity, Type and Agent Location
ResourcePool	The resource pool block allows agents to seize and release a resource such as a section of track which prevents other train agents from occupying that section.	Capacity
Logic block	***Description***	***Parameters***
Seize in out preparedUnits	The seize block seizes a set number of resource pools which are defined in the seize block.	Seize, Number of Units, Seize policy
Release in out wrapUp	The release block was used to release all the seized pools held by an agent at a time in the process chart.	Release, Seize blocks,
Parameter	An agent may have parameters. Parameters are frequently used for representing some characteristics of the modelled object.	-
Function F	A function was used to return values every time the function was called on in the model. The user can define their own function such as deciding on which line to place a train on in the depot for unloading/loading.	-
Variable V	An agent may contain variables. The block holds some data units.	-
Output	An output element was used for storing a data value once the simulation has finished such as the number of wagons entering a depot.	-

Figure 3-8 displays a typical logic flow chart for a railway corridor. Each of the logic blocks have a different purpose and allow for a system of trains to pass through the system for a specified time period. The parameter, function, variable and output blocks cannot be viewed in the figure, however, they were used to aid in the control of the trains while in the depots and travelling between stations. A short description of each logic block's purpose for the specific simulation can be viewed in the figure.



1). Initiation of the model where trains will arrive at a specified position on the track at a stated rate.

Begins measuring the time a train enters the system, the time is recorded in the timeMeasureEnd block.

2). The train will attempt to seize the enter1 resource block which will allow the train to access the next section of track.

3). Once the enter1 resource block is seized the train will then move to a specified position on the track.

4). Once the train has reached the position on the track specified in the trainMoveTo2 block, the enter1 resource block will be released allowing other trains the opportunity to seize it.

5). Once the train has reached the position on the track specified in the trainMoveTo5 block, the train will be removed from that section of track and replaced on another track by the TrainEnter block.

6). The delay block was used to simulate a train moving between two crossing loops. The amount of time a train spent travelling between the two stations was calculated from the distance between these two points.

7). The train enter block was used to bring a train back into the network however, the train is placed at the beginning of the next crossing loop.

The process flowchart follows a similar structure for the remainder of the crossing loops until the train enters a depot.

Figure 3-8: Typical layout of the logic blocks used in AnyLogic to simulate the operations along a railway corridor

Figure 3-9 displays a crossing loop that would allow trains travelling in opposite directions to pass one another (layout of the crossing loop not to scale).

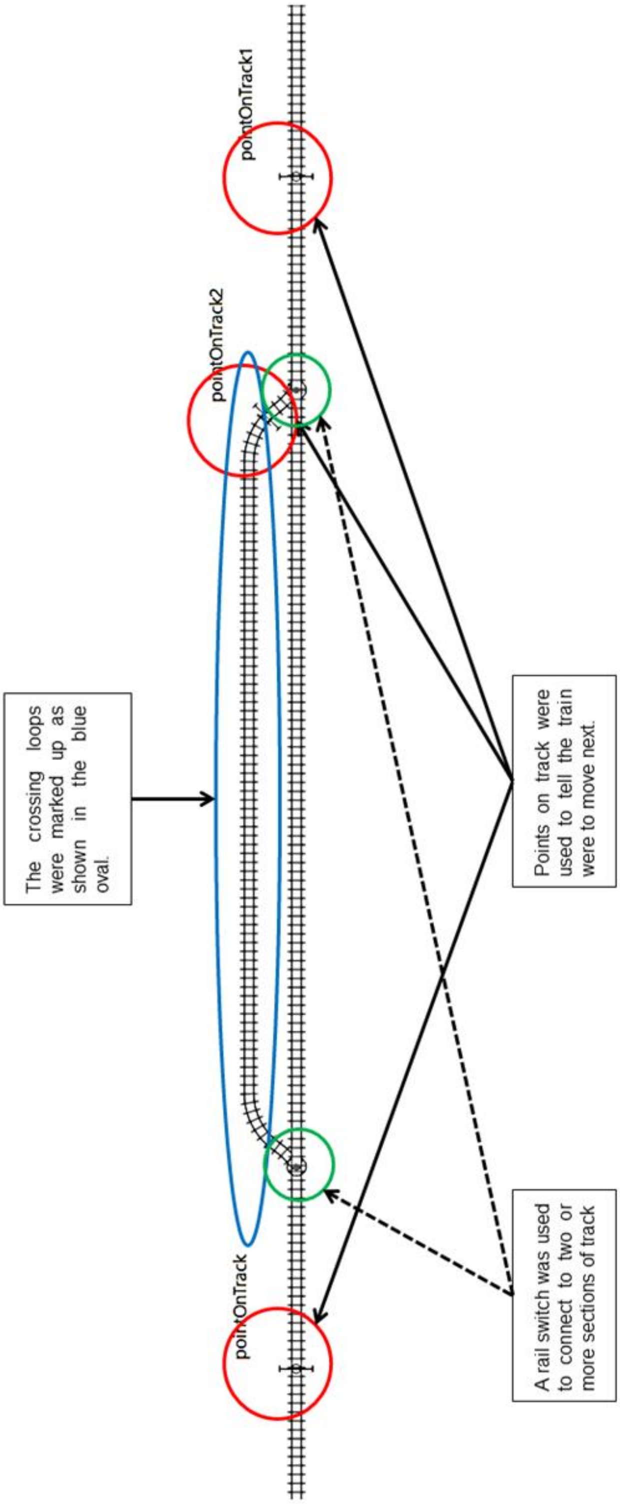


Figure 3-9: Crossing loop space mark-up compiled in AnyLogic for a single line corridor

Figure 3-10 displays the layout of a depot on a single line railway. The first loop was used to turn a locomotive set around, thereby allowing the wagons to be pushed into the depot. The train set, after unloading or loading, can then be pulled out of the depot by the locomotives which will then be at the front of the train.

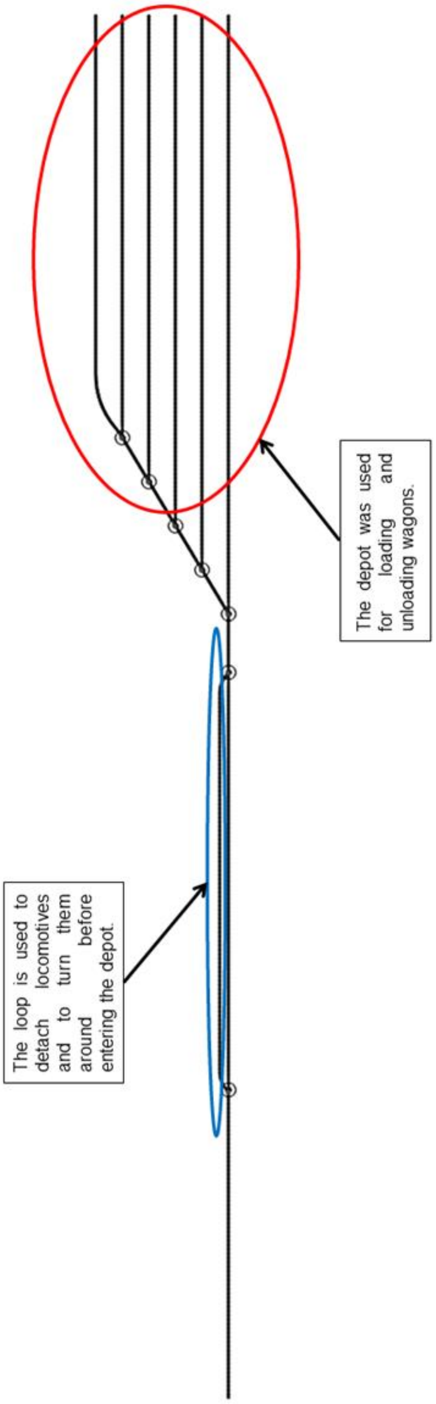


Figure 3-10: Layout of a single line depot compiled in AnyLogic

3.3.2 Simulation Model Parameter Calibration and Validation

Data inputs for a simulation model can either be measured directly or if the inputs are unknown, they can be calibrated (Koutsopoulos & Wang, 2007). Calibration can be observed as the optimisation of reducing the error between the model's output and the field data.

The model parameters which produce the lowest difference between the observed and simulated values would provide the best model. A popular measure of goodness-of-fit is the Root-Mean-Square Percentage Error (RMSPE) (Hourdakis et al., 2003). The RMSPE allows the mean difference between the observed and simulated values to be determined as a percentage of the observed data's mean. The lowest calculated RMSPE indicates the best fit. The RMSPE is defined as follows:

$$RMSPE = \sqrt{\frac{1}{N}\sum_{n_s=1}^{N}\left(\frac{Y_{n_s}^{sim} - Y_{n_s}^{obs}}{Y_{n_s}^{obs}}\right)^2} \qquad \textbf{(3.2)}$$

Where:

$Y_{n_s}^{sim}$ = simulated measurements at a space-time point

$Y_{n_s}^{obs}$ = observed measurements at a space-time point

n_s = space-time point

N = number of observations

Table 3-11 displays the parameters used to perform calibration of the microsimulation model. The parameter was selected based on the findings made in literature. The RMSPE was used to observe the differences between the simulated and observed values and an acceptable RMSPE was considered to be within 10% of the observed true mean (Balakrishna et al., 2007). Since a freight orientated standard gauge single line railway does not exist within South Africa, the observed values were calculated using first principles or in other instances collected from known standards and documents.

Table 3-11: Parameter used to calibrate a microsimulation railway model

Measure of Performance	***Description***	***Acceptable RMSPE***
Network travel time	The network travel time is the time required for a train set to pass between two points at opposite ends of the network.	10 %

3.3.3 Simulation Model Optimisation

Simulation model optimisation involves the analysis of the system while using different input parameters per run. The set of parameter values which provide the best objective output would be the optimised values for the system. A heuristic method was used since a local optimum is substantial for a railway corridor. A heuristic technique seeks good solutions at reasonable computational cost however, feasibility or optimal solutions are often not guaranteed (Song & Irving, 2001).

Table 3-12 displays the parameters which were varied during the optimisation exercise, which was aimed at maximising the number of trains passing through a railway corridor. Parameters related to the locomotive’s performance such as its acceleration, deceleration, maximum speed and available traction were left unaltered for the optimisation. The maximum line speed was not changed from 80 km/h since it is a standard speed for heavy haul operations within South Africa (Transnet, 2016).

Electric traction was utilised for the analysis and the axle loading was set at 26 tonnes per axle. The maximum gradient was kept at 1:100 and the total line length was also fixed. The crossing loop length was taken as a function of the train length used in the simulation.

A good indication of how well a track system is operating, is to analyse the difference between the minimum running time along a track network and the simulated average running time, namely the delay. Dingler et al. (2010) indicate that delay is the additional time it takes a train to travel on a route due to conflicts with other traffic. The variation in the number of crossing loops will alter the amount of time a train will spend waiting to occupy a section of track, thereby affecting the amount of delay the train experiences.

Table 3-12: Parameters varied during the optimisation experiment

Parameter	***Description***
Crossing loop spacing	The distance between crossing loops was varied to understand how this affected traffic flow and ultimately throughput of the line.
Wagons per train	Wagons per train was varied to identify what best train length versus depot handling time relationship would lead to the maximum throughput.

3.4 SUMMARY OF METHODOLOGY

The methodology chapter described which information was important in evaluating a railway corridor's performance. This included the analysis of the annual tonnage, the expected tonnage growth along the corridor, the condition of the infrastructure and lastly the capacity of the corridor.

The method of economically evaluating a railway corridor utilised three main economic evaluation techniques which included the B/C ratio method, the IRR method and the PW method. The manner in which the revenue and costs were determined was described so that the alternatives could correctly be evaluated in the cost model.

Simulation using AnyLogic was described and various diagrams and figures were used to summarise how an AnyLogic railway simulation was compiled. The various libraries and functions were described as well as the method in which the optimisation of the simulation was conducted.

In the next chapter, the results of the analysis conducted in the study focussing on the main objectives of identifying the various corridors which could benefit from a gauge intervention, are discussed. Economical analyses are used to verify whether the intervention would outperform the base case. Lastly, the most beneficial gauge change alternative for each corridor, if more profitable than the base case, is simulated.

4 ANALYSIS AND DISCUSSION OF RESULTS

This chapter provides the analysis and interpretation of results from the methodology described in Chapter 3. Section 4.1 provides a summary of the core network and describes the corridors used in the analysis. This includes the corridors' predicted freight growth rates, condition and capacity. From the information presented it could be noted that some corridors do not transport enough volume to warrant gauge changes.

Section 4.2 discusses the results of the economic evaluation and makes recommendations based on the results of this analysis. The section also evaluates the effects of a varying freight growth rate and construction period on the analysis.

Section 4.3 discusses the simulation of the most profitable recommendation as well as verification, calibration and optimisation of the simulation model.

4.1 REVIEW OF THE CORE NETWORK CORRIDORS

Table 4-1 displays the corridors identified for analysis. The 9 corridors in the table form part of the following 5 systems:

- Natal corridor;
- Coal line;
- Iron ore line;
- Manganese line, and
- North-eastern system.

The Department of Transport (2009) indicates that for a premium of R 3.46 million/km, to convert to standard gauge, it is only a viable option if the line moves volumes greater than 30 mtpa. Table 4-1 indicates that as of 2015, only the Coal export line and the Iron ore line exceed this volume. The Natal corridor is predicted to grow in the years to follow and exceed 50 mtpa by 2030.

The remainder of the corridors in Table 4-1 do not move enough volume to warrant a conversion from narrow to standard gauge. Although growth is expected to increase along these corridors, it would be recommended that they remain narrow gauge. These corridors therefore, will not benefit from a gauge conversion. An economic analysis of these corridors can be viewed in Appendix A.

Table 4-1: Summary of the key corridors in South Africa (Transnet, 2016)

Corridor	*Total Volume Transported (mtpa)*			*Growth rate per annum (%)*	*Directional split*	
	2015	*2030*	*2045*		*To Port (%)*	*From Port (%)*
Natal Corridor: Reitvallei – Booth	26.28	50.49	73.44	3.96	84.8	15.2
Coal line: Lephalale – Ogies	89.61	113.62	133.44	1.47	98.1	1.9
Coal line: Ogies - Richards Bay	100.52	107.3	153.31	0.93	97.3	2.7
Iron ore line: Sishen – Saldanha	62.02	63.22	73.83	0.55	99.5	0.5
Manganese Line: Hotazel – Ngqura	6.67	16.35	27.85	5.52	95.8	4.2
NE System: Groenbult – Kaapmuiden	10.3	14.63	20.84	2.37	98.9	1.1
NE System: Greenview – Komatipoort	20.68	26.57	36.15	1.78	62.4	37.6
NE System: Komatipoort - Richards Bay	8.1	10.25	14.15	1.73	94.8	5.2
NE System: Musina – Pyramid	1.94	5.1	10.69	6.25	58.7	41.3

Table 4-2 displays the section properties for each of the lines identified. Centralised Traffic Control (CTC) is the preferred train control system. However, some lines still operate using the Track Warrant System (TWS) and the Radio Train Order (RTO) system. Steep gradients affect grade resistance and ultimately the number of wagons that can be run per locomotive. Axle loading, traction and line type vary depending on the line's purpose and traffic. Many of the lines use dual traction which has led to operational challenges and the procurement of specialised locomotives.

Table 4-2: Properties of the corridors identified for potential intervention (Transnet, 2016)

Corridor	*Line Type*	*Axle Load*	*Traction*	*Train Control*	*Sharpest curve*	*Steepest gradient*
Natal Corridor: Reitvallei – Booth	Double	20 t	3 kV DC	CTC	220 m	1:45
Coal line: Lephalale – Ogies	Single/ Double	20/26 t	Diesel/3 kV DC/25 kV AC	CTC/ TWS	153 m	1:75
Coal line: Ogies - Richards Bay	Double	20/26 t	3 kV DC	CTC	153 m	1:100
Iron ore line: Sishen – Saldanha	Single	30 t	50 kV AC	CTC	800 m	1:250
Manganese Line: Hotazel – Ngqura	Single/ Double	20 t	3 kV DC	CTC/ RTO	302 m	1:100
NE System: Groenbult – Kaapmuiden	Single/ Double	18.5/20 t	Diesel/3 kV DC	TWS/ CTC	200 m	1:50
NE System: Greenview – Komatipoort	Single	20 t	3 kV DC	CTC	250 m	1:66
NE System: Komatipoort - Richards Bay	Single	20 t	Diesel/3 kV DC	TWS	250 m	1:120
NE System: Musina – Pyramid	Single/ Double	20 t	Diesel/3 kV DC	TWS/ CTC	200 m	1:50

Table 4-3 displays the condition of the corridors. Red indicates that the infrastructure requires an upgrade or attention. Yellow indicates that the infrastructure may be correct for the operation, but maintenance may be required to ensure that the condition does not worsen. Green indicates that the infrastructure is in a good condition.

Table 4-3: Condition of the corridors identified for potential intervention (Transnet, 2016)

Corridor	*Formation*	*Structure*	*Perway*	*Electrical*	*OHTE*	*Signals*	*Telecoms*	*Overall*
Natal Corridor: Reitvallei - Booth	🟨	🟨	🟥	🟨	🟥	🟨	🟨	🟨
Coal line: Lephalale - Ogies	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨
Coal line: Ogies - Richards Bay	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Iron ore line: Sishen - Saldanha	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟩
Manganese Line: Hotazel - Ngqura	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟨
NE System: Groenbult - Kaapmuiden	🟨	🟨	🟥	🟨	🟥	🟨	🟨	🟨
NE System: Greenview - Komatipoort	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨
NE System: Komatipoort - Richards Bay	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
NE System: Musina - Pyramid	🟨	🟨	🟨	🟩	🟩	🟥	🟥	🟨

Table 4-4 displays the utilisation, in terms of percentage, for the corridors identified. For Table 4-4 the constraining and highest utilisation along a corridor has been selected as the utilisation expected for the period stated. The values are for a situation were no investments are made on the network, but the future predicted growth has materialised. It has been assumed that all the manganese transported on the Iron ore line has been diverted onto the Hotazel – Ngqura line hence, the jump in the line's utilisation percentage between 2015 and 2030.

Table 4-4: Utilisation of the corridors identified for potential intervention (Transnet, 2016)

Corridor	*Utilisation (%)*		
	2015	***2030***	***2045***
Natal corridor: Reitvallei - Booth	< 60	>130	>130
Coal line: Lephalale - Ogies	60 - 80	80 - 95	105-130
Coal line: Ogies - Richards Bay	80 - 95	105-130	>130
Iron ore line: Sishen - Saldanha	80 - 95	95 -105	105 -130
Manganese line: Hotazel - Ngqura	60 - 80	> 130	>130
NE system: Groenbult - Kaapmuiden	< 60	60 - 80	95 -105
NE system: Greenview - Komatipoort	< 60	60 - 80	80 -95
NE system: Komatipoort - Richards Bay	< 60	< 60	80-95
NE system: Musina - Pyramid	< 60	60 - 80	95 - 105

4.2 RESULTS OF THE ECONOMIC EVALUATION OF RAILWAY PROJECTS

This section discusses the inputs of the cost model and the resulting outputs. For each of the three corridors identified, for potential intervention, a set of possible interventions have been postulated and evaluated. In the analysis of each corridor, the MDS plans have been set as the base case. Bogie changing and dual gauge bogies were not considered because of the additional complexities introduced into operations when they are implemented. Bogie changing is mainly used in Europe to move from a standard to broad gauge rail system. The bogie changing system requires the construction of gauge change facilities and expensive lifting equipment to lift the entire wagon or coach to replace the bogies (Department of Transport, 2009). Dual gauge bogies carry a high cost since the system has to be attached to every wagon on a trainset and the system adds additional unsprung mass (Department of Transport, 2009).

Table 4-5 displays the parameters used for the economic evaluation of each of the corridors. The analysis period was set at 30 years, the discount rate was set to 2.5 % and the freight growth rate was varied depending on the corridor’s predicted growth rate. A sensitivity analysis was conducted on the freight growth rates for each of the corridors identified. The construction duration was also varied for the alternative cases. The outcomes of the results of the analyses were not sensitive to the discount rate, however, the monetary value of the present worth would change depending on the discount rate.

Table 4-5: Parameters for economic evaluation

Parameter	***Symbol***	***Value***
Analysis period	n	30 years
Discount rate	i_d	2.5 %
Construction duration	-	Varied
Freight growth rate	r_{fg}	Varied

4.2.1 Economic Analysis of North Eastern System, Manganese System and Gauteng to Cape Systems

Table 4-6 displays the results of the economic analysis conducted on the North Eastern System, Manganese System and Gauteng to Cape Systems. The results in all cases indicated that following the plans described in the MDS would be the most profitable since there standard gauge project's construction cost is too great for the volumes transported on these lines. The analysis was conducted for a 30 year analysis period and a 2.5 % discount rate. The corridors do not transport enough freight to warrant a gauge change intervention.

Table 4-6: Economic analysis results for North Eastern System, Manganese System and Gauteng to Cape Systems

Corridor	***Project***	***B/C Ratio***	***IRR***	***PW (R million)***
Gauteng - Cape Town	MDS	1.186	0.028	19,096
	3rd Rail	0.226	-0.093	-297,118
	Conversion	0.242	-0.090	-271,897
Manganese System	MDS	1.273	0.042	40,775
	3rd Rail	0.410	-0.067	-180,129
	Conversion	0.336	-0.077	-250,640
NE: Musina - Pyramid	MDS	2.395	3.354	29,669
	3rd Rail	0.374	-0.059	-70,626
	Conversion	0.394	-0.057	-64,773
NE: Groenbult - Kaapmuiden	MDS	3.856	2.050	93,180
	3rd Rail	0.950	-0.004	-613
	Conversion	0.939	-0.005	-2,012
NE: Greenview - Komatipoort	MDS	3.351	2.500	159,044
	3rd Rail	1.387	0.033	68,266
	Conversion	1.412	0.035	70,983
NE: Komatipoort - Richards Bay	MDS	2.007	2.500	44,731
	3rd Rail	0.578	-0.046	-58,383
	Conversion	0.614	-0.042	-49,762

4.2.2 Coal line Cost Model

A major construction project along the Coal line would lead to operational bottlenecking and put strain on the Komatipoort – Richards Bay line to transport coal to the port in Richards Bay.

Table 4-7 displays the alternatives evaluated for the Coal line. Case A requires following the plans put forward in the MDS for the Coal line. Case B, transhipment, entails the complete stop of operations along the section in one direction while construction takes place. A new standard gauge double line with 25 kV AC electrification would be constructed during this period. Case C, constructing a 3rd rail, would result in the same system constraints during construction as Case B, however, post construction both narrow and standard gauge trains would be able to operate along the line.

Table 4-7: The Coal line alternatives for evaluation

Project	*Case*	*Project Description*
MDS	A	Follow plans described in the MDS.
Transhipment	B	Convert the Ermelo-Richards Bay section to standard gauge and tranship Coal at Ermelo to increase export volumes along the Ermelo-Richards Bay section. Axle loading would increase to 30 tonnes per axle.
3rd Rail	C	Upgrade the current line to allow for a dual gauge system along the Ermelo-Richards Bay section increasing export volumes. Axle loading would increase to 30 tonnes per axle.

Table 4-8 displays the economic evaluation outcomes for the predicted freight growth rate of 0.93 %. Case A has the best B/C ratio, IRR and present worth indicating that it is the economically superior alternative. Although Cases B and C are economically feasible, the selection of either of them cannot be justified when compared to Case A. The construction durations were also varied however, for a shorter construction duration Cases B and C are still not as profitable as Case A.

Table 4-8: Coal line economic evaluation for predicted freight growth rates

Project (duration)	*Case*	*B/C Ratio*	*IRR*	*Present Worth (R million)*
MDS	A	1.619	0.206	349,924
Transhipment (6yrs)	B.1	1.285	0.047	204,581
Transhipment (10yrs)	B.2	1.272	0.046	195,250
3rd Rail (6yrs)	C.1	1.310	0.051	218,377
3rd Rail (10yrs)	C.2	1.297	0.049	209,045

Figure 4-1 displays, for each of the cases, the tonnage lost due to capacity restrictions as a result of the construction taking place for Case B and C. Case A does not lose any tonnage since by 2025 all of the projects planned for the line are completed. All the available capacity on the line is estimated to be completely utilised in 2025 hence, the upgrades Transnet have proposed. An increase in construction duration also causes additional tonnage lost due to the prolonged bottlenecking on the line.

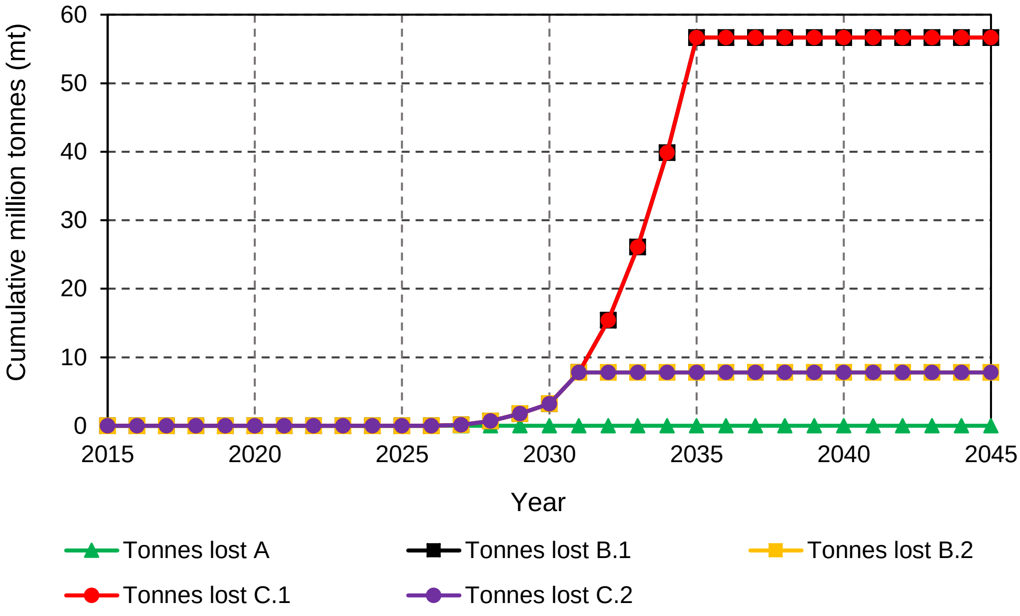


Figure 4-1: Tonnage lost and capacity on the Coal line for each of the alternatives

Figure 4-2 displays a sensitivity analysis of the present worth values of the cases for a varying freight growth rate, r_{fg}, per annum. The figure indicates that in a variable economic climate, Case A will still be the most economically viable alternative. The figure also indicates that with reduced construction durations, Cases B and C are still less profitable than Case A.

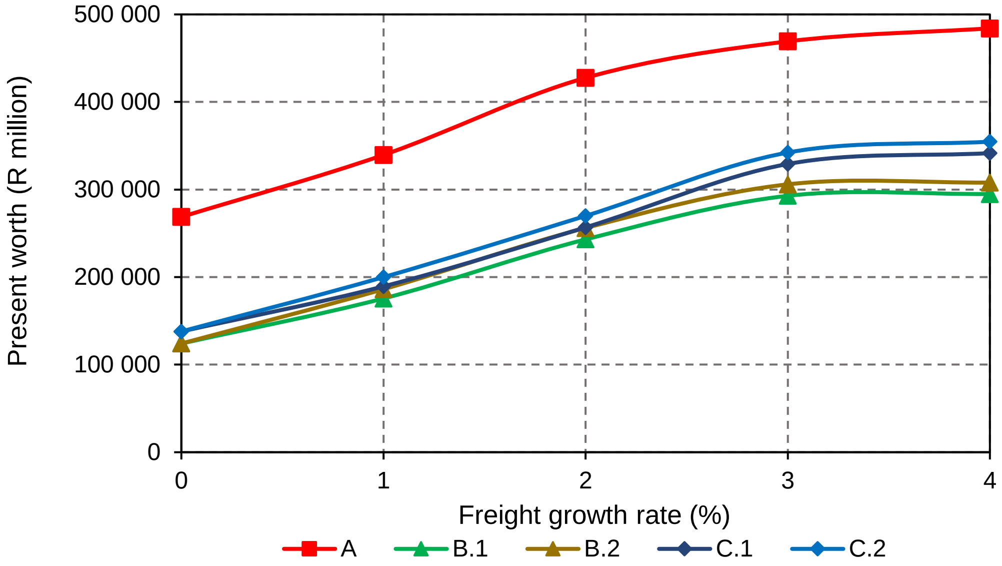


Figure 4-2: Sensitivity analysis of the freight growth rate versus project present worth on the Coal line

4.2.3 Iron ore line Cost Model

The Iron ore line operates as a single line and it is in the best condition of all the corridors in the network as can be seen in Table 4-3. Since this line is a single line, any upgrades or maintenance that are performed on the line would cause operations to stop completely. The line is also over 850 km in length, resulting in any construction project having a high cost associated with it.

Table 4-9 displays the alternatives which would best suit the corridor. A third rail would allow the current rolling stock arsenal to be supplemented by a standard gauge fleet and for axle loading to be increased to global standards for standard gauge.

Table 4-9: The Iron ore line alternatives for evaluation

Project	*Case*	*Project Description*
MDS	A	Follow plans described in the MDS.
3rd Rail	B	Upgrade the current line to allow for a dual gauge system. The line would remain a single line with crossing loops however, axle loading would increase to 34 tonnes per axle.

Table 4-10 displays the results of the economic analysis performed on the two cases. The Iron ore line is well established, therefore, the only major plans put forward in the MDS include the extension of crossing loops and the addition of crossing loops at bottlenecking locations. For Case B, the construction duration was varied to view the effects it would have on the economic analysis. A construction duration of 6 years is unlikely, however. For the study it was however evaluated to observe whether Case B.1 could become more profitable than Case A. The addition of a third rail would not be feasible as can be seen in the table, even for a construction duration of 6 years. It is worthwhile noting that a reduced construction duration leads to a more profitable operation under the circumstances evaluated.

Table 4-10: Iron ore line economic evaluation for predicted freight growth rates

Project (duration)	*Case*	*B/C Ratio*	*IRR*	*Present Worth (R million)*
MDS	A	1.889	0.937	348,887
3rd Rail (6yrs)	B.1	1.447	0.037	218,329
3rd Rail (10yrs)	B.2	1.219	0.021	121,643
3rd Rail (15yrs)	B.3	0.884	-0.013	-33,067

Figure 4-3 displays the cumulative tonnage lost for each of the cases. The line would be able to support wagons loaded to 34 tonnes per axle once the third rail has been constructed which would enable heavier trains to be run on the line. The MDS plans proposed by Transnet indicate that the line will have enough capacity to transport the predicted tonnages for the corridor, therefore no tonnes are lost due to lack of capacity. The figure indicates that the longer the construction duration, the greater the amount of tonnage lost. While construction takes place for Case B, no trains are able to use the line.

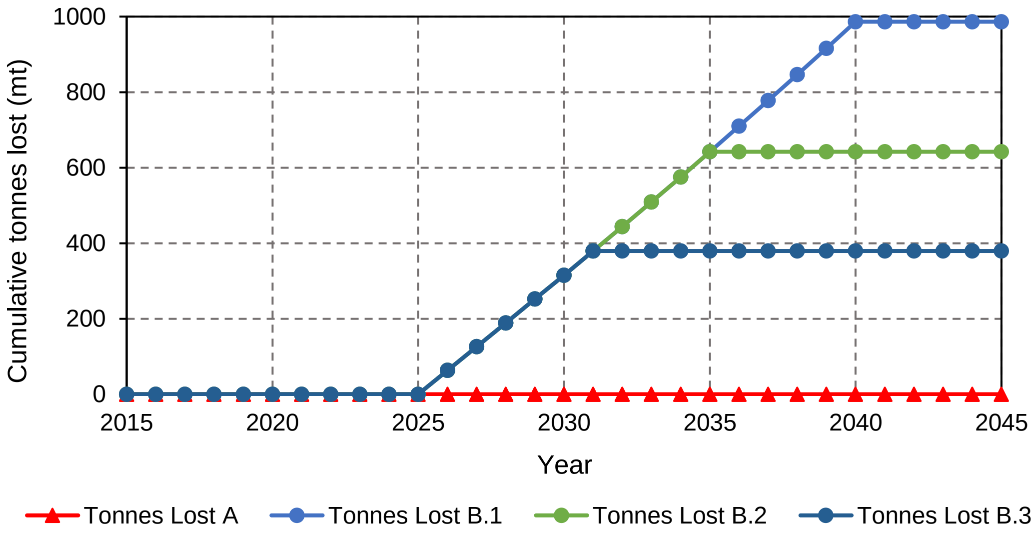


Figure 4-3: Cumulative tonnage lost on the Iron ore line for each alternative

Figure 4-4 exhibits a sensitivity analysis of the present worth of the cases for a varying freight growth rate per annum. If the freight growth rate increases, the plans proposed in the MDS, Case A, would remain more profitable than Case B, the construction and operation of a third rail corridor.

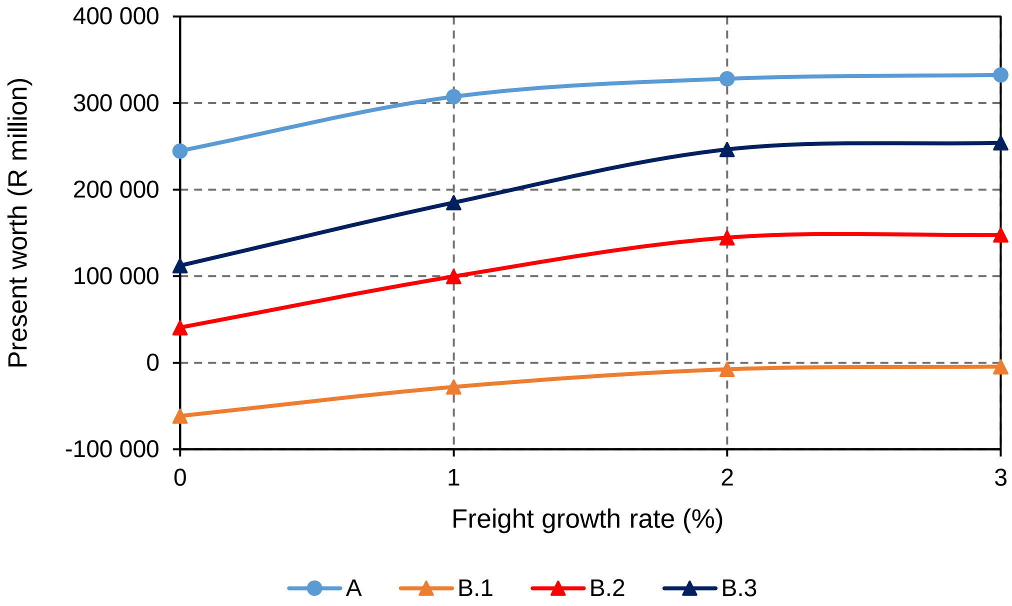


Figure 4-4: Sensitivity analysis of the freight growth rate versus project present worth on the Iron ore line

4.2.4 Natal Corridor Cost Model

The Natal corridor moves general freight between Gauteng and the port in Durban. Table 4-1 indicates that the corridor is likely to experience growth of close to 4 % per annum in the next 30 years.

Table 4-11 displays the cases evaluated for the Natal corridor. Case B, the construction of a third rail, would allow for both narrow and standard gauge rolling stock to operate on the same line, reducing the amount of rolling stock required. A ring fenced standard gauge line would require the construction of a standard gauge single line railway parallel to the current narrow gauge corridor. This line could be used for double stacked containers and would supplement the narrow gauge corridor, freeing up much needed capacity. For Case C, the standard gauge line was assumed to only carry the predicted container volumes by means of double stacking for the analysis done to obtain the results displayed in Table 4-12.

Table 4-11: The Natal corridor alternatives for evaluation

Project	*Case*	*Project Description*
MDS	A	Follow plans described in the MDS.
3rd Rail	B	Upgrade the current line to allow a dual gauge system. Axle loading would increase to 26 tonnes per axle to allow for double stacking of containers.
Ring Fenced SG	C	Construct a line parallel to the current NG corridor in SG and with an axle loading of 26 tonne per axle. The SG line was assumed to be used for only container traffic. Current NG corridor to follow the plans in the MDS.

Table 4-12 displays the results of the economic evaluation performed on the different cases. The results indicate that following the MDS would lead to the most profitable outcome. Constructing a third rail would cause bottlenecks during construction and would require major capital investment. The addition of a standard gauge single line does not lead to a profitable project under the conditions evaluated. The construction length was varied in the analysis and led to Cases B and C becoming more profitable, however, the cases remained unfeasible.

Table 4-12: Natal Corridor economic evaluation for predicted freight growth rates

Project (duration)	*Case*	*B/C*	*IRR*	*PW (R million)*
MDS	A	1.403	0.033	109,682
3rd Rail (6yrs)	B.1	0.807	-0.016	-125,067
3rd Rail (10yrs)	B.2	0.782	-0.018	-141,686
Ring-Fenced SG (6yrs)	C.1	0.973	-0.002	-10,224
Ring-Fenced SG (10Yrs)	C.2	0.954	-0.004	-21,315

Figure 4-5 displays the cumulative tonnes lost along the corridor for each of the cases. By 2026 all the cases reach capacity thus inducing a loss of tonnage which could be transported along the line. It should be noted that construction ends in year 2030 for Cases B.1 and C.1 and ends in 2035 for Cases B.2 and C.2, resulting in more capacity being made available on the corridor.

The standard gauge single line is underutilised in this scenario, indicating that the line would be able to carry more tonnage which would lead to Case C becoming more profitable if the opportunity to do so was realised.

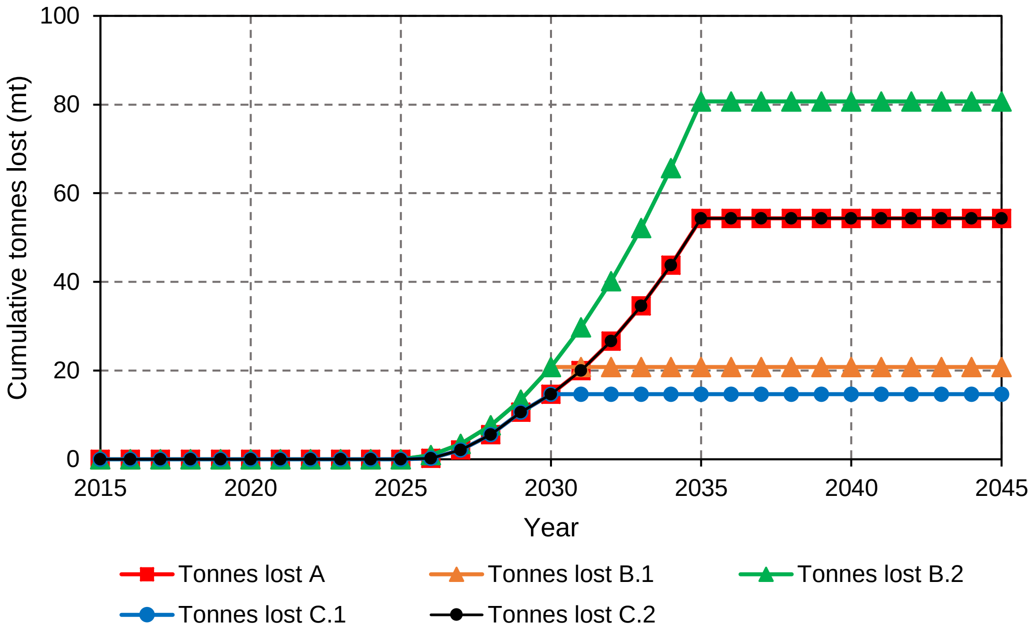


Figure 4-5: Tonnage lost on the Natal corridor for each of the alternatives

Figure 4-6 displays the present worth values of the cases for varying freight growth rates. This was only conducted for a 10-year construction period, since it is the more likely situation. For Case C, it was noted that an opportunity exists along the Natal corridor. Rail held a market share of 15 % of the freight transported along the Natal corridor in 2016, which indicates that in 2045 the Natal corridor, including both road and rail, could transport 223 million tonnes of freight between Gauteng and Durban (Naidoo, 2015).

In Case C, the standard gauge railway line could be used to transport a large share of the freight along the corridor. From the initial operational analysis, it was noted that the standard gauge line could carry an additional 80 mtpa on top of the 18.1 mtpa of containers, which the line would carry from the predicted rail traffic.

Should future environmental policies be implemented, rail would be the favoured mode of transport over road due to lower environmental costs. If the standard gauge railway line was constructed, rail would be well positioned to occupy a larger market share along the corridor and reduce environmental costs.

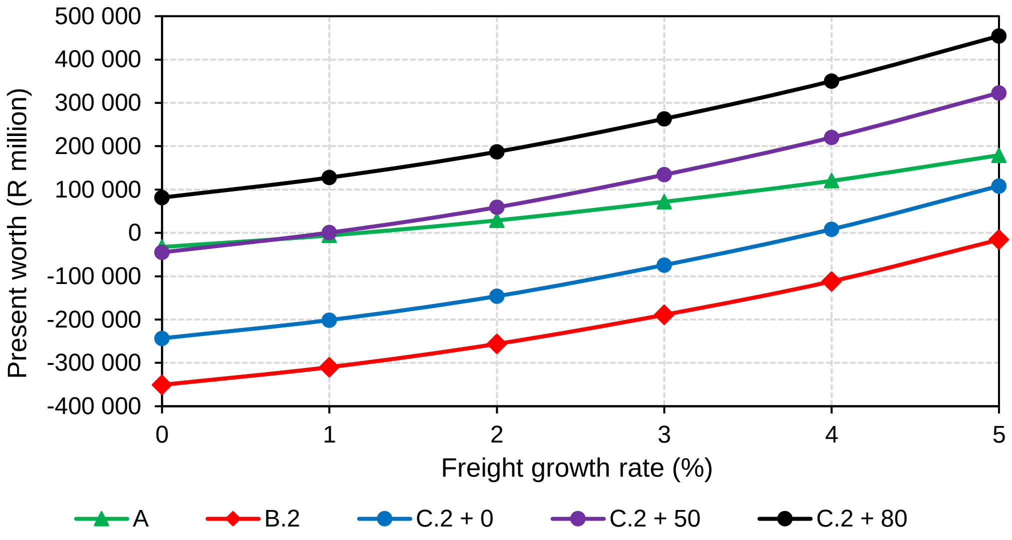


Figure 4-6: Sensitivity analysis of the freight growth rate versus project present worth

Figure 4-7 displays the present worth's of Cases A and C, where Case C carries a varying amount of additional tonnage on the standard gauge line. The freight growth rate was set at the predicted rate of 3.96 % per annum. Under these conditions, if the standard gauge line was to carry an additional 37.5 mtpa, Cases A and C would have the same present worth values. Only the newly constructed line in Case C would be able to carry additional tonnage without jeopardising the future operations on the corridor due to its low utilisation without the additional tonnage prescribed.

Transporting commodities with rail would also induce an environmental benefit due to the reduced externality costs such as accidents, noise, congestion and emissions. A confidence interval has been included in Figure 4-7 for a 95 % confidence level with upper and lower limits. The average externality cost savings of rail over road transport were obtained from Havenga et al. (2012). This additional benefit of transporting the commodities on road, as opposed to rail, indicates that Cases A and C have equal present worth values between an additional 24 and 30 mtpa.

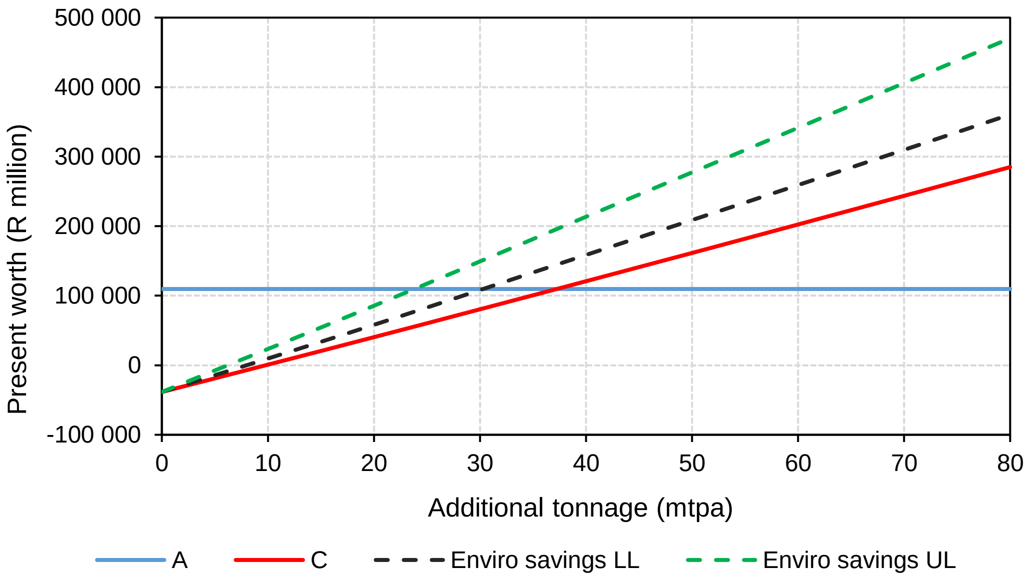


Figure 4-7: Present worth of additional tonnage, from road corridor, transported on Case C compared to Case A for predicted freight growth rates

4.3 SIMULATION AND OPTIMISATION OF THE STANDARD GAUGE LINE

From the economic analysis conducted in Section 4.2, the only feasible standard gauge intervention which may be possible to implement realistically, was the ring fenced standard gauge single line operating concurrently with the narrow gauge line between Durban and Gauteng.

4.3.1 Standard Gauge Single Line Design Calculations

Table 4-13 displays the results of the calculation of the heat input per wheel for a downhill grade of 1:100, Ψ, which was selected as the maximum grade for the standard gauge line. A maximum of 42 wagons per locomotive can be drawn under the stated assumptions. An axle load, W, of 26 tonnes per axle was selected and it was assumed that the train traversed the slope fully loaded at 70 km/h.

Table 4-13: Calculation of the heat input per wheel during breaking

Parameter	*Value*	*Units*	*Comments & Explanations*
Net downhill force per tonne - f_{dt}	98.07	N/t	$\frac{F_g}{\Psi}$
Rolling resistance per tonnes - f_{rt}	11.77	N/t	$137.3 \cdot (W)^{-0.754}$
Downhill push per tonne - f_d	86.30	N/t	$f_{dt} - f_{ft}$
Wagons - W_n	42	-	Assumed
Locomotive mass - L_m	200	tonnes	Assumed
Total train mass - $m_{t\ total}$	4,568	tonnes	$W_n \cdot 4 \cdot W + L_m$
Downhill force - $f_{d\ total}$	394.22	kN	$f_d \cdot m_{t\ total}\ /\ 1000$
Breaking effort at 70 km/h - f_{BE}	190.00	kN	Assumed from braking curve
Friction breaking effort - f_r	204.22	kN	$f_{d\ total} - f_{BE}$
Heat input in wheels - Q	3,970.90	kW	$f_r \cdot v$
Heat per wheel - Q_w	11.82	kW/wheel	$\frac{Q}{8W_n} < 12$

Table 4-14 displays the results for the calculation of the number of wagons per locomotive on an incline with a grade of 1:100. To haul 200 wagons, a minimum of 6 locomotives are required under the stated assumptions based on the work conducted by Lombard (2017). The number of wagons one locomotive can haul on the incline was determined before the number of locomotives to haul 200 wagons was calculated.

Table 4-14 Calculation of the number of locomotives to haul 200 wagons on an incline for the standard gauge line

Parameter	*Value*	*Unit*	*Comments & Explanations*
Maximum tractive effort - TE_{max}	454	kN	Assumed
Train mass - m_t	$104 \cdot W_n$	tonnes	$W_n \cdot W \cdot 4$
Locomotive mass - L_m	200	tonnes	Assumed
Tractive effort required for uphill – let $TE = TE_{max}$			$\frac{F_g}{\Psi}(L_n \cdot L_m + m_t) + m_t \cdot 0.1373(W)^{-0.754}$
W_n for 1 locomotive	38	-	Number of wagons 1 locomotive can haul
200 wagons require	6 (5.26)	-	Number of locomotives to safely haul 200 wagons

Table 4-15 displays the total number of locomotives and wagons required to meet total envisaged throughput. In this scenario, only the containers are carried along the line with no additional tonnage shifted onto the line from road. The wagon payload is given by, W_p, and was set at 84 tonnes. The cycle time, T_{cycle}, was calculated to be 23 hours. The line was also expected to operate, T_{op}, 315 days per year.

Table 4-15: Total number of locomotives and wagons required to transport the base case container tonnage

Parameter	*Value*	*Unit*	*Comments & Explanations*
Throughput envisaged - T_{exp}	Varied	mtpa	Use 18.1 mtpa for the base case
Ruling grade	100	1: Ψ	-
Train mass - m_t	$104 \cdot W_n$	tonnes	$W_n \cdot W \cdot 4$
Wagons per locomotive - W_n	38	-	$TE = \frac{F_g}{\Psi}(L_n \cdot L_m + m_t) + m_t \cdot 0.1373(W)^{-0.754}$
Throughput per cycle	3,192	tonnes	$W_n \; x \; W_p$
Trips per wagon per annum - W_t	328	-	$\frac{T_{op}}{T_{cycle}}$
Throughput per wagon per annum - T_w	27,552	tonnes	$W_p \; x \; W_t$
Throughput per locomotive per annum - T_L	1.05	mt	$W_n \; x \; W_p \; x \; W_t$
Wagons required - $W_{required}$	657	-	$\frac{T_{exp}}{T_w}$
Locomotives required	18	-	$\frac{T_{exp}}{T_L}$ or $\frac{W_{required}}{W_n}$

Figure 4-8 displays the 1:100 railway line and ground elevation longitudinal profile between Durban and Roodekop, Gauteng. The 110 km between Durban and Pietermaritzburg had to be designed at a ruling grade of 1:80 to avoid a long tunnel being constructed between these two points. Each locomotive would be able to haul 25 wagons along this section. The tunnel and bridge limits were set at -30 m and 30 m respectively therefore, any cutting deeper than 30 m would require a tunnel to be constructed and any fill higher than 30 m would require a bridge to be constructed. The section between Pietermaritzburg and Roodekop was designed at 1:100. Five tunnels, totalling 30 km in length, would be required to be constructed for the 1:100 ruling grade, as well as 25 km of bridges.

Figure 4-9 displays a railway line designed at a ruling grade of 1:200, however, the extra tunnelling results in an additional R 84.6 billion worth of construction costs. The reduced grade would allow more wagons to be hauled per locomotive, ultimately increasing the throughput per locomotive per annum. High speed passenger trains would be able to operate on either of the profiles since the maximum grade is less than 1:40.

Figure 4-10 displays the plan layout of the standard gauge single line laid between Durban and Roodekop, Gauteng at a ruling grade of 1:100. The line closely follows the current narrow gauge line. The colour of the points indicates the grade at which the line would be constructed at. The ruling grade between Pietermaritzburg and Durban could not be designed at a grade less than 1:80.

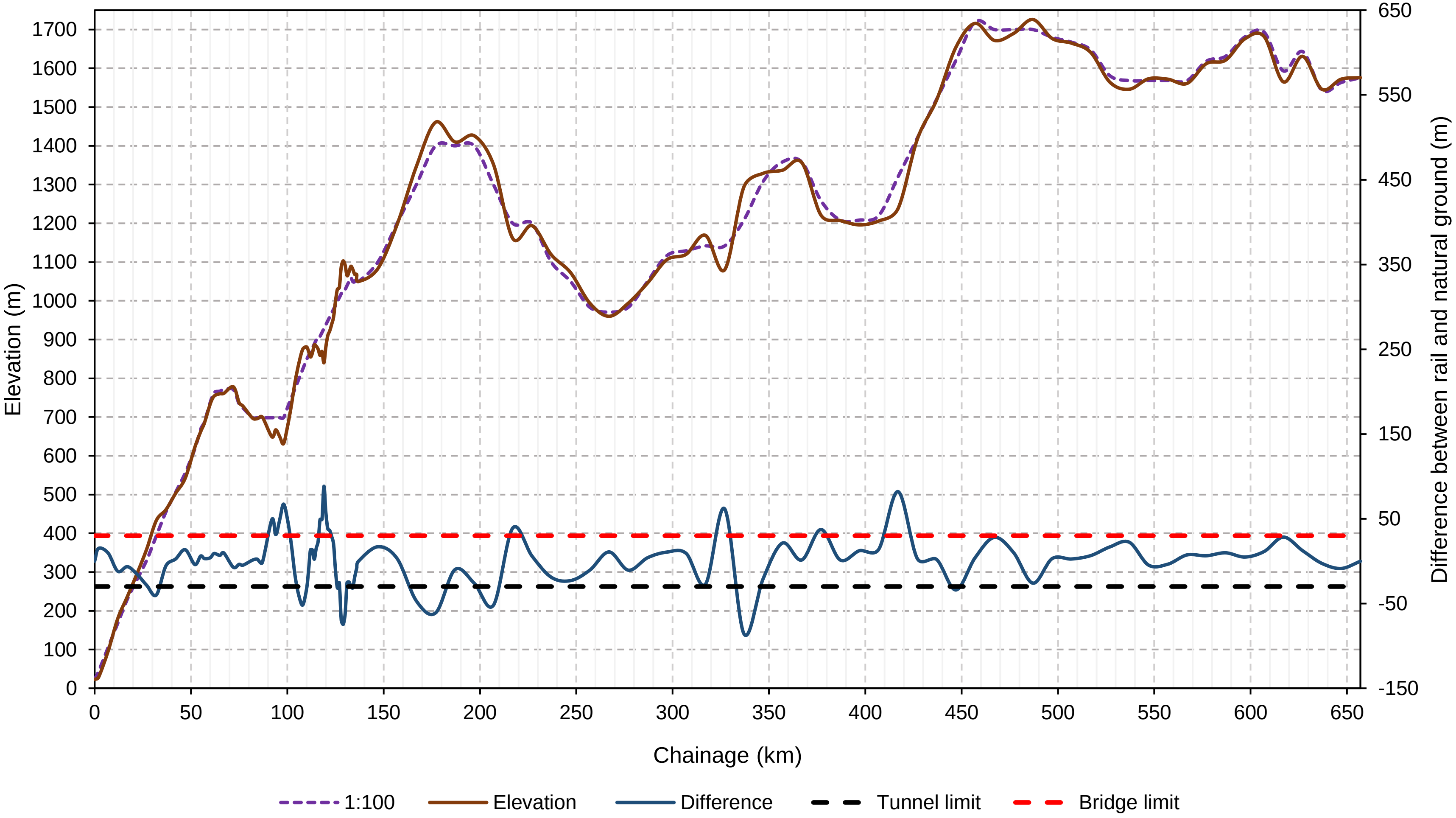


Figure 4-8: Elevation and 1:100 railway line longitudinal profile between Durban and Roodekop

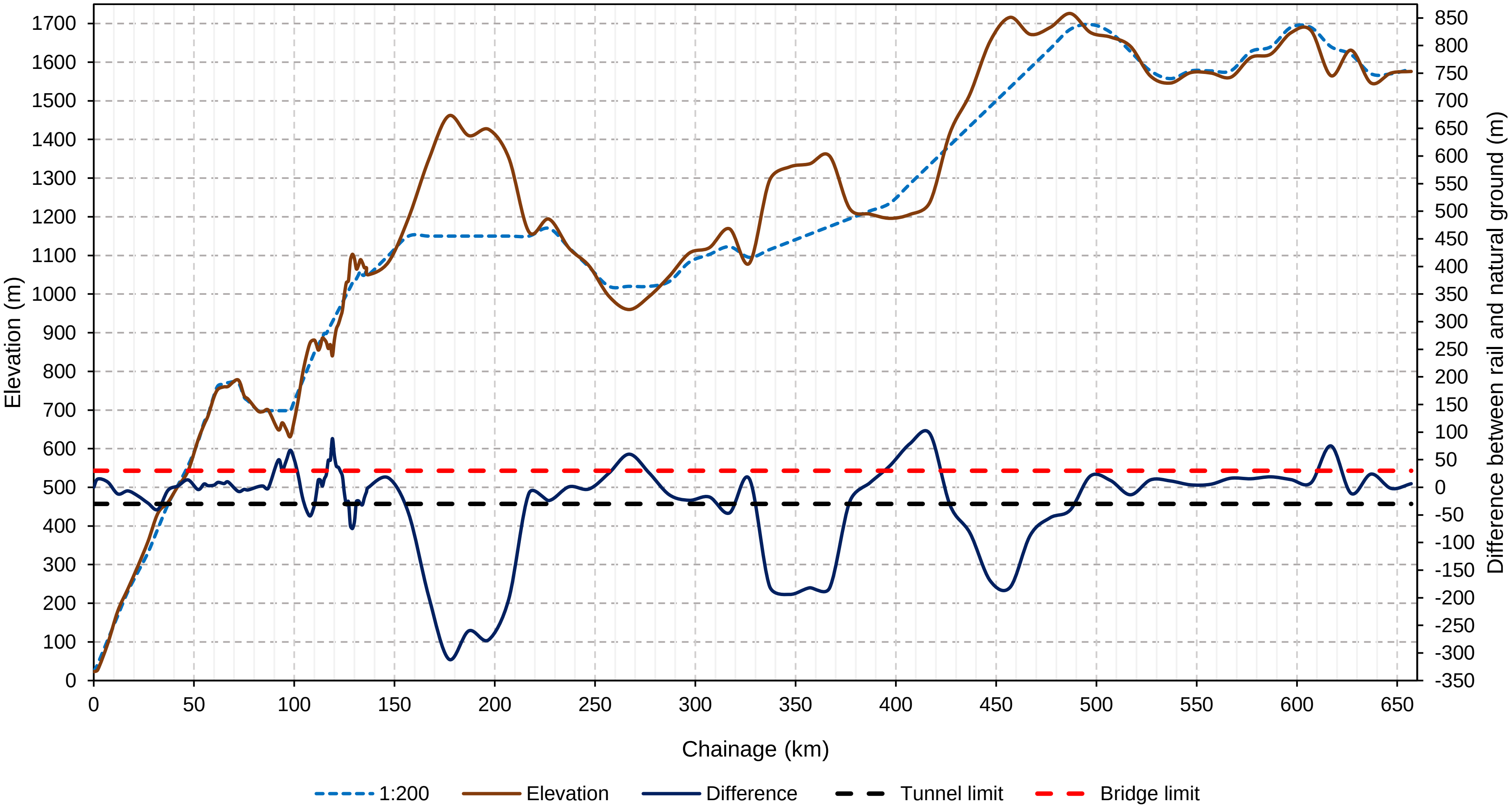


Figure 4-9: Elevation and 1:200 railway line longitudinal profile between Durban and Roodekop

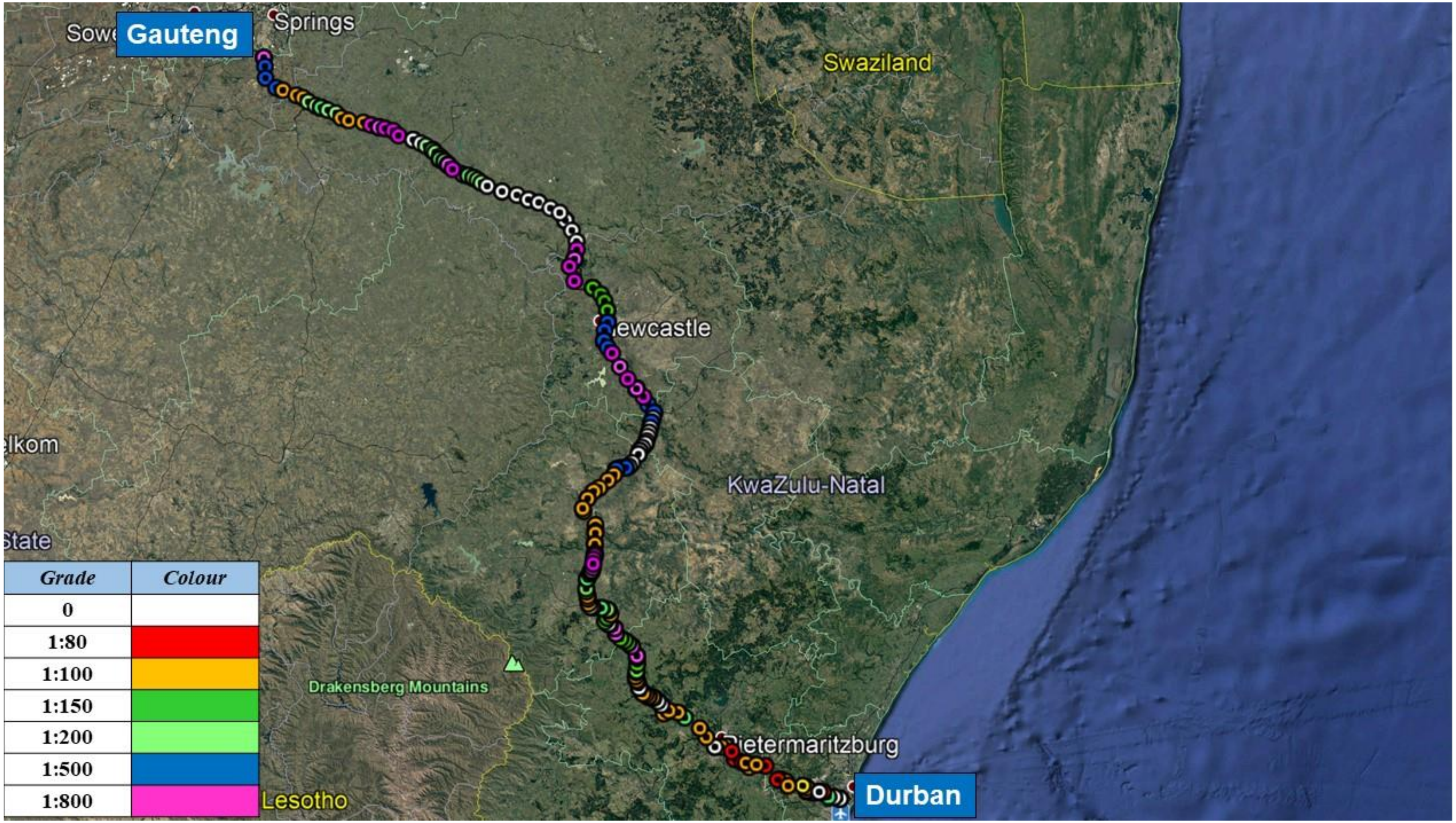


Figure 4-10: Plan view of the ring-fenced standard gauge single line between Durban and Gauteng

4.3.2 Simulation Model Outputs

The simulation was able to output the maximum permissible number of tonnes expected per annum for the standard gauge railway single line as well as the average time to travel the network. The addition of high speed trains which travel up to 160 km/h would be able to run on the proposed alignment, however, the addition of high speed trains to a freight corridor, consisting of slower moving freight trains, would induce large delays to both train types as seen by Sogin et al. (2013). A further study could focus on scheduling and optimisation of these operations to minimise delay however, the outcome will likely lead to reduced revenue generation along the corridor by mixing these two operations on one line.

Table 4-16 displays the calibrated and uncalibrated travel times for the single line standard gauge railway line. The travel times were compared to an expected route travel time, which was calculated from first principles. The route travel time was calculated assuming that the maximum uphill speed was 36 km/h, the maximum downhill speed was 70 km/h and, that on straight sections, the train would be able to travel at 80 km/h with acceleration and deceleration rates of 0.5 m/s^2 and 1 m/s^2 respectively. None of the uncalibrated simulation travel times exceeded 10%. However, the model was calibrated in any case and led to RMSPE values of less than 1 %.

Table 4-16: Comparison between the calibrated and uncalibrated travel times along the standard gauge single line

Crossing loop spacing (km)	*Travel time (direction)*	*Calculated travel time (mins)*	*Simulation travel time uncalibrated (mins)*	*RMSPE uncalibrated (%)*	*Simulation travel time calibrated (mins)*	*RMSPE calibrated (%)*
80	Up	630	588.07	6.66	631.18	0.19
	Down	572	536.44	6.22	573.11	0.19
60	Up	630	667.42	5.94	632.42	0.38
	Down	572	609.33	6.53	574.33	0.41
40	Up	630	683.01	8.41	630.01	0.00
	Down	572	624.89	9.25	571.89	0.02
35	Up	630	656.09	4.14	625.78	0.67
	Down	572	601.01	5.07	570.69	0.23
30	Up	630	665.49	5.63	631.69	0.27
	Down	572	610.10	6.66	572.21	0.04

Table 4-17 displays the scenarios evaluated in the simulation. Five crossing loop spacing distances were evaluated to establish how the number of crossing loops affected the number of trains that could pass through the system per day. It was noted that as the number of crossing loops on the line increased, the average number of trains per day that could pass through the system increased.

Table 4-17: Single line standard gauge railway average trains per day

Crossing loop spacing (km)	*Number of loops*	*Average trains per day*
30	22	23.04
35	19	22.15
40	16	20.57
60	11	16.94
80	8	16.00

Figure 4-11 indicates the average delay for the varying number of crossing loops. It was noted that as the number of crossing loops on the line increased, the amount of delay experienced per train was reduced. Less time is spent waiting at crossing loops when there are more loops which leads to reduced interaction between trains. Despite the costs associated with constructing additional loops, the system can operate more efficiently, and more loops will lead to greater throughput per annum.

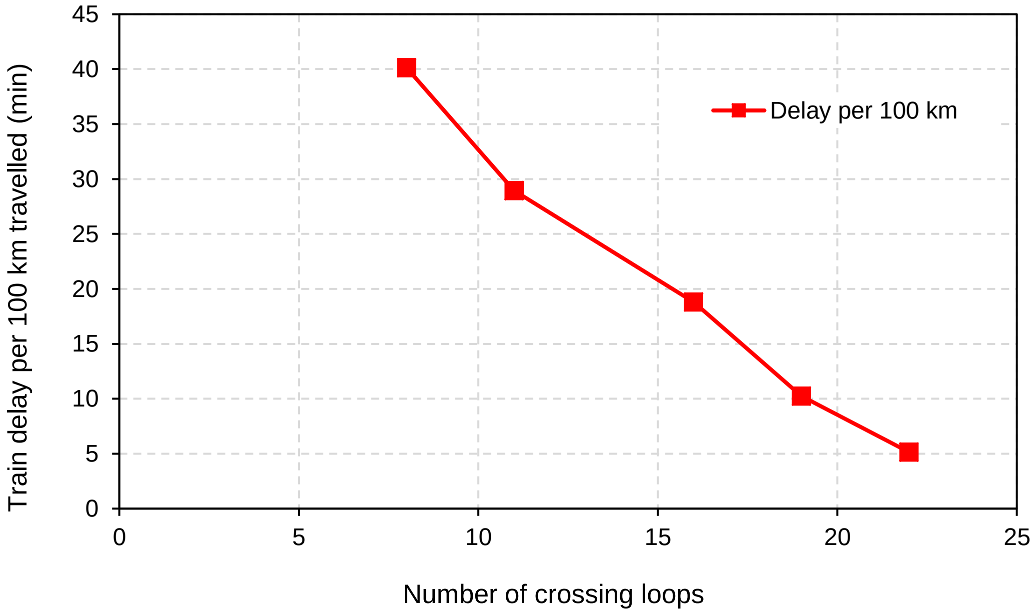


Figure 4-11: Delay experienced by trains per 100 km travelled for a varying number of crossing loops

Figure 4-12 displays the number of tonnes transported for varying crossing loop spacing and train lengths. The figure indicates that running longer trains will lead to more tonnage being transported by the standard gauge line. It is therefore most beneficial to run 210 wagon trains.

The number of crossing loops affects the duration of time a train will spend waiting to occupy a section of track. Too few crossing loops leads to underwhelming annual tonnages, however, there is a slightly reduced construction cost.

As the number of crossing loops increases, so does the permissible annual tonnage along the line. In Section 4.2.3 it was required that the line be able to transport 98.1 mtpa if the line was used to transport the 80 mtpa of additional freight from the road. To meet the 98.1 mtpa, a minimum of 17 crossing loops should be constructed at spacings of 40 km and train sets should transport, on average, at least 180 wagons per trip.

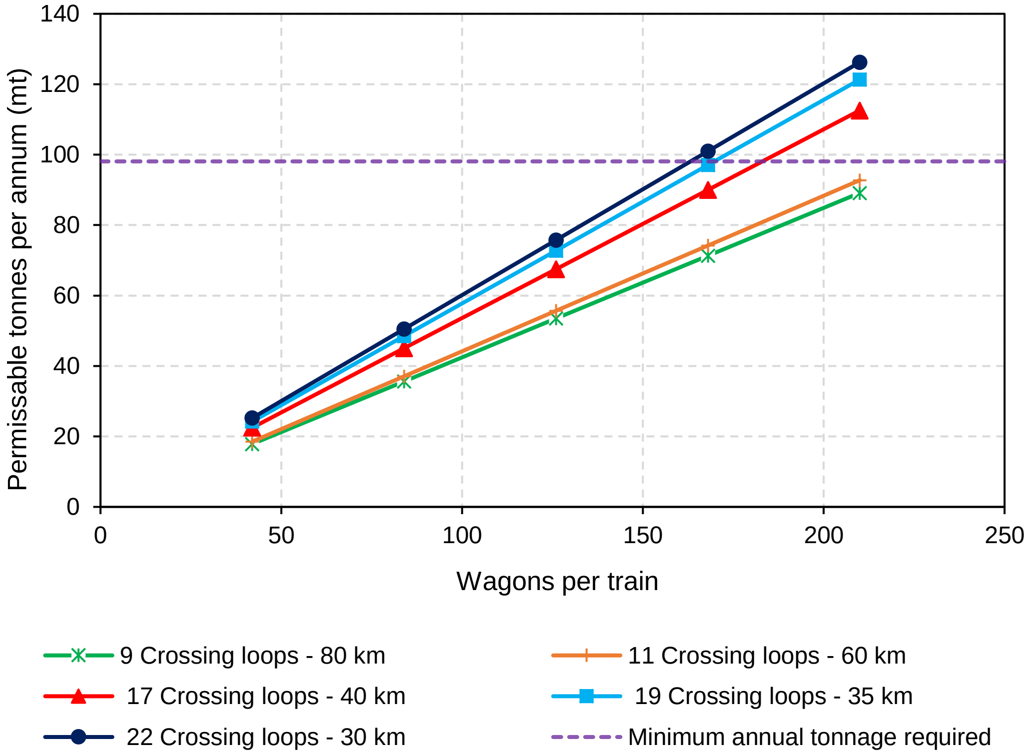


Figure 4-12: Permissible tonnes through the system as a function of crossing loop spacing and wagons per train

4.4 SUMMARY OF ANALYSIS AND DISCUSSION OF RESULTS

Chapter 4 reviewed the South African core railway network with the focus being on determining which corridors could potentially benefit most from a gauge change intervention. From the analysis of the outcomes, it was noted that only the Coal line, Iron ore line and the Natal corridor could potentially benefit from gauge change interventions.

The results of the economic evaluation indicated that only the Natal corridor provided an opportunity which would lead to an economically successful project, with the benefits exceeding that of the base case. It was identified that the Coal and Iron ore lines would benefit from a gauge change intervention, however, the benefits of the gauge change would not outweigh those of the base case.

The results of the simulation of the single line standard gauge railway, which would run parallel to the Natal narrow gauge corridor, displayed that the line would be able to transport the required volume to make the project more profitable than the base case. It was also observed that increasing the number of crossing loops and wagons would lead to a more optimal operation.

5 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of this study are presented in Sections 5.1 and 5.2 respectively.

5.1 CONCLUSIONS

The conclusions made with regard to the study have been summarised into determining which corridors could potentially benefit from a standard gauge intervention, what type of standard gauge intervention would be best suited to the respective corridors and how the intervention implemented will affect operations along the corridor.

5.1.1 Corridors that could Benefit from a Standard Gauge Intervention

It was noted from the analysis that corridors would be required to transport a large amount of tonnage to economically warrant an intervention. Three corridors were identified that could economically benefit from a standard gauge intervention which included the Coal export line, the Iron ore line and the Natal corridor. The remainder of the corridor’s within South Africa are not expected to transport enough tonnage to warrant a standard gauge intervention. These corridors would economically benefit more from following the plans proposed by Transnet in the Market Demand Strategy.

The Department of Transport (2017) and Van der Meulen (2010) suggested that the corridor between Hotazel and Ngqura could potentially become a standard gauge corridor. The conclusions of this study do not rule out this possibility but rather suggest that this may only be possible if most of the rail traffic that would travel to Cape Town, is redirected to this port and if the manganese is exported along this line concurrently.

It was recommended by The Department of Transport (2017) that a standard gauge conversion between Polokwane and Noupoort be performed along with a conversion to standard gauge of the De Aar and Cape Town line and the Kimberley to Gauteng line. This would be highly unfeasible and would require major government subsidy to cover the costs of these operations.

The Department of Transport (2017) also recommended the construction of three passenger orientated standard gauge corridors along with the construction of a high-speed line between Durban and Gauteng. This study was focussed on freight transport however, the World Bank (2012) states that passenger railway services require high passenger volumes to avoid government subsidy. It was also noted that passenger train services will very rarely cover their associated infrastructure costs and strict long-term budgeting will be required. A thorough understanding of the project’s long-term operations and benefits will need to be well understood before high speed passenger lines can be constructed to this scale.

5.1.2 The Best Suited Interventions for the Corridors Identified

Breaks-of-gauge have many complexities associated with them and not all corridors would benefit from the same standard gauge intervention.

For the Coal line, it was noted that the implementation of either a standard gauge conversion or constructing a third rail would ultimately lead to an economically profitable project. However, the Coal line runs at close to 100 % capacity as a narrow gauge corridor, therefore any disruptions would lead to a major loss of revenue for Transnet. As a result, the transhipment and third rail projects did not emerge as profitable as Transnet’s Market Demand Strategy.

The Iron ore line spans over 850 km of single track between Sishen and Saldanha. Any upgrades or conversions performed on the line would lead to the halting of operations and a direct loss of revenue to Transnet. The line is well established as a narrow gauge corridor and this was made evident in the outcomes of the economic analysis. The Department of Transport (2017) and Van der Meulen (2010) both recommended that the line remains a narrow gauge line which is supported by this study.

The last corridor identified for potential standard gauge intervention was the Natal Corridor. The two alternatives identified included the addition of a 3rd rail to the current narrow gauge railway line or the construction of a standard gauge line parallel to the current narrow gauge corridor. It was determined that it would not be economically feasible to implement either of the alternatives when compared to Transnet’s Market Demand Strategy. It was however identified that the standard gauge would be highly underutilised in the base case analysis and that an opportunity existed to transport additional freight, which would otherwise be transported by road. If an additional 37.5 mtpa were transported by the standard gauge line, Transnet’s Market Demand Strategy would not be the most economical option. The standard gauge ring fenced line was therefore simulated to better understand its ability to transport the required tonnage and to determine whether the estimated operational projections could materialise through the determination of the maximum annual throughput.

5.1.3 The Standard Gauge Intervention’s Effect on Operations

A ring-fenced standard gauge line would have very limited interaction with the narrow gauge network, therefore the break-of-gauge issue is avoided. From the simulation it was observed that a standard gauge single line would be able to transport in excess of 100 mtpa if 17 or more crossing loops are constructed. The delay experienced from train interactions was reduced as the number of crossing loops was increased. If the line were to be constructed, 19 or 22 crossing loops should therefore be constructed to relieve operational stress on the system when the line begins to reach the expected capacity. Longer trains led to improved annual throughput, but inefficient depot operations could lead to long cycle times and reduced annual throughput.

5.2 RECOMMENDATIONS

The following recommendations are made for future research in the field:

- South African railways should not stray from narrow gauge but rather work towards a future where standard gauge and narrow gauge operations can coexist. Interoperability with the rest of Southern Africa will work best on a narrow gauge network since the neighbouring countries all run trains on narrow gauge networks.
- Rail may be tasked with becoming the country’s freight transportation backbone (Department of Transport, 2017). Current operations and future plans do not place rail in a position to carry the possible additional tonnage. Rail will need to be reformed through policy similar to those put forward by The Department of Transport (2017). However, the policies should be put forward with a better understanding of the financial and economic implications of each project on the country as a whole.
- The construction and operation of a standard gauge freight orientated corridor between Durban and Gauteng was found to be a possibility. This study should act as a steppingstone towards a future more detailed feasibility study. This will however require key role players, possibly from the private sector, to take up the mantle of this project. A high-speed line would likely be possible, but the social and environmental benefits will likely be the driving force behind such a project and not the financial projections which would likely be insipid.
- The results of the economic analysis may vary depending on the analysis period, discount rate, prices of rolling stock, construction costs and revenue estimations. Should a project such as the construction of a standard gauge

single line be undertaken, the project value would undoubtedly change since direct quotations would be known from suppliers and construction companies. Therefore, it is likely that the estimated benefits could be greater than those specified in the economic analysis conducted in this study.

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