UNIVERSITY OF CAPE TOWN

Railway Tunnels Management System in South Africa – Concrete Structural Elements

Prepared by:

Luba Jean-Pierre THAKO (BEng Civil Engineering)

Supervised by:

Professor Pilate MOYO

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"I've come to believe that each of us has a personal calling that's as unique as a fingerprint – and that the best way to succeed is to discover what you love and then find a way to offer it to others in the form of services, working hard, and also allowing the energy of the universe to lead you."

Oprah Winfrey

Abstract

A reliable transportation network is key to economic development and social well-being of communities. Since 19th century, rail transport has provided the most efficient link between South African's wealthy mineral heartland and the seaports. In developing this rail network, a considerable number of railway tunnels were built due to the topography of the coastal regions. These **tunnels are ageing**, their operational and environmental conditions are constantly changing. Thus, their management practice should be optimised to adequately respond to the needs of the organisations managing them and for them to continue providing a safe and sustainable service. Therefore, this study **reviewed the current railway tunnels management practice in South Africa and proposed an approach to improve it**, considering the existing structures management systems. Further, it focuses on the **concrete structural elements** and their **related defects** due to the harsh environments of these tunnels. Therefore, the *Procedures to enhance tunnels management applied* consisted in outlining the gaps uncovered in the current railway tunnels management practice in South Africa and enhance this practice considering the structures management systems reviewed. This is done by improving the components of each module and integrating them in the proposed **railway tunnels management system in South Africa**. First, it dealt with the inventory module, designed inventory forms for items and for concrete structural elements and their components to record, inspect and monitor. Second, it designed a Tunnel Inspection Programme that set the inspection intervals, the requirements for the inspection team members, the tools and techniques and procedures to apply. This programme specified also the method of evaluating the defects and the definition of the score and the relative score of the components of elements and the health of the tunnel. Third, it developed a Tunnel Monitoring System that targeted the most critical and vulnerable elements and set the techniques and tools to monitor them. Finally, it integrated all the modules in the system designed. As *results*, this research has proposed a computerised tunnel management system that enhances the current practice in South Africa. This arises from the scrutinised practice in light of the existing structures management systems reviewed. From the analysis of the existing inventory data on railway tunnels and on the heavy haul lines in South Africa, relevant information was obtained. Thus, an inventory module has been developed comprising *tunnel inventory forms* that classify the items to be recorded and inspected. This module also described the concrete structural elements and their specific components. A *Tunnel Inspection Programme* has been designed, specifying the frequency of inspections based on the condition of tunnels, their ages, and the unpredictability and the harshness of their environments. This programme has also promoted the relevant techniques to be applied to inspect concrete structural elements and the appropriate tools to be used. Additionally, the requirements for inspection team concerning the qualifications and experience of each member have been provided. This programme has also recommended the use of the current DER rating system, emphasising that the scope of this study refers to concrete structural elements that should all be rated and recorded. Additionally, it has designed a Tunnel Monitoring System specific to the most critical and vulnerable concrete structural elements of railway tunnels. This system includes a set of tunnel monitoring strategies, the setting up of the system and the sensory system. It finally integrated all these sub-systems into the main Railway Tunnel Management System in South Africa. In *conclusion*, this research proposes the integrated computerised railway tunnel management system for South Africa. It also set the "big picture" of the overall tunnel structures and the tunnels on the heavy haul lines currently managed by Transnet TFR in South Africa. Additionally, it sustains the current DER rating system and proposes its application to all the defects on the concrete structural elements, instead of the worst defect on the inspected element. As *recommendations*, the railway tunnels authority should adopt a monitoring system for each tunnel on the heavy haul lines. Also, the authority should make available information on all existing monitoring systems on railway tunnels and the most critical data collected. Moreover, the authority should make available the previous railway tunnels inspection files to be uploaded to the proposed system. Apart from this, we recommend a further comprehensive study to integrate the inspection of non-structural elements to the proposed system. Finally, we recommend to the management authority to organise a comprehensive study of the water leakage issues on railway tunnels to better understand and adequately respond to them.

Key words: Railway Tunnel, Management System, South Africa, Concrete, Structural Element, Heavy Haul Lines.

The following are the links that make accessible the systems designed:

Proposed Improved System:

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System reflecting the current practice:

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Acronyms and abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASR	Alkali-Silica Reaction
BER	Bureau for Economic Research
BIM	Building Information Modelling
BMS	Bridge Management System
BMTS	Bridge Maintenance subsystem
BRRS	Bridge Rehabilitation/ Replacement subsystem
CCP	Chemical Churning Piles
CDG / HDG	Completely Decomposed Granite / Highly Decomposed Granite
CEDD	Civil Engineering and Development Department
CESI	Condition, Extent, Significance, and Intervention.
COSMOS	Computerised System for the Management of Structures
COTO	Committee of Transport Officials
CSIR	Centre for Scientific and Industrial Research
DBSA	Development Bank of Southern Africa
DoT	Department of Transport
DPLG	Department of Provincial and Local Government
D&B	Drill and Blast
EPB	Earth Pressure Balance
EPBM	Earth Pressure Balance Machine
EPWP	Expanded Public Works Programme
FBG	Fibre Bragg Grating
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HHT	Heavy haul tunnels
HiSMIS	Highways Structures Management Information System
ICE	Institution of Civil Engineers
IDD	Inventory Data Description

IFRS	International Finance Reporting Standards
IHHA	International Heavy Haul Association
IMIESA	International Infrastructure Management Manual
INGENIUM	Association of Local Government Engineering NZ Inc
IPWEA	Institute of Public Works Engineering of Australia
IRC	Infrastructure Report Card
ISO	International Organization for Standardization
ITIS	Integrated Transportation Information System
Km	Kilometre
KRT	Kaohsiung Rapid Transit
LPR	Linear Polarisation Resistance
MEED	Middle East Business Intelligence
MFMA	Municipal Finance Management Act
MOS	Monitor Optics Systems
MPF	Maintenance Priority Factor
MS	Microsoft
MSA	Moving South Africa
Mtpa	Mega tons per annual
NAMS	National Asset Management Steering Group
NATMAP	National Transport Master Plan
NBI	National Bridge Inventory
NDP	National Development Plan
NDT	Non-destructive testing
NLTA	National Land Transport Act
NLTTA	The National Land Transport Transition Act
NLTSF	National Land Transport Strategic Framework
NRA	National Roads Agency
NTI	National Tunnel Inventory
NTIS	National Tunnel Inspection Standards
PenDOT	Pennsylvania Department of Transportation
PFMA	Public Finance Management Act
PRASA	Passenger Rail Agency of South Africa
RSA	Republic of South Africa

RSR	Railway Safety Regulator
RT.ZA	Railway Tunnels in South Africa
RTMS.ZA	Railway Tunnels Management System in South Africa
SA	South Africa
SABS	South African Bureau of Standards
SADC	Southern African Development Community
SAICE	South African Institution of Civil Engineering
SANRAL	South African National Roads Agency Limited
SANS	South African National Standard
SAR	South African Railways
SAR&H	South African Railways & Harbours
SARTAT	South African Railway Tunnels Analysis and Trends
SART.DB	South African Railway Tunnels Database
SATS	South African Transport Services
SCC	Surrey County Council
SCL	Sprayed Concrete Lining
SDG	Sustainable Development Goals
SHM	Structural health monitoring
SIRS	Structural Inventory Record System
SJG	Super Jet Grouting
SNTI	Specifications for National Tunnel Inventory
SPSS	Statistical Package for the Social Sciences
SU	Stellenbosch University
TAT	Tunnels Analysis and Trends
TBM	Tunnelling Boring Machine
TE	Transnet Engineering
TFR	Transnet Freight Rail
TIM	Tunnel Inventory Management
TIP	Tunnel Inspection Programme
the dplg	Department: Provincial and Local Government
TuMoS	Tunnel Monitoring System
TOMIE	Tunnel Operations, Maintenance, Inspection and Evaluation
UCT	University of Cape Town

UK	United Kingdom
USA	United States of America
VBA	Visual Basic Application
WSNs	Wireless Sensor Networks

1. Introduction

1.1 Background and Context

A reliable and healthy transportation infrastructure is critical to improving the economic and social well-being of society. In South Africa, the White Paper on National Transport Policy sets the vision for South African Transport. This Transport system should provide safe, reliable, effective, efficient, and fully integrated transport operations and infrastructure. Hence, this system would best meet the needs of freight and passenger customers at improving levels of service and cost. Furthermore, this would support government strategies for economic and social development whilst being environmentally and economically sustainable (Department of Transport [DoT], 1996: 3). Overall, this quality of transport infrastructure is not only obtained by building new infrastructure, but also by assuring the existing infrastructure remains fit for purposed operations. The following Figure 1-1 presents the South African Rail Network.

Figure 1-1: South African Rail Network

(Department of Performance Monitoring and Evaluation & Development Bank of Southern Africa, 2012)

The construction of railway tunnels in South Africa, especially on heavy-haul lines, mostly proliferated during the development of the rail network. These tunnels facilitate the construction of direct links between the nearest ports and the industrial heartland (Figure 1-2 to 1-4) (Mitchell, 2014: 1). Currently, these tunnels are ageing and many of them approach or perform beyond their service life. Also, the tunnels on the heavy-haul lines are experiencing increase of the traffic load and flow or frequency. Therefore, to appropriately embrace the opportunities and tackle the challenges related to the heavy-haul industry, they need to be efficiently managed and maintained. If so, they will continue to provide safe and sustainable service. Finally, their authorities need appropriate and consistent programmes and systems, and adequate resources. Current management systems (local and international) will be reviewed in the South African's network context and a better approach specific to railway tunnels will be proposed.

Figure 1-2: South African Coastlines Map

(Department of Environmental Affairs, n.d.)

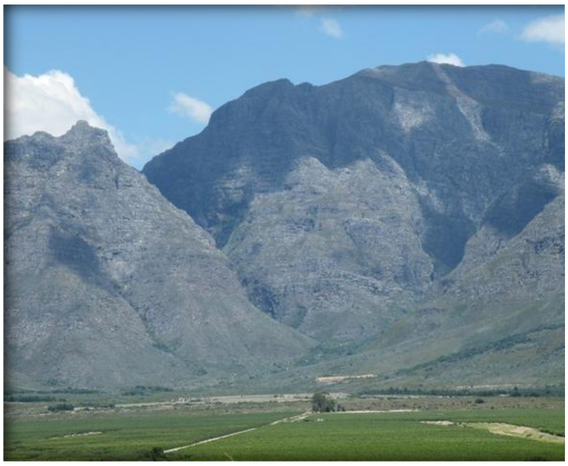


Figure 1-3: Natural Obstacle

Figure 1-4: Rail Tunnel External View

(Fleming, 2005)

Transnet Freight Rail (TFR), Transnet's largest operating division, is a world-class freight rail company specialising in heavy haul and general freight transportation. Also, TFR is a profitable and sustainable freight railway business, which contributes to the competitiveness of the South African economy (Transnet SOC Ltd, 2017: 2) (Figure 1-5). Among its main objectives, it targets a prominent level of performance that provides capacity ahead of demand and aligns to the sustainability of development plans (DoT, n.d.: 11).

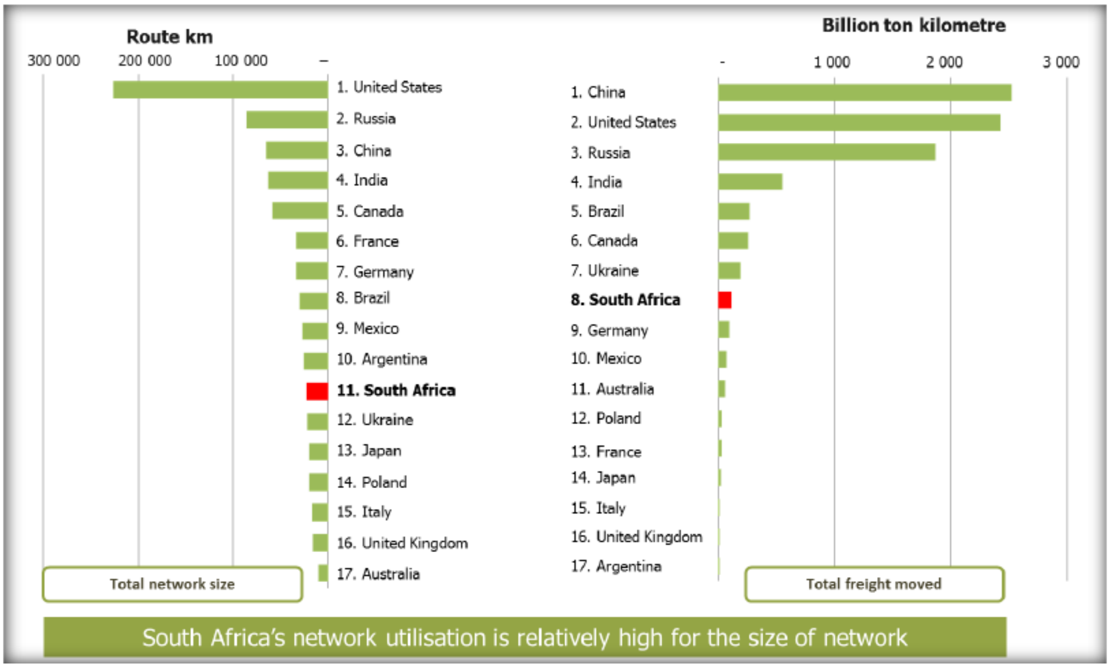


Figure 1-5: Railway Network Comparative Performance

(Transnet SOC Ltd, 2016)

1.2 Problem Statement

Railway tunnels are integrated components of the rail infrastructure and play a key role in reducing the travelling time and the detours on the network. Currently, to guarantee the safety of rail infrastructure and provide reliable services, the heavy-haul lines in South Africa are adapting to any changes related to their operations. Also, the ageing infrastructure needs considerable attention as it may approach its service life or perform beyond it. Therefore, the concrete structural elements of railway tunnels, located in harsh environments, need to be efficiently inspected and monitored. Hence, consistent inspections and planned maintenance of railway tunnels will mitigate the risk of their failure. Finally, sufficient effort needs to be put in place, locally and internationally, in research regarding the management and maintenance of tunnels on heavy-haul lines.

1.3 Purpose and Significance

The purpose of this research is to contribute towards the ongoing endeavour in improving the management and maintenance of tunnels on the heavy-haul lines in South Africa. As a review of the existing systems, it will identify and assess the gaps of these systems, catalogue current good practice and propose an approach to enhance it. In detail, it will provide a guideline on inventory, inspection and monitoring of concrete structural elements of heavy-haul lines to guarantee the level of service required. Also, it will provide a tool that will constitute a platform integrating the whole management system of these tunnels. This will facilitate the recording and retrieving of inspection data and provide timely information and trends.

As a result, the integration in routine operations and the daily use of the proposed tunnel management system will promote safe and sustainable management practices. This will provide timely information on the tunnel inventory stock and promote an efficient and effective use of inspection records. Moreover, it will improve the decision-making process of assessing the criticality of tunnel components and planning for maintenance. Finally, this research aligns with the current aim to foster the development of heavy-haul lines in South Africa and will contribute to increasing and sharing the knowledge on railway tunnels management systems.

1.4 Research Objectives

1.4.1 Main Objective

This research scrutinised the current railway tunnels management practice in South Africa and proposed an approach to improve it in light of the existing structures management systems.

1.4.2 Specific Objectives

This study identified the heavy haul lines in South Africa and the tunnels on the sections of these lines. It also illustrated the common defects on concrete structural elements of railway tunnels specifically due to their harsh environments. After, it defined and described a structure management system and its components. Additionally, it overviewed the existing structure management systems from various countries (Canada, USA, Japan, Switzerland, Germany, RSA, Australia, New Zealand). Further, it reviewed the current railway tunnels management practice in South Africa. Finally, it proposed an improved guideline on management practice of railway tunnels.

1.5 Scope and Limitations

This research focused on tunnels managed by TFR and more specifically on the heavy-haul railway tunnels in South Africa. It narrowed to the concrete structural components of these tunnels including liners, portals, roofs girders, tunnel ceiling structures, tunnel invert structures, interior walls, cross passageway, columns and piles. It mainly considered the defects on these elements due to the harsh environments of these tunnels. The drainage system (open gravity flow, closed gravity flow, and pumped flow), other systems (emergency exits, accessory components including ventilation and lighting, electrical, mechanical, functional) and the domain of equipment were beyond the scope of this research. Also, the monitoring system presented did not describe the data acquisition and transmission system, the related data processing and analysis system, a specific data management system, a structural health evaluation system based on monitoring data. However, it is considered as a component of critical inspections. Finally, the financial aspects including the whole life costing are not a part of this study.

1.6 Dissertation Outline

This dissertation was structured as follows:

Chapter one, "**Introduction**", introduced the study and provided a background and context of this research. It constituted the ground of this study and headed up the review of the existing literature and the procedures to be applied. Chapter two, "**Literature Review**", presented relevant literature related to the context of this study. Firstly, it briefly introduced the heavy haul lines in South Africa. Secondly, it succinctly described the defects on concrete structural elements of railway tunnels. Thirdly, it presented a definition and description of a management system and its components. Finally, it summarised the existing bridge, tunnel and structure management systems and highlighted their strengths and weaknesses. Chapter three, "**Procedures to Enhance Tunnels Management**", described the procedures implemented to reach the objectives assigned to this study. It presented the processes to consider when undertaking inventory, inspection or monitoring of heavy-haul tunnels in South Africa. Chapter four, "**Data Analysis and Findings**", provided the analysis of inventory data and regrouped the benefits of the structures systems reviewed that translated the optimum railway tunnels management system for South Africa. More importantly, it proposed a best integrated approach for the concrete structural elements of railway tunnels. Finally, chapter five, "**Conclusions and Recommendations**", concluded that study and presented some recommendations.

2. Literature Review

2.1 Introduction

This chapter of the literature review constitutes the backbone of this research as it relates to its main concepts. It synopsises the heavy-haul lines in South Africa, outlines the defects on concrete structural elements of railway tunnels, defines and describes a management system. Most importantly, this review of the literature overviews the existing structure management systems and presents the current railway tunnels management practices in South Africa. In fact, rail lines, tunnels, bridges, highways are transport infrastructure that connect people to their daily routines and other activities (United States of America [USA]. Colorado Department of Transportation, 2013: ES-3). Moyo and Nordengen (2018) highlighted that bridges and tunnels are among the significant and critical discrete components of a transportation system.

Overall, bridges and tunnels owners express their concerns about ageing tunnel assets and the optimisation of the allocation of limited funding for their maintenance and preservation (Allen et al., 2015: 1). Therefore, Tunnels Management Systems developed around the world set ways to ensuring that the structures built will appropriately satisfy the expectations of the authorities, the operators and the end users. This in relation to the level of service required and the safety of the structures and the surrounding environments.

Tympakianakia et al. (2018: 179) recognises the impact of research on aiming for a holistic and reliable transport system from an economic and quality of life perspective. In fact, the outcome of the related research should unveil the vulnerability of the transport system and propose ways to improve it. To relate this current research to previous works enlightening the amendment of transport systems in South Africa and abroad, this chapter of the literature review is provided. It summarises the main concepts and themes related to railway tunnels management systems in South Africa, with emphasis on concrete structural elements of these tunnels. Among them, this chapter refers to the heavy haul lines in South Africa, the defects on concrete structural elements of railway tunnels and the definition and description of a management system. Finally, it reviews the existing structures management systems in use in South Africa and abroad.

2.2 Heavy Haul Lines and Tunnels in South Africa

From its first utilisation in the sixteenth century, railway infrastructure has been a reference of capacity, speed, reliability and environmentally friendly for all terrestrial transport modes (Centro de Estudio Materiales y Control de Obras S.A., 2014: 12). Indeed, the goal of a railway is to safely, rapidly and regularly transport people and freight from one place to another. This should be done comfortably and on time. Zaayman (2016) specified that the railway system authority should contribute to the above goal by ensuring the reliability, availability, maintainability, affordability and safety of the infrastructure. Fortunately, worldwide, agencies managing the transport systems are striving to adequately respond to current and future challenges. For example, Russell & Gilmore (1997: 3) decorated an initial step presenting a process to assure the public that the American national transportation infrastructure is as safe and efficient as possible. And, in South Africa, Muir & Gouws (2017: 607) described Transnet Freight Rail (TFR) as the business unit which manages the South African freight railway lines.

Currently, heavy haul (HH) railway transport operates the longest and heaviest freight trains in the world to convey large amounts of bulk commodities from mining areas to dedicated export terminals (Busatta & Moyo, 2017: 599) (Figure 2-1). Therefore, TFR should mitigate the negative consequences of running longer/heavier trains on the service life of existing civil structures serving HH lines (Busatta & Moyo, 2017: 599). In fact, increasing axle loads has been and continues to be important for railways to meet the needs of customers. Leeper & Allen (2015: xi) identified the impact of vehicles with very heavy axle loads on the wheel/rail interface and the preservation of the industry's excellent safety record. This mainly concerns metallurgists, engineers, and railway managers.

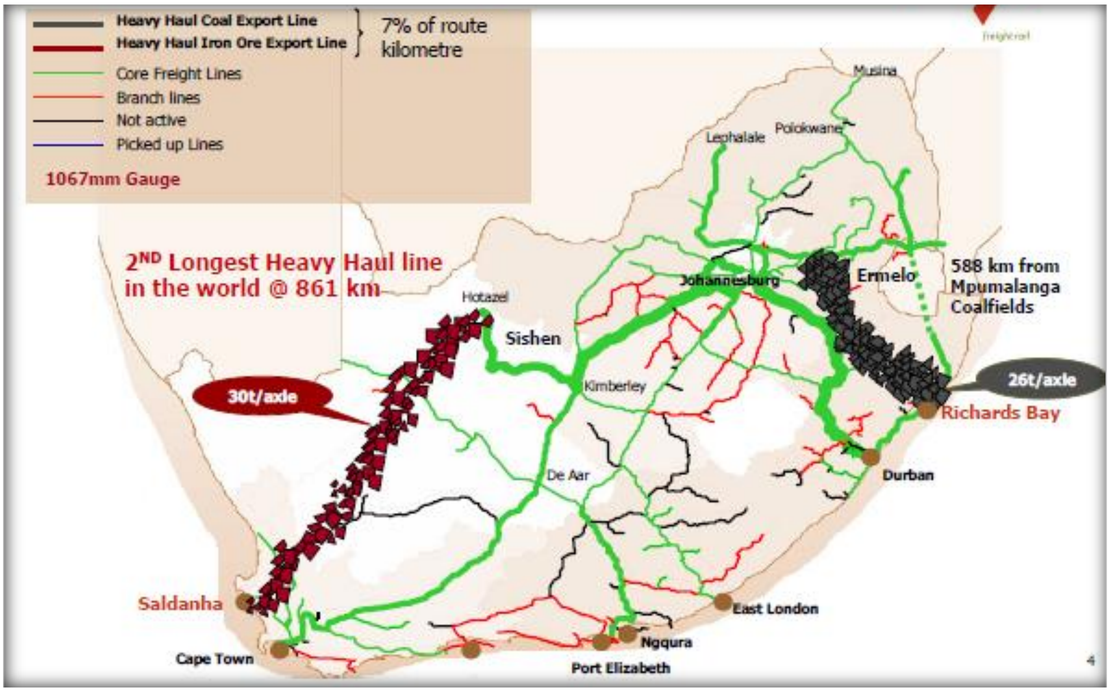


Figure 2-1: Heavy Haul Lines in South Africa

(Kuys & TFR, 2011)

It should be noted that the Sishen-Saldanha Iron Ore Line and the Richards Bay Coal Line operated by TFR are among the world leaders in the field of heavy haul transportation (TFR, n.d.: 14).

Jiyuan (2017) proposed an upgrade of the transport infrastructure to appropriately meet the requirements of heavy-haul transportation. This will satisfy the increase in transport capacity, and subsequently improve operational efficiency and economic benefits by increasing axle load. For Busatta & Moyo (2017: 599), the serviceability and safety of the civil infrastructure serving the lines are critical for heavy haul railway transport. This has been confirmed by the Japan Society of Civil Engineers (2010: 2) who referred to civil engineering structures with a service period of 50 to 100 years. This society recommended that those structures should require remedial measures under the conditions where performance requirements vary in changing social situations. This includes wheel load increases on bridges due to the traffic of larger vehicles and other unfavourable phenomena.

2.2.1 The Sishen-Saldanha Ore Line (axle loading: Ore line at 30t/axle)

The ore handling plant is located at Saldanha Bay, 160 km north-west of Cape Town. The following Figures 2-2 and 2-3 describe its link to the mine at Sishen by a railway system that serves for iron ore transport (Djordjevic, n.d.: 577). The iron and steel parastatal Iscor built the 861 km Sishen–Saldanha line, and it was opened in 1976. TFR (previously South African Railways and Harbours) started managing this line in 1977 and, further, the line was electrified (TFR, n.d.: 15). The following Figure 2-2 gives the synopsis of this line and locates the loops on it.

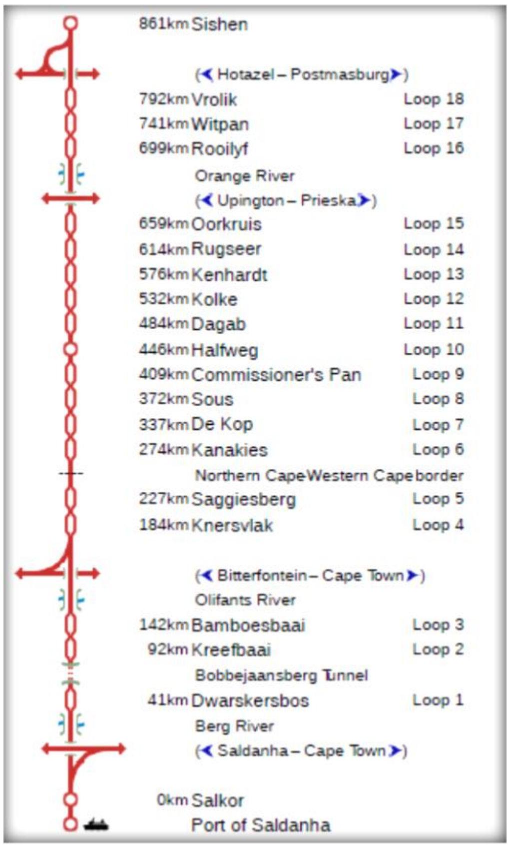


Figure 2-2: The 861 km Sishen-Saldanha Ore Line

(Boonzaaier, 2008)

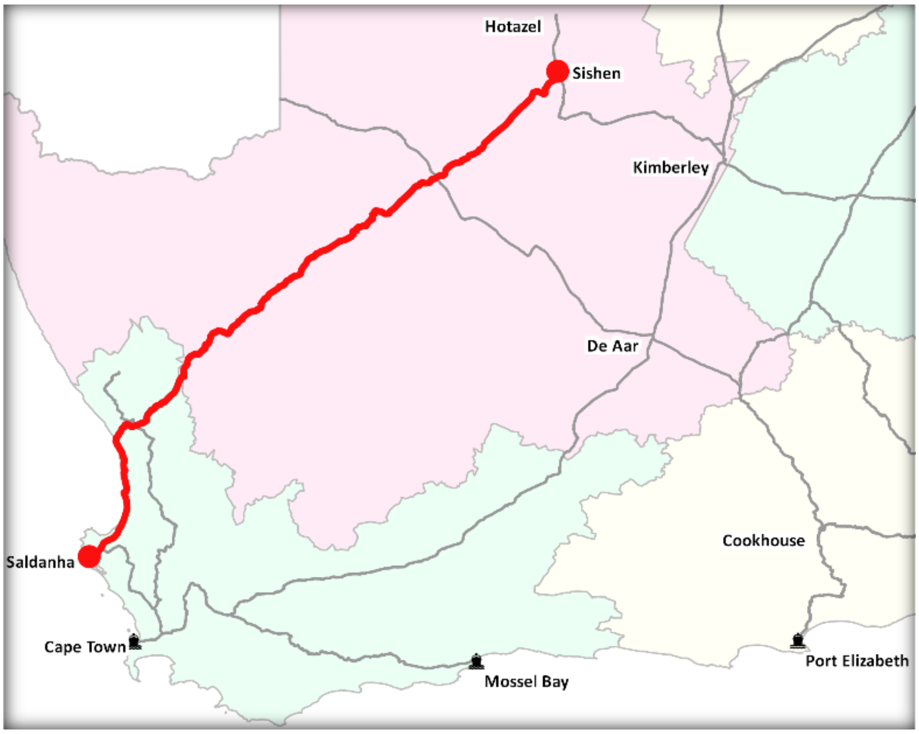


Figure 2-3: Export Ore System - Status Quo Map
(Transnet SOC Ltd, 2016)

2.2.2 Bobbejaansberg (Baboon Point) Tunnel

This tunnel of 787.7 m length, built in 1975, is located on the Iron Ore Export Line (OREX) between Sishen and Saldanha, in the North Western Cape region (Figure 2-4). It goes through Baboon Point, Elands Bay at the West Coast of the Western Cape Province (Figures 2-5 and 2-6) and is the only tunnel in the Sishen - Saldanha railway line. Bobbejaanberg means Baboon Mountain.

Figure 2-4: Tunnel through Baboon Point, Elands Bay, Western Cape Province
(Getty Images, n.d.)

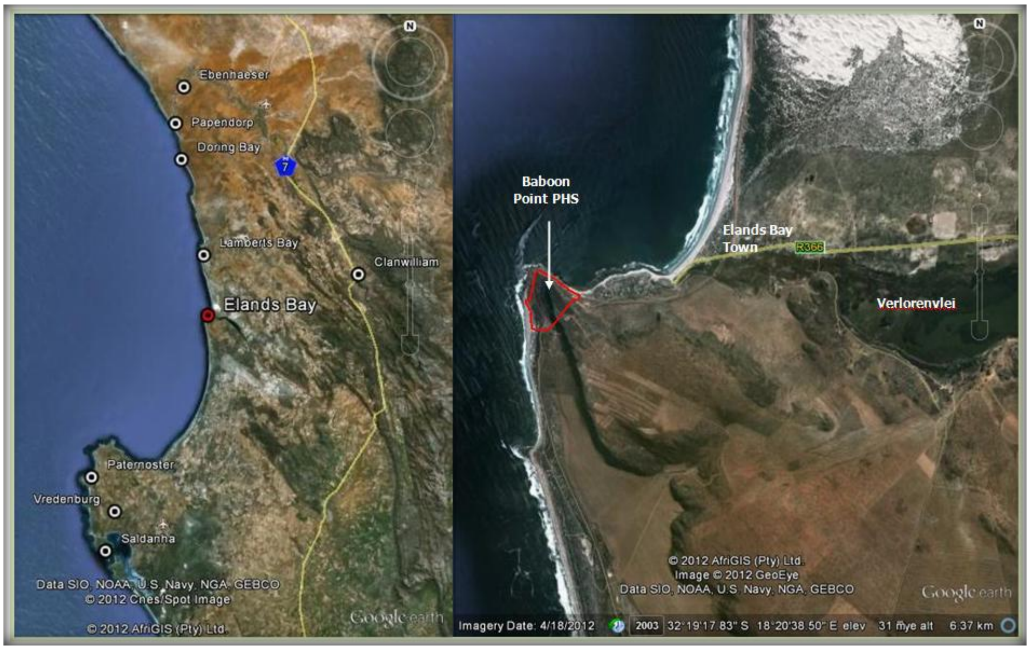


Figure 2-5: Baboon Point, Elands Bay
(Baboon Point Provincial Heritage Site, 2013)

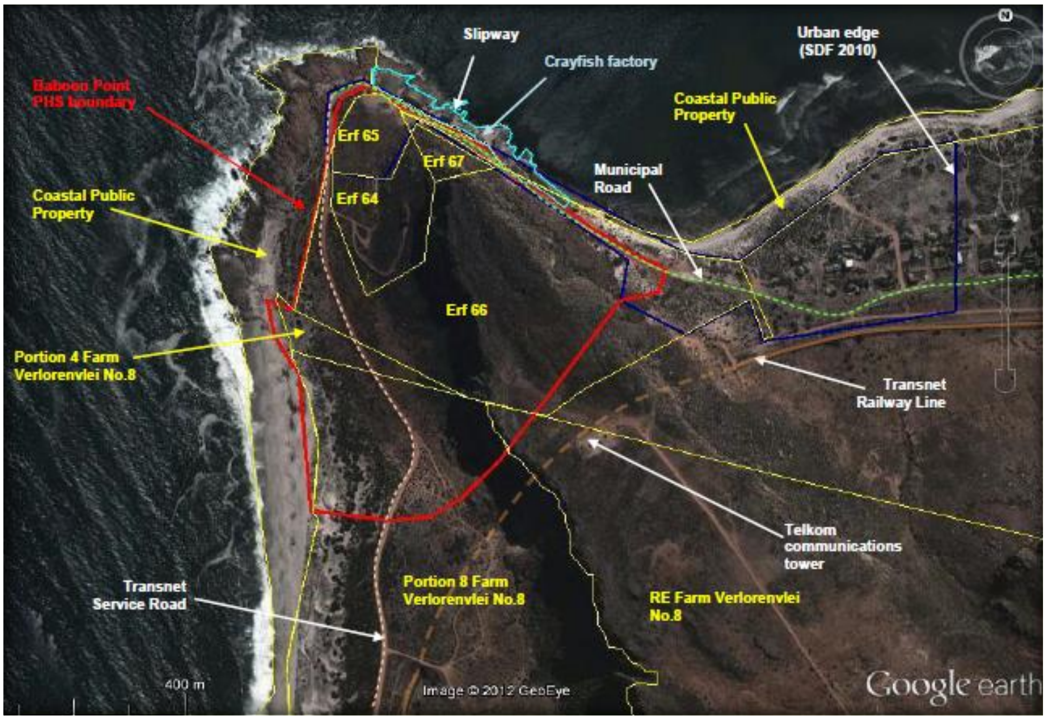


Figure 2-6: Tunnel through Baboon Point, Elands Bay (Plan Vue)
(Baboon Point Provincial Heritage Site, 2013: 16)

2.2.3 The Richards Bay Coal Line (axle loading: Coal line at 26t/axle)

South Africa plays a key role in global coal markets. The country possesses significant coal reserves and the aim to expand coal exports will increase the earnings and foreign revenue as Eberhard (2011 cited by Hancox & Götz, 2014) revealed. TFR manages the Richards Bay coal line which delivers coal from the Mpumalanga region to Richards Bay, where the coal export facility is located (Muir & Gouws, 2017: 607). The rail line has 580 km from Mpumalangas's 44 coal-rich mines, passes through the Highveld and ends at Richards Bay. It is a double line, bi-directionally signalled and fully electrified (TFR, n.d.: 15). This coal, first mined in 1857 on a commercial basis, positions South Africa as the current 6th largest coal producer in the world (Hancox & Götz, 2014: 172). However, the inadequate rail capacity to the coast is among the major challenges that obstruct the increase of coal exports (Eberhard, 2011: 1).

The extent of the Richards Bay coal line exposes it to various natural obstacles (Figure 2-7) that necessitated the construction of bridges, viaducts, tunnels along the line (Macchi et al., 2012: 72). From a civil engineering perspective, this line presents 137 bridges and 37 tunnels, and the Overvaal tunnel is a single tunnel of 4 km of length (Kuys & TFR, 2011: 7). The Coal Line runs through the existing Overvaal Tunnel, located in Mpumalanga between Ermelo and Piet Retief (Muir & Gouws, 2017: 607).

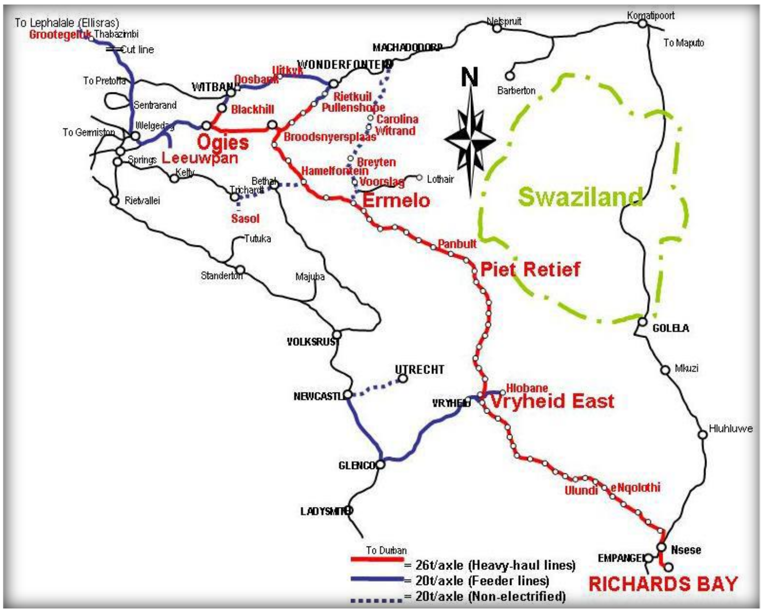


Figure 2-7: South African Coal Line

(Kuys & TFR, 2011)

The following Table 2-1 provides a few details of the tunnels on the coal line in the Northern Natal region.

Table 2-1: Tunnels on the Coal Line

Id #	Section	Area Status	Tunnel Name	Year	L (km)
1	Vryheid - Empangeni	Dassieshoogte - Lenjanedrif	Coal Line1 Tun. No 1	1970	0.3019
2	Vryheid - Empangeni	Dassieshoogte - Lenjanedrif	Coal Line2 Tun. No 1	1984	0.3019
3	Vryheid - Empangeni	Bloubank - Nhlazatshe	Coal Line1 Tun. No 2	1971	1.3356
4	Vryheid - Empangeni	Bloubank - Nhlazatshe	Coal Line2 Tun. No 2	1985	1.3356
5	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line1 Tun. No 3	1971	0.3015
6	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line2 Tun. No 3	1973	0.3015
7	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line1 Tun. No 4	1973	0.1822
8	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line2 Tun. No 4	1973	0.1822
9	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line1 Tun. No 5	1971	0.4865
10	Vryheid - Empangeni	Nhlazatshe - Izolof	Coal Line2 Tun. No 5	1973	0.4865
11	Vryheid - Empangeni	Izolof - Eqwasha	Coal Line1 Tun. No 6	1971	0.2617
12	Vryheid - Empangeni	Eqwasha - Uloliwe	Coal Line1 Tun. No 7	1987	2.8853
13	Vryheid - Empangeni	Eqwasha - Uloliwe	Coal Line2 Tun. No 7	1973	1.7086
14	Vryheid - Empangeni	Ulundi - Ilangakazi	Coal Line1 Tun. No 8	1986	2.9079
15	Vryheid - Empangeni	Ulundi - Ilangakazi	Coal Line2 Tun. No 8	1971	0.8951
16	Vryheid - Empangeni	Ulundi - Ilangakazi	Coal Line2 Tun. No 9	1971	0.5269
17	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line1 Tun. No10	1972	0.7042
18	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line2 Tun. No10	1986	0.4766
19	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line1 Tun. No11	1972	0.4838
20	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line2 Tun. No11	1986	0.4798
21	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line1 Tun. No12	1985	0.3136
22	Vryheid - Empangeni	Ilangakazi - Intsamanzi	Coal Line2 Tun. No12	1973	0.3136
23	Vryheid - Empangeni	Intsamanzi - Enqolothi	Coal Line1 Tun. No13	1973	0.2816
24	Vryheid - Empangeni	Intsamanzi - Enqolothi	Coal Line2 Tun. No13	1973	0.2816
25	Vryheid - Empangeni	Enqolothi - Umunywana	Coal Line1 Tun. No14	1972	0.2988
26	Vryheid - Empangeni	Enqolothi - Umunywana	Coal Line2 Tun. No14	1986	0.2988
27	Vryheid - Empangeni	Enqolothi - Umunywana	Coal Line1 Tun. No15	1972	1.4913
28	Vryheid - Empangeni	Enqolothi - Umunywana	Coal Line2 Tun. No15	1986	1.4964
29	Vryheid - Empangeni	Umunywana - Isangoyana	Coal Line1 Tun. No16	1987	2.4424
30	Vryheid - Empangeni	Umunywana - Isangoyana	Coal Line2 Tun. No16	1972	0.8853
31	Piet Retief - Vryheid	Paulpietersburg - Mahulumbe	Coal Line1 Tun. No 1	1987	2.16
32	Piet Retief - Vryheid	Mqwabe - Zungwini	Coal Line2 Tun. No 1	1974	0.7791
33	Piet Retief - Vryheid	Mswaneni - Sikame	Coal Line1 Tun. No 2	1973	0.6427
34	Piet Retief - Vryheid	Mswaneni - Sikame	Coal Line2 Tun. No 2	1988	0.5586

Id #	Section	Area Status	Tunnel Name	Year	L (km)
35	Piet Retief - Vryheid	Mswaneni - Sikame	Coal Line1 Tun. No 3	1988	0.565
36	Piet Retief - Vryheid	Mswaneni - Sikame	Coal Line2 Tun. No 3	1973	0.5997

2.2.4 Overvaal Rail Tunnel

Freightdatabank.com estimation of 2014 revealed that 127 Mtpa of Transnet's freight passes through the Overvaal rail tunnel. Therefore, the performance of this tunnel is critical, especially for the future increase of traffic. The existing tunnel has a horse-shoe profile of approximately 5 m width and 6 m height and is situated on the only single track section of the line. It was completed and commissioned in 1976. It is located approximately 30km south east of Ermelo and is approximately 4 km long. From the eastern and western portals, the tunnel was built as cut and cover structures, and the drill and blast excavation starting in competent rock with adequate cover. Since completion, the tunnel has increasingly experienced maintenance challenges, exacerbated by the fact that it is currently the only single line section of the Coal Line (Muir & Gouws, 2017: 607). Therefore, the structural performance of the existing tunnel (Figure 2-8) has been less than satisfactory over its 40 years period of service.

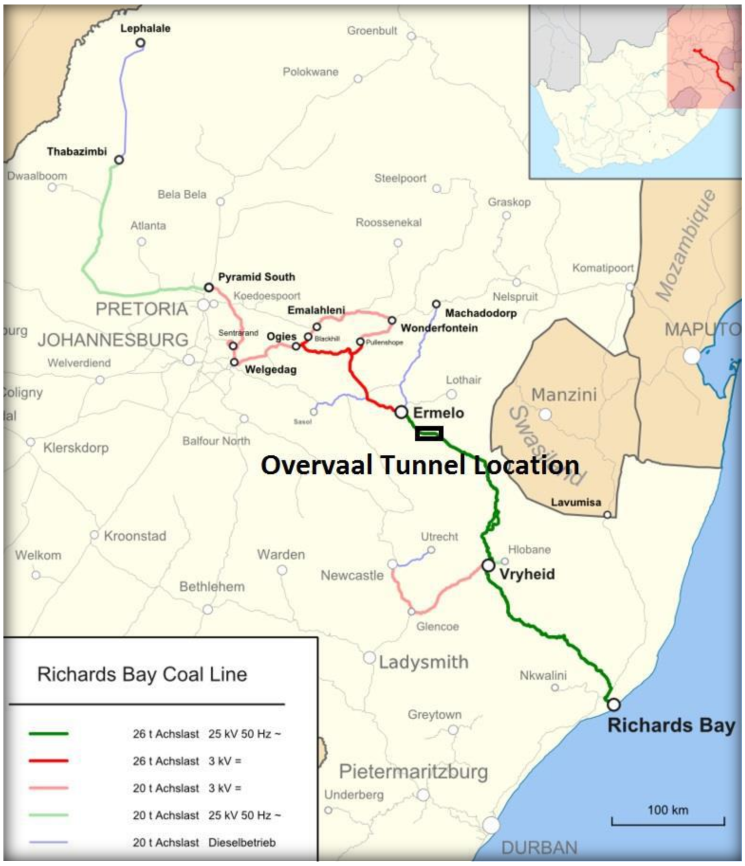


Figure 2-8: Location of the Existing Tunnel

(Gräbe & Fröhling, 2017)

High groundwater ingress, track slab deformation and bowing of the sidewalls towards the eastern end of the tunnel are the three main problems identified. This resulted in extensive wide cracks in the lining intrados (Muir & Gouws, 2017: 608). It is feared that any fatal incident leading to the closure of this single track section of the line would have severe economic consequences. This justifies the need and the urgency of the construction of the new Overvaal Tunnel to alleviate the negative impact of failure of the single line section. Moreover, the new tunnel will increase the capacity of the coal line. The new tunnel, located on the Highveld escarpment, will hopefully secure the coal line and prevent the economic benefits provided by the coal line from being compromised.

2.2.5 Railway Transit Tunnel Shapes

Ellipticity is the index of measuring the deformation of tunnel section, which is defined by the length of the long axis of the actual section shape of the shield tunnel minus that of short axis. Huang et al. (2018: 307) specified that the elliptical deformation of the tunnel section forms are due to the dislocation and extrusion between the segments. Therefore, the excessive elliptical deformation of tunnel section will lead to the invasion of the tunnel structure and will endanger the safety of train operation. More critically, it causes the variation of the structural stresses, subsequently causing *structural cracking*. Also, the excessive deformation of joints will provoke the failure of the waterproof material and will subsequently favour *water leakage*. Hilar Hilar. Matous and Martin (2009) proposed that the two railway tunnel configuration is the safest design for railways carrying heavy freight traffic. However, this configuration should have a parallel service or escape tunnel, and is often the most expensive to construct. Zare, Bruland & Rostami (2016: 55) stated that Drill and Blast (D&B) and Tunnel Boring Machine (TBM) are the two dominating excavation methods in hard rock tunnelling.

Figures 2-9 to 2-12 provide the typical shapes for rail transit tunnels, that relate to the method/ground conditions in which they were constructed.

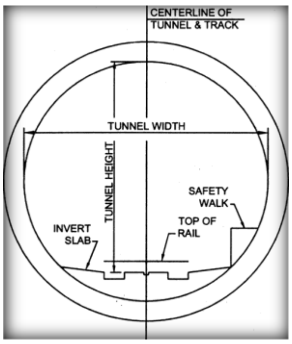


Figure 2-9: Circular Tunnel with a Single Track

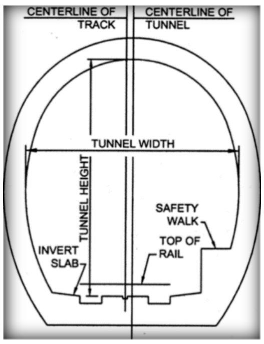


Figure 2-10: Oval Tunnel with a Single Track

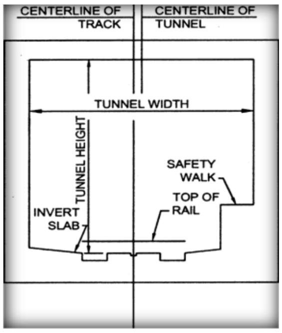


Figure 2-11: Single Box Tunnel with a Single Track

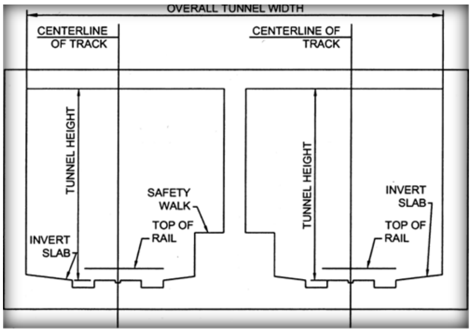


Figure 2-12: Double Box Tunnel with a Single Track

(USA. Federal Highway Administration, 2015)

Figure 2-10 is the shape that represents most of the tunnels in South Africa.

2.3 Defects on Concrete Structural Elements of Railway Tunnels

Concrete structures fundamentally support our society as infrastructures (Japan Society of Civil Engineers, 2010). Hence, concrete performance is critical for underpinning a country's basic services, social, environmental, political and economic activities (Kessy, Alexander & Beushausen, 2015: 47). Therefore, a concrete structure should preserve its functionality during the intended service life (Takewaka & Kaneko, 2001: 2). However, as concluded Molefe (2015: 1), despite its high strength, the functionality of reinforced concrete elements is compromised if subjected to defects due to harsh environment conditions. Apart from this, in several important ways, the characteristics and needs of structural elements of tunnels are distinct from those of more modern structures (McKibbins, Elmer & Roberts, 2009) (Figure 2-13). Menendez et al. (2018: 117) described the structural performance of tunnels as time-dependent. This is due to the deterioration processes induced by natural and man-made impacts, changes in load criteria, or the simple effect of ageing. Finally, Chibulu (2016) admitted that *the impact of deterioration or damage to a concrete structure is the reduction of its intended service life*.

Figure 2-13: Railway Tunnel Internal View
(Gräbe & Fröhling, 2017)

2.3.1 Defects in Tunnel Liner

Changes in structural elements manifested as defects, displacement, leakage and lining cracking characterise the degradation of the structural performance (Liu et al., 2018: 135). Therefore, investigation and evaluation of the lining damage is an essential work to monitor the evolution of the health of a tunnel. They help to mitigate the risk grade during the service life of the tunnel (Huang et al., 2018: 303). Massone & Nazar (2018: 14) established that prefabricated segment linings, projected (shotcrete) concrete linings, and in-situ concrete linings are the three different systems generally used for concrete tunnel linings. Furthermore, Menendez et al. (2018: 117) specified that the majority of tunnel linings use reinforced concrete. Therefore, *the damage of lining may weaken the structural performance, affect the durability of the structure and even cause accidents* (Huang et al., 2018: 303).

Galler & Lorenz (2018: 2) recognised that, over the tunnel lifetime, the linings are exposed to various environmental conditions. Unfortunately, *the most common visible defects in tunnel lining are cracks to the structure, spalling of the concrete and efflorescence* (Menendez et al., 2018: 117). Under those aggressive environment conditions, cracking become very detrimental for its consequences in terms of durability. This makes the serviceability condition particularly important for tunnel linings (Buratti, Ferracuti & Savoia, 2013: 249). Moreover, cracking may induce a significant increase in concrete permeability and let water inflows in the tunnel when no seal has been installed behind the concrete lining (Briffaut et al., 2016: 221). While it is admitted that the cracks in the lining are the prevailing forms of damage, the typical cracks are longitudinal cracks and the cracks on the joints edges (Huang et al., 2018: 309).

2.3.2 Concrete Cracking

Cracks are defined as linear fractures in the concrete caused by tensile forces exceeding the tensile strength of the concrete. Spalling, whereas, is the detachment of hardened concrete that leave a roughly circular or oval depression (Menendez et al., 2018: 117). Huang et al. (2018: 309) mentioned that *longitudinal cracks have the greatest impact on the stability and safety of tunnel structures*. They also stated that longitudinal cracks usually appear on the vault of the lining, which reduces the ability of the structure to resist external forces. Another major issue is the early-age cracking of concrete structures because it increases permeability and diffusivity. Moreover, it accelerates the penetration of liquid, gas and aggressive agents. As a result, the serviceability of these structures could immoderately be reduced. Briffaut et al. (2016: 221) presented external loading as one of the causes of early-age cracking, along with internal or external restraint caused by autogenous, drying and thermal shrinkage.

Limiting the concrete cracking is an important way of maintaining the structural integrity (Caratelli et al., 2010: 285). Kizito (2013) proposed, for example, tensile relaxation to accommodate the reduction of tensile stresses in concrete which leads to mitigation of cracking in restrained concrete members. He also recommended a deep study of tensile relaxation behaviour of concrete to promote its role in reducing, prolonging or eliminating the manifestation of cracks in concrete. Therefore, sound study of tensile relaxation behaviour of concrete should be promoted because of its role in mitigating the manifestation of cracks in concrete. Beside the negative effects of concrete cracking, *corrosion of embedded reinforcing steel ranks as the main cause of many reinforced concrete structures exhibiting unacceptable levels of deterioration* (Yam, 2004: 1).

2.3.3 Corrosion of Reinforcing Steel

Tigeli (2010) asserted that *the main cause of structural damage in reinforced concrete (RC) structures is corrosion of reinforcement*. He further demonstrated that corrosion results in cracking and staining of RC structures thus impairing their service limit state. An interest in reinforced concrete strength evolution of tunnel lining under corrosion conditions has been demonstrated by Zhiquiang and Mansoor (2013, cited by Bagnoli et al. 2015: 416). Surely, as stated by Nganga (2011: 1), RC structures are continually under attack by aggressive substances in the environment (oxygen, chlorides, carbon dioxide, and water). This results in the initiation and aggravation of corrosion process. In fact, *corrosion reduces the cross-sectional area of corroded steel and, subsequently, reduces the stiffness and capacity of the structure to carry loading*. This may result in structural failure if not detected and repaired or strengthened. Moreover, he stated that *cracks develop and widen as the level of corrosion increases*. Gregan (2012: 1) concluded that to restore the original durability and life of a corrosion damaged RC structure, a concrete repair technique needs to be implemented.

2.3.4 Structural Durability

Durability problems in reinforced concrete (RC) structures are an issue of global concern. They negatively impact economic growth, the sustainability of natural resources and the safety of people (Kessy, Alexander and Beushausen, 2015: 47). The International Standards Organisation (ISO) defines *durability as the capability of a structure to perform its intended function over a specified period of time under the influence of agents anticipated in service* (ISO 15686-8:2008 cited by Muigai, 2008: 1). *For railway tunnels, the structural durability is often jeopardised by the steel reinforcement corrosion* (Caratelli et al., 2010: 284). In fact, the durability of RC structures is linked to the interactions with the service environment, in which the ingress of harmful substances is highly significant (Muigai, 2008: 1). Moreover, Li et al. (2017: 139) specified that the durability of concrete against chemical attacks not only relates to environmental factors, but also to the materials. Therefore, limiting the transportation of aggressive agents into concrete will subsequently enhance the durability of the concrete structure. However, a deep awareness of the penetrability of aggressive agents into concrete is crucial to achieve this objective (Muigai, 2008: 17).

Bagnoli et al. (2015: 415) recommend that the design of underground concrete structures considers the influence of operational environment on concrete durability. Fundamentally, *durability design should be concerned with predicting the longevity of structures, comparing life cycle costs, mitigating deterioration and optimising the selection of material* (Muigai, 2008: 1). This is translated by the ability of the concrete to resist the penetration of aggressive agents during the concrete's intended service life of RC structures (Muigai, 2008: 1). And, in reality, tunnel environments are characterised by dust, humidity, absence of natural light, and the existence of toxic substances among others (Menendez et al., 2018: 117).

Kessy, Alexander & Beushausen (2015: 47) recognised that the complexity and variety of durability problems can be dealt with by considering existing mitigation measures. They cited Rostam (2003) who described two means of ensuring durable concrete, i.e. avoidance of the deterioration mechanisms, and optimisation of material compositions and proportions. Also, *the cover depth was found to be the most sensitive parameter in the durability design* (Muigai, 2008). Nganga (2011: 2) repeated the conclusion of (Bentur et al., 1997) that the durability of RC structures is dependent on protection of concrete cover to reinforcement - resistance to aggressive substances. This in turn depends on its penetrability and thickness.

2.3.5 Concrete Spalling

Bezgin (2015: 279) affirms that, when the internal stresses develop beyond the direct tensile strength of concrete, it causes concrete spalling. Huang et al. (2018: 309) also specified that *concrete spalling consists of steady development of edge cracks around an area*. Overall, spalling usually occurs at the edges of the joints. Among its devastating consequences, spalling reduces the section thickness, and further exposes the reinforcing steel as it destroys concrete cover (Bezgin, 2015: 279). At first, concrete spalling does not cause a great safety risk to tunnel structure, however it may pose a safety threat to running trains. Therefore, Huang et al. (2018:

310) recommends a bold approach of clearing away and repairing concrete spalling to mitigate the risk of train operations. A tunnel fire increases the temperature of the structure and concrete spalling is manifested for temperature ranging from 300 ºC and as high as 500 ºC. Subsequently, the temperature of the embedded steel reinforcements will rise up (Bezgin, 2015: 279). Another critical defect that impairs the structural performance of tunnel structures is leakage.

2.3.6 Water Leakage

Groundwater intrusion creates more problems to tunnel's concrete liners and reinforcing steel concrete than any other combination of tunnel structural problems (Russell & Gilmore, 1997: 1). In fact, on the one hand, unexpected water inflow in a tunnel provokes several problems relating to the working activity of the infrastructure. An example of this can be the forced interruption of railway if the groundwater level becomes a threat. On the other hand, groundwater flow into the tunnel generates seepage forces on the cross-section of the tunnel that compromises the structural safety of the infrastructure (Bagnoli et al., 2015: 416). Finally, the exposure of concrete structures of the tunnels to aggressive water causes potential chemical attacks (Li et al., 2017: 139).

Huang et al. (2018: 312) established that the number of leakage points is higher around the weathered argillaceous sandstone. Also, water leakage is generally associated by white calcification that gradually forms a relatively hard calcareous layer at the leakage location. Li et al. (2017: 139) concluded that chloride attack on the concrete structures of the tunnel is due to the presence of chlorides in the leakage underground water. Also, chloride contamination on the surface of pre-cast concrete segments is linked to the presence of NaCl crystallizations. They also commented that calcium leaching develops when the concrete endures flowing leakage water, and it goes along with decalcification and magnesium incorporation. Another problem to the structural integrity of tunnels, directly linked to leakages and cracks, especially close by the joints, is the differential settlement.

2.3.7 Differential Settlement

Hu et al. (2018: 144) referred to previous work done by Feng et al. (2017). He concluded that *superfluous differential settlements occasion the structural damage or leakage on structures and joints whereas equal settlements have no harm to tunnel structures*. A few practical examples of the negative impacts of differential settlements to the structural integrity of tunnels are provided. The largest differential settlement on both ends of the Shanghai Outer-Ring E-7 element reached 245mm after sand jetting (Wei and Su, 2014 cited by Hu et al., 2018), and that of the Yongjiang Tunnel in Ningbo, China was 181.5mm after 11 years of service (Zhang, 2007; Shao and Li, 2005 all cited by Hu et al., 2018). Leakages and cracks occurred close to elemental joints for both tunnels. Similarly, leakages appeared at the bottom of joints when the Baytown Tunnel in USA showed a settlement of 450mm and an angular distortion of 1.6×10^{-3} rad (Schmidt and Grantz, 1979) (Hu et al., 2018: 144).

2.4 Definition and Description of a Management System

According to the International Organisation for Standardisation (ISO) Management Systems (MSs) are *'the way in which an organisation manages the inter-related parts of its business to achieve its objectives'* (ISO, 2018 cited by Hernandez-Vivanco, Bernardo, and Cruz-Cazare, 2018). In fact, *effective management of infrastructure health conditions is the core of desired asset quality level* (Jamshidia, 2018: 185). Similarly, organisations should adopt the absolute managerial practices that optimise innovation efficiency and consequently, expect to grow substantially and sustainably (Hernandez-Vivancoa, Cruz-Cázaresa & Bernardoa, 2018: 1). Russell & Gilmore (1997: 2) indicated that management of infrastructure systems is typically profitable if operated from a set of reviewed and proven processes that can be repeated. This considers that individual issues of work performance are put aside. As performance of railway structures gradually declines, railway infrastructure management will alleviate the business pressure in rail transport (Macchi et al., 2012: 71). It will also assist in keeping the performance of railway structures at or above an acceptable level (Tottori & Ichikawa, 2006).

Railway tunnels are among critical structures having a long service life and are situated in very harsh environments. Therefore, they may be classified into the higher maintenance category (Takewaka & Kaneko, 2001: 4). In addition, Moyo & Nordengen (2018) specified that effective bridge and tunnel asset management practices are required that will provide the best value from limited resources having a long service life. Allen et al. (2015: 3) also highlighted that maintaining these assets in a state of good repair is preeminent to maintaining the viability of the overall transportation network. Indeed, as Liu et al. (2017: 879) specified, *most systems experience a degradation process before failure and the degradation indicators can be measured over time*.

Tunnels structures, designed for a lifetime of about 100 years, raise concerns to their owners as they approach their life expectancy or perform beyond it (Bagnoli et al. 2015: 415). In fact, railway and road tunnels have increased in both total length and number and will continue to do so on a global scale (Menendez et al., 2018: 117). Kocha, Vonthronb & Königb (2017: 78) reveal that, traditionally, the entire tunnel design information is available in the form of independent, dispersed and heterogeneous data files. In fact, tunnelling project documents are usually available in distinct types, scales, and formats, originate from loosely coupled and dispersed resources, but are strongly interdependent. Also, a few types and formats of data are CAD drawings, text reports, spreadsheets, diagrams and images. This complicates their integration in design, simulation and visualisation models. Indeed, required data has to be re-organised from multiple resources, and documents have to be scanned for appropriate information and parameters (Kocha, Vonthronb & Königb, 2017: 79).

While tunnels are built with long life cycles (Cambridge Systematics, 2013: 6-6), a considerable amount of them were built a few decades ago. This raises the concerns to improve the current methods employed for their management, monitoring and inspection (Attard et al., 2018: 180). Therefore, the effective management of older infrastructure tunnels requires some specialist knowledge and a rigorous approach (McKibbins, Elmer & Roberts, 2009). However, based on the interviews conducted by Allen et al. (2015: 1), only very few tunnel owners are using a formalised asset management approach for maintaining and preserving their tunnels. The interviews also revealed that most tunnel owners prefer a formalised asset management approach that is simple to implement and considers levels of service (their goals and objectives). Additionally, the specific tunnel conditions (i.e., good, fair, poor, severe), and other useful characteristics would improve their work (Allen et al., 2015: 1).

To efficiently continue using railway tunnels assets in the future it is necessary to manage and maintain their structural elements appropriately. McKibbins, Elmer & Roberts (2009) specified that this should be done with due respect to, and a relevant understanding of, their special characteristics and needs. Meanwhile, the challenges mainly consist of their extended period in service and changing requirements. Thus, tunnels owners are called to analyse the various guarantees that concern their structures, and ensure the appropriate inspections are timely conducted (Centre d'Etudes des Tunnels, 2015: 13). In other words, inspection, assessment and maintenance are required to ensure that these structures remain in safe condition and continue to provide reliable levels of service (Menendez et al., 2018: 117).

2.4.1 Basics of Maintenance of Infrastructure

Early detection of damage is essential for effective maintenance of civil infrastructure (Dzvukamanja, 2008: 1). In fact, concrete structures need to be maintained continuously over their lifetime. Takewaka & Kaneko (2001: 3) frame the *maintenance procedure as consisting of initial inspection, deterioration prediction, inspection, evaluation, judgment, remedial measures, and recording*. The Japan Society of Civil Engineers (2010: 1) defined maintenance as the act of maintaining the performance of a concrete structure within the allowable range during its service period. Also, Shin & Jun (2015: 119) defined maintenance as *all technical and managerial actions taken during usage period to maintain or restore the required functionality of a product or an asset*. This links the importance of maintenance to design and construction of the structure. Verbert, De Schutter & Babuška (2017: 2) state that a better estimation of the current and future health of infrastructure due to available data allows a better decision on the need and the timing of maintenance. This means that the performance of a concrete structure will be controlled and improved by maintenance activities within the defined service life (Takewaka & Kaneko, 2001: 2).

Hwang et al. (2018: 604) provided the *general classification of maintenance policies consisting of corrective maintenance, breakdown maintenance, regular maintenance such as time-based preventive maintenance*, etc. Takewaka & Kaneko (2001: 4) propose *four categories for maintenance actions including the preventive maintenance, corrective maintenance, observational maintenance and non-inspection maintenance*. Firstly, preventive maintenance is a set of activities to prevent the appearance of visible deterioration on the structure during the service life. Hwang et al. (2018: 604) described preventive maintenance as time-based maintenance and condition-based maintenance (or predictive maintenance), prognostics and health management (PHM). Secondly, corrective maintenance considers appropriate counter measures after appearance of degradation on structures. Thirdly, observational maintenance is performed based on visual inspection without any direct measure and permits certain deterioration of the structure. Finally, *non-inspection maintenance is applied to the structure in which the direct inspection is difficult or practically impossible to be performed, such as underground structures*.

This constrains the maintenance manager to compile maintenance plans ahead, develop a system for integrating the maintenance work, and finally perform maintenance. The integration considers all steps from assessment comprising investigations, detection of deterioration, prediction of models, evaluation and selection of remedial measures (Japan Society of Civil Engineers, 2010: 4). Therefore, *the state of the structure will be of utmost importance and will assist the maintenance manager to meticulously predict time-based variations of the performance of the structure*. This includes the structural integrity, safety, serviceability, jeopardy to third parties, aesthetic appearance, etc. Any deviations to the baselines defined for these parameters will be look at carefully, as they may start or reveal the deterioration of an element of the structure. All the deteriorations identified will be recorded to the system that will direct the manager to make relevant and informed decisions on the steps forward.

2.4.2 Tunnel Deterioration

The complexity and interconnection of civil engineering infrastructure express the need for a robust mechanism to regularly investigate their deterioration state, functionality and reliability (Stephenson, Barta, & Manson, n.d.: 1). In fact, *the performance of structures deteriorates with time*. The Japan Society of Civil Engineers (2010: 4) specifies that *the evolution and level of deterioration is related to the quality of material that constitute the structure, structural regions or members, and the environmental condition*. Therefore, a deterioration can be defined as the process that adversely affects the performance of a structure over time due to its defects and damages. They are caused by the impact of naturally occurring chemical, physical or biological actions, repeated actions such as those causing fatigues, normal or severe environmental influences, and wear due to use, abuse, and others (Takewaka & Kaneko, 2001: 4). Liu et al. (2017: 201) propose a model to integrate the aging and degradation effect into system failure.

The determination of the degradation state of underground concrete tunnels is a crucial issue for maintaining and monitoring the performance of these infrastructures (Bagnoli et al., 2015: 415). For example, the degradation of the tunnel lining may reduce the concrete thickness along the length of aged tunnels (Bagnoli et al., 2015: 417). Unfortunately, as noted by Bagnoli (2015: 416), despite their criticality, the current degradation state of underground structures and the potential risks related to their aging processes are still unknown to their owners. And Centre d'Etudes des Tunnels (2015: 14) advises the use of an advanced monitoring system when the deteriorations observed on a tunnel can jeopardise its safety or its serviceability. Takewaka & Kaneko (2001: 5) recommend that the inspection detects any changes in the performance of a structure and/or occurrence of deterioration. Obviously if undesirable signs of deterioration can be detected in its early stage, suitable timely remedial action can be taken. The selection of locations for inspections, items to inspect and tools to use for inspection will methodically influence the quality of information obtained.

2.4.3 Tunnel Inventory

The Committee of Transport Officials (COTO) of South Africa (2016: 16) stated that *the first step in the implementation of a structures database is to compile an inventory of all structures*. **The inventory consists of a list of all structures within the network with comprehensive details of the features and major dimensions of the structure, its type and location, the materials it is made of, etc**. In fact, Tunnel Inventory improves the knowledge and the tracking of tunnel conditions, and the updating of the Tunnel Management System. Bergeson & Ernst (2015: 20) emphasised that the inventory and inspection data will also allow patterns of tunnel deficiencies to be identified and tracked, which will help to ensure public safety. Thus, *a proper inventory and assessment of the condition of tunnel elements is the cornerstone of sound tunnel management* (USA. U.S. Department of Transportation, 2015: 1-2).

2.4.4 Tunnel Inspection

A slight carelessness may cause tunnel structure accident (Huang et al., 2018: 303). This can be sustained by the natural fact that infrastructure shows signs of deterioration, over time, due to ageing and stresses which may eventually cause problems in structural integrity. Consequently, *to ensure safety in concrete tunnels, periodic inspections have to be conducted* (Attard et al., 2018: 180). Russell & Gilmore (1997: 1) described an *inspection program for rail transit tunnels and underground structures as a formally adopted system of institutional objectives, standards, and procedures that collectively describe the tunnel inspection practice*. At each stage of the inspection, the expected performance of the tunnel is checked with reference to a baseline. The outcome of the inspection will assist to interpret and evaluate the conditions of the tunnel and predict future behaviour. Takewaka & Kaneko (2001: 3) referred to initial defects as placing-induced defects, such as cracking, honeycombs, cold joints, sand streaking, etc.

Russell & Gilmore (1997: 1) realised that, in the USA and abroad, rail tunnel inspection had a long way to become a professional practice. In fact, insufficient information seems to be available, and few professional organisations are investing in the practice of rail tunnel inspection. Moreover, **the inconsistency of tunnel inspection standards raised appropriate concerns related to tunnel inspection practice**. Nevertheless, groundwater intrusion and the subsequent damage caused by tunnel leaks is the major problem affecting tunnels. This has been agreed by transit agencies, their consultants and professional peers (Russell & Gilmore, 1997: 1). Consequently, an underground tunnel section with a history of leaks, will require frequent inspections on that section of the tunnel. *The inspection team, inspection frequency and various inspection protocols including scheduling, inspection type (visual vs. destructive testing methods), inspection documentation (photos, sketches, narratives of the inspection) and management focus (inspection planning and accountability) need to be standardised*.

The American Public Transportation Association (2004) referred to the inspection intensity based on the criticality of the structural element. Therefore, Takewaka & Kaneko (2001: 5) considered *six categories of inspection, based on the methods used and their frequency*. These are *'initial inspection', 'routine inspection', 'regular inspection', 'detailed inspection', 'extraodinary inspection', and 'monitoring'*. Likewise, Centre d'Etudes des Tunnels (2015: 13) considers *one-off actions that include the initial detailed inspections (IDI), specific inspections at the end of contractual guarantees, actions linked to unforeseen events*. Also, specific detailed inspection can be conducted either during a periodic detailed inspection, or at another time. *The initial detailed inspection defines a reference state against which the other monitoring actions can be used to assess how it changes*. *Routine and regular inspections are carried out while the structure is in service and may call for further detailed inspection* (Takewaka & Kaneko, 2001: 5).

2.4.5 Tunnel Monitoring

Monitoring a civil engineering structure includes all the controls and inspections that reveal its condition and any changes from a reference state (Centre d'Etudes des Tunnels, 2015: 12). In fact, Structural Health Monitoring Systems (SHMS) serve to monitor structural integrity and provide information used to detect overloading and to alert asset managers of any due maintenance (Mmekwa, 2017: v). For Prins (2017: 1), the analysis of data obtained labels trends that unveil the performance and health of the structure and assist in highlighting potential modes of failure. *Monitoring a structure can be continuous, periodic or one-off, based on the performance of the structure*. Centre d'Etudes des Tunnels (2015: 12) considers, on the one hand, *periodic monitoring as including annual inspections, assessment visits, periodic detailed inspections (PDI), detailed inspections of parts of structures*. On the other hand, *continuous monitoring records the defects and abnormal events on an ongoing basis*.

The main aim in monitoring is to control the degradation of critical infrastructure. However, monitoring can also be used for continuous measurement on critical assets, as railway tunnels (Jamshidia, 2018: 186). As the information obtained from SHMS is reliable and accurate, it can be used to represent the actual condition of a structure and for maintenance planning (Mmekwa, 2017: 1). Still, the evaluation of tunnel structure damage requires a large amount of detection data (Huang et al., 2018: 305). With regard to important tunnels, sensor-based continuous monitoring programs can be used for their functionality and structural integrity (Yanga et al., 2018: 235). To summarise, an adequate tunnel monitoring system will contribute to optimise the maintenance activities and, subsequently, minimise its failure’s likelihood.

2.4.6 Tunnel Failure

The consequences of structural failure of railway tunnels can be considerably mitigated through adequate tunnel inspection and needed repairs (Russell & Gilmore, 1997: 2). Thus, the structural performance of these tunnels will be checked through the measurement of critical quantities that characterise their behaviour (Yanga et al., 2018: 235). Also, the Civil Engineering and Development Department – CEDD of the Government of the Hong Kong Special Administrative

Region reported, up to October 2012, 52 overseas cases of tunnel failures and 6 Hong Kong cases of tunnel failures. The list of these tunnel failures is presented as follows (Table 2-2):

Table 2-2: Tunnel Failures

Id#	Tunnel Name	Location	Date
Overseas cases			
1	Green Park	London, UK	1964
2	Victoria Line Underground	London, UK	1965
3	Southend-on-sea Sewage Tunnel	UK	1966
4	Rørvikskaret Road Tunnel on Highway 19	Norway	18 March 1970
5	Orange-fish Tunnel	South Africa	1970
6	Munich Underground	Germany	1980
7	Holmestrand Road Tunnel	Norway	16 December 1981
8	Gibei Railway Tunnel	Romania	1985
9	Moda Collector Tunnel, Istanbul Sewerage Scheme	Turkey	1989
10	Seoul Metro Line 5 – Phase 2	Korea	17 November 1991
11	Seoul Metro Line 5 – Phase 2	Korea	27 November 1991
12	Seoul Metro Line 5 – Phase 2	Korea	11 February 1992
13	Seoul Metro Line 5 – Phase 2	Korea	7 January 1993
14	Seoul Metro Line 5 – Phase 2	Korea	1 February 1993
15	Munich Underground	Germany	27 September 1994
16	Heathrow Express	UK	21 October 1994
17	Los Angeles Metro	USA	22 June 1995
18	Motorway Tunnels	Austria	1993 - 1995
19	Docklands Light Rail	UK	23 February 1998
20	Athens Metro	Greece	1991 - 1998
21	Lærdal Road Tunnel on European Highway E 16	Norway	15 June 1999
22	Sewage Tunnel	Hull, UK	1999
23	Taegu Metro	South Korea	1 January 2000
24	Channel Tunnel Rail Link	UK	February 2003
25	Météor Metro Tunnel	France	14 February 2003
26	Oslofjord Subsea Tunnel	Norway	28 December 2003
27	Shanghai Metro	China	2003
28	Tunnel Failure	Japan	2003
29	Guangzhou Metro Line 3	China	1 April 2004

Id#	Tunnel Name	Location	Date
30	Singapore MRT	Singapore	20 April 2004
31	Kaoshiung Rapid Transit	Taiwan	29 May 2004
32	Oslo Metro Tunnel	Norway	17 June 2004
33	Kaoshiung Rapid Transit	Taiwan	10 August 2004
34	Hsuehshan Tunnel	Taiwan	1991 - 2004
35	Barcelo Metro	Spain	27 January 2005
36	Lausanne M2 Metro	Switzerland	22 February 2005
37	Lane Cover Tunnel	Australia	2 November 2005
38	Kaoshiung Rapid Transit	Taiwan	4 December 2005
39	Nedre Romerike Water Treatment Plant Crude Water and Potable Water Tunnels	Norway	2005
40	Hanekleiv Road Tunnel	Norway	25 December 2006
41	Stormwater Management and Road Tunnel (SMART)	Malaysia	2003 - 2006
42	Sao Paulo Metro Station	Brazil	15 January 2007
43	Guangzhou Metro Line 5	China	17 January 2008
44	Langstaff Road Trunk Sewer	Canada	2 May 2008
45	Circle Line 4 Tunnel	Singapore	23 May 2008
46	Hangzhou Metro Tunnel	China	15 November 2008
47	Cologne North-South Metro Tram Line	Germany	3 March 2009
48	Brightwater Tunnel	USA	8 March 2009
49	Seattle's Beacon Hill Light Rail	USA	July 2009
50	Cairo Metro Tunnel	Egypt	3 September 2009
51	Shenzhen Express Rail Link		27 March 2011, 4 May 2011 and 10 May 2011
52	Hengqin Tunnel	Macau	19 July 2012
	Hong Kong cases		
1	MTR Modified Initial System	Prince Edward Station, Nathan Road	12 September 1977
2	MTR Island Line	22 Hennessy Road	1 January 1983
3	MTR Island Line	Shing On Street, Shau Kei Wan	23 July 1983
4	MTR Island Line	140-168 Shau Kei Wan Road	16 December 1983
5	Kowloon Southern Link Contract KDB 200	Canton Road	21 October 2006
6	Kowloon Southern Link Contract KDB 200	Salisbury Road	3 June 2007

2.4.7 Priority-based Management Systems

It is difficult to prioritise maintenance and preservation implementation of railway infrastructure comprising tunnels. In fact, tunnel preservation often competes with other transportation elements, such as bridges and pavement, for available funding (Allen et al., 2015: 1). Niitsu (2014: 33) stated that *priority is determined based on inspection results and line importance*. In addition, Montoya et al. (2017: 551) recommends the *classification of some elements that will assist for analysis*. For example, the **type and level of existing damages on the tunnel through visual inspection, the different structural elements ranked for their criticality**. When prioritising preservation actions, tunnel managers often consider the safety of the structure, the system element condition, reliability to keep the tunnel open and other relevant parameters. Allen et al. (2015: 1) observed, however, that *current practice is more reactive based on current condition and available funding, instead of proactive from a formalised asset management approach*.

2.4.8 Condition-based Management Systems

Information collected using condition-based monitoring is used to optimise maintenance practice and ideally locate the areas of the structure in immediate or future needs (Jamshidia, 2018: 185). Thus, *condition-based maintenance (CBM) is used for a system subject to a continuous-time degradation process, to prevent unforeseen failures* (Liu et al., 2017: 879). EN 13306:2010 defines CBM as "Preventive maintenance that includes a combination of condition monitoring and/or inspection and/or testing, analysis and subsequent maintenance actions". Therefore, *a "CBM solution" is the application of a particular monitoring solution to a specific case* (failure mode or element). Guillén et al. (2016: 170) stated that CBM monitors the condition of components and systems and determine a dynamic preventive schedule. Additionally, ISO 13372:2012 standard defines CBM as "Maintenance performed as governed by condition monitoring programmes".

For a given system, a “CBM program” is the application of affiliated CBM solutions and requires management and maintenance task planning (Guillén et al., 2016: 170). In fact, *CBM is carried out considering that systems mainly undergo a degradation process before failure* (Liu, 2017: 200). **From a CBM, the condition information on a system will be used to carry out maintenance actions only when “required”** (Liu et al., 2017: 200). The following are the *three steps characterising a procedure of CBM: condition data acquisition, reliability or remaining lifetime estimation/prediction, and optimal CBM decision making* (Jardine, Lin & Banjevic, 2006 cited by Liu et al., 2017: 879). Shin & Jun (2015: 119) differentiated the CBM approach that help to identify and solve problems prior to the occurrence of damage from the traditional time-oriented approach of preventive maintenance.

2.5 Review of the Existing Structures Management Systems

Bridges and tunnels are key elements of the horizontal transportation systems around the world. However, their ages may become the most determinant factor of their deterioration or failure. Inaction or carelessness from the management may result in catastrophic consequences including loss of life, property, negative impact to the environment and the economy (Khanzada, 2012: 100). Therefore, the authorities managing these structures are called to adequately and efficiently respond to the inevitable challenges brought by the ageing of bridges and tunnels. At least for the last forty years, structures (bridges, tunnels, etc.) management systems have been developed, implemented, improved or in the process of development. Small, Philbin, Fraher & Romack (1998: A-1 / 2) highlighted that these systems were primarily initiated to *respond to the pressing need for a substantial mechanism of decision support*.

A few “developed countries” started worrying about the state of their ageing infrastructure and adopted approaches that have been assisting them in managing appropriately their bridges and tunnels. Wood & Hutt (1994: 7) realised that at least twenty states in the United States of America, several provinces in Canada were already implementing comprehensive structure management systems. This applied as well for at least four European countries and several states in Australia. They also noticed that most large agencies from those countries used *existing databases, electronic data processing equipment and software to develop their own systems*. This widely gave the opportunities to develop and implement structure management systems in even relatively small countries or regions. However, the size of the system and its level of complexity should be adapted to the technical capacities available, local needs and conditions.

A few components seem to be common to Bridge Management Systems (BMS) and they apply as well to tunnels and other civil engineering structures. Among them, Wood & Hutt (1994: 7) listed *a descriptive inventory of the bridge; a component to identify bridge condition and deficiencies*. This should include a *method of ranking the structure considering its adequacy to meet strength, safety and operational requirements, and its importance to public use*. They also considered a *component for inspection of the structure and recording the results of inspection*. Additionally, a *component to translate inspection results into structure condition information and to set priorities for maintenance and remedial works considering cost and budget constraints*. Another component should *record maintenance work done on each structure including a method of comparing achievements with cost and other performance targets*. Finally, a *component that optimises multiple maintenance, rehabilitation and replacement options for the structure inventory, on the national level*.

The package comprising these components will assist the structure managers to meeting the aim of all structure management systems. This consists in optimising the management of the structure stock in an efficient way by providing and processing appropriate data and obtaining relevant and useful information. Currently, the United States and Denmark have so far been leading the development of BMS. The most widely known BMS is the American system Pontis (Flaig & Lark, 2000: 99-100). The following sections present, for a set of countries, the development of their structure management systems (mostly including Bridge Management Systems and Tunnel Management Systems), detailing the above components.

2.5.1 Canada

a. Bridge Expert Analysis and Decision Support – BEADS

This Bridge Management System (BMS) has been developed, from the early 1970s to 2002, by the *Department of Infrastructure of the Alberta Province* (Hammad, Yan & Mostofi, 2007: 2). This province counts 9800 Municipal and 4100 Provincial bridges in its bridge stock. This system is a computerised system that distinguishes itself from systems developed in other provinces by its structure and scope. Additionally, it forms a *key component of the Transportation Infrastructure Management System (TIMS) which is a comprehensive system*. Its condition rating system presents 9 categorisations.

b. Pontis

The *Department of Transport of Manitoba province* uses this BMS to manage its bridge stock comprising 1200 provincial bridges. It uses a scale of 5 condition rating system and is a computerised BMS. Moreover, it supports the whole bridge management cycle from bridge *inspection and inventory data collection, analysis and predicts the needs and performance measures for bridges* (Hammad, Yan & Mostofi, 2007: 2). Additionally, it proposes an optimal preservation policy and develops projects for an agency's capital plan.

c. Nova Scotia Bridge Management System – NSBMS

This BMS was developed by the *Department of Transportation & Public Works of the Nova Scotia province* between 1999 and 2003. It serves to manage the 4000 Provincial bridges using a 4 scales condition rating system. These bridges are specified by the type of their construction material as 60% for timber bridges, 20% for concrete bridges and 20% for steel bridges. Finally, this system is identical to the Ontario BMS (Hammad, Yan & Mostofi, 2007: 2).

d. Ontario Bridge Management System – OBMS

This BMS was developed by the *Ministry of Transport of Ontario province* between 1989 and 1999. It is used for the 3000 Provincial bridges with a condition rating system of 4 scales. It is a computerised BMS comprising a *deterioration model, a cost model and operation rules for treatment selection and costing*. In addition, the *Ontario Structure Inspection Manual (OSIM)*, designed by the province of Ontario, is largely used as bridge inspection system in Canada with 5 provinces using it for their inspections. OSIM has a numerical rating and inspection manual and serves as reference to the design of a previous inspection systems in Quebec (Ellis, Thompson, Gagnon, & Richard, 2008: 78). Finally, the Ontario BMS presents an analytical framework facilitating the calculation and representation of suitable information to the decision at hand.

e. Quebec Bridge Management System – QBMS

This computerised BMS was developed by the *Ministry of Transportation of the Quebec province (MTQ)* to manage its 9000 structures. These structures consist of 4300 provincial bridges, 4400 municipal bridges, retaining walls and other structures (Hammad, Yan & Mostofi, 2007: 3). QBMS was developed between 2005 and 2007 and has a scale of 1 to 6 condition rating system, 6 being a new condition of an element of the bridge. The defects are recorded in considering 4 condition states for each bridge component from A for Excellent through B for Good and C for fair to D for Poor. Then each condition state will serve to finalise the severity of the defect (Ellis, Thompson, Gagnon, & Richard, 2008: 78). The final rates will serve to propose the remedial actions and their corresponding costs by the "Système de Gestion des Structures" (SGS) and they speculate the deterioration models.

Among the management indices considered by SGS, the bridge condition index (BCI or IES in French) is the only one that intervenes in the analysis and for performance measure. When improving the SGS and setting baselines for budgets, other indices may be considered. Also, the QBMS has a *deterioration model, a cost model and a treatment model* and split his structures as made of 0.3% of timber, 75.8% of concrete, 16.7% of steel and 7.2% of other types of material. It is called System de Gestion des Structures (SGS) and has an *inventory and inspection module* that was operational since 2007 and a *strategic planning module (MPS)* was finished in 2008. Its models contribute to provide work options at the element, project and program levels.

The elements and condition states of QBMS apply the concept of the Ontario Structure Inspection Manual. Additionally, it operates a network-level budgeting and performance analysis and presents an automated project scoping and treatment selection. Its reporting and analytical support modules incorporate the Strategic Planning Module (MPS). Also, its new manual defines specific bridge elements and their conditions are rated for severity and extent. Its productive database contains the entire inspection workflow process including acceptance and review of imported inspection reports.

The Ministry of Transport of Québec (MTQ) operates an enterprise Oracle database of its structure inventory and inspection data including structural evaluation results and data. It practises a decentralised management and decision-making process that gives the central office decisions on major bridge-level and all program-level and network-level structures. This office also manages the strategic planning data and analysis software performing all analysis in SGS Strategic Planning Module (MPS). On the other hand, 14 regional offices make decisions on bridge-level maintenance and repair and the inventory and inspection data (Ellis, Thompson, Gagnon, & Richard, 2008: 79).

f. Prince Edward Island Bridge Management System – PEIBMS

This is a BMS from the *Department of Transportation & Public Works of Prince Edward Island province* that manages 200 bridges. This system, homologous to Ontario BMS, was developed in 2007 and has a scale of 1 to 4 condition rating system. It also distinguishes its bridges based on the types of their materials with 50% for timber, 25% for concrete and 25% for steel.

2.5.2 United States of America

Most state departments of transportation of the United States of America (USA) possess Bridge Management Systems (BMS) for their bridge stock. These systems are consistent in *monitoring bridge condition and performance, and in responding to their needs* (Markow, 2008: 29). At national level, the National Bridge Inspection Standards (NBIS), from the 1970s, presents a single and integrated method to collect data on public bridges (Markow, 2008: 30). In addition, the NBIS mandated the Federal Highway Administration (FHWA) and state departments of transportation (DOTs) to monitor bridge condition and performance nationally. This consistently consisted in diagnosing bridge needs, setting criteria of project selection for federal bridge funding, and so promoting the public safety (Markow, 2008: 30). Therefore, this legislation became the foundation of the current state of practice in bridge inspection and bridge management (Small, Philbin, Fraher & Romack, 1998: A-1 / 1).

The bridge inspection information from various DOTs is collected annually and sent to the Federal office and stored in the National Bridge Inventory (NBI) database (Small, Philbin, Fraher & Romack, 1998: A-1 / 2). Exceptionally, Oregon records bridge inspection condition information at the element level in Pontis since 1993 (Mach, D. & Hartman, 2008: 16). Dekelbab, Al-Wazeer & Harris (2008: 163) proposed a change of the two years interval for bridge inspection to a longer inspection interval. Thus, the available funds will be optimally allocated to high-priority maintenance activities.

The National Bridge Inventory (NBI) database assists in predicting bridge conditions and in making informed decisions. It uses Microsoft Excel and Access, Visual Basic, eXtensible Markup Language, and Javascript (Thompson, Hearn, & Hyman, 2008: 105). Its data is arranged according to the standard catalogue and the condition outcomes is obtained from the combination of costs, units of measurement and corresponding quantities.

From the NBI information, projects are prioritised based on the condition and assessment ratings of bridges and the federal funds are correspondingly allocated. The sufficiency rating is based on structural adequacy and safety, serviceability and functional obsolescence, and significance to the public. A point deduction system serves for rating the conditions of bridges and a structure in perfect condition is rated 100. Bridge structural deficiency (SD) and functional obsolescence (FO), two ratings set by the NBIS, are the key performance measures that agencies continue to monitor today (Markow, 2008: 30). Therefore, each deficiency will decrease the score for each category. **The final rating is the sum of the structural (55%), functional (30%), and essentiality (15%) scores** (Small, Philbin, Fraher & Romack, 1998: A-1 / 2).

The condition rating considers 47 structural elements of each bridge, including 25 components of each span of a bridge, over the general components common to all bridges (Agrawal, Kawaguchi, & Zheng, 2008: 119). And the bridge condition rating scale arrays from 1 to 7, 7 corresponding to new and 1 to a failed condition. Agrawal, Kawaguchi & Zheng (2008: 119) specified that the deterioration rates for each bridge element appraise the effects of key factors, such as bridge material type. Despite multiple revisions of the NBIS, the definition and application of these bridge condition ratings have remained fundamentally unchanged for more than 30 years (Markow, 2008: 30).

a. Pontis Bridge Management System

Pontis is a product of FHWA and is extensively known and used globally (Flaig & Lark, 2000: 99-100). This management system applies a 'top-bottom' approach that prioritises a set service goals for the network and, subsequently, implements the selected bridge projects considering these goals. At least forty-two States of the USA are implementing it (Small, Philbin, Fraher & Romack, 1998: A-1 / 4). Pontis is characterised by its improvement optimisation coupled with a maintenance optimisation, a cost models, a program integration and its prediction models. It considers a network level and prioritises planned remedial actions along with predicting needs, future conditions, and executing strategic economic analysis.

Pontis integrates data from the existing NBI and the analysis of inspection data is performed at the project level on an element-by-element basis. More interestingly, Pontis comprises a total of 120 basic bridge elements (bearing, stringer, pier column, etc.) to choose from and assigns (from a maximum of five) a condition state or rating. However, the use of Pontis has been confined to the storage of inventory data for certain states, ignoring its multiple accounts. Fortunately, many others benefit from its decision assistance capacity (Mach, D. & Hartman, 2008: 16).

b. Bridgit Bridge Management System

This BMS was developed by the NCHRP and has similar condition rating system, database and deterioration models with Pontis. And yet, Bridgit considers a 'bottom-up' method to prioritise repair works that optimises the required action for each bridge and outlines the projects to carry out. This decision is based on the available budget and the requirements of the network (Flaig & Lark, 2000: 100). Bridgit is used in India and other countries planned to adopt it (Small, Philbin, Fraher & Romack, 1998: A-1 / 4). In the USA, Bridgit is operational in Maine and considerable more states were exploring the system for possible implementation. Also, plenty of Metropolitan Planning Organisations were expected to implement it. In 1998, the following 10 states contacted AASHTO to develop Bridgit as an official AASHTO Project: Colorado, Kansas, Louisiana, Maine, Wisconsin, Ohio, Oklahoma, Virginia, Washington, Wyoming (Small, Philbin, Fraher & Romack, 1998: A-1 / 5).

c. Pennsylvania Bridge Management System

The Pennsylvania BMS, from the *Pennsylvania Department of Transport (PenDOT)*, completed in 1987, presents specific components and features that integrate with other department systems.

It comprises a *Structural Inventory Record System (SIRS), a Structure Cost data inventory file, a Bridge Maintenance subsystem (BMTS), and a Bridge Rehabilitation/Replacement subsystem (BRRS)* (Ryall, 2010: 16). Also, it determines the present needs and predicts future needs using various scenarios. The BMTS subsystem prioritises the work to accommodate the funding and resources available. Finally, the system develops a deficiency point assignment considering a relative weight for each component and his elements.

d. Tunnel Management System for Highway and Rail Transit and SIDERA

SIDERA, developed by SICE, is a comprehensive software platform accommodating the outcomes of centralised management of intelligent transport systems (Sociedad Ibérica de Construcciones Eléctricas, S.A. [SICE], n.d.). It is used in USA, Colombia, Chile, Australia, Spain and Portugal. It mainly acquires data from all tunnel sensors and integrates the information and subsequent changes to control elements. Moreover, it manages and records maintenance work and provides an easy multi-language interface. It also displays interactive maps and schematics of facilities, equipment status and accident development all the times. Similarly, the Tunnel Management System for both highway and rail transit tunnels is a system that is managed by the FHWA and FTA of the USA. This system is also applied in Puerto Rico and comprises a computerised database for inventory, inspection and repair. It is closely linked to an Inspection Manual and a Maintenance and Rehabilitation Manual.

2.5.3 Japan

a. Japanese Bridge Management System (J-BMS)

This BMS has been developed in response to the need of rehabilitation and maintenance of the damaged concrete bridges in Japan (Miyamoto, Kawamura, & Nakamura, n.d.: 1). It comprises an evaluation component for bridge performance and a rehabilitation module combining the minimisation of maintenance cost and the maximisation of quality. Its platform functions with Visual Basic and C language (Miyamoto, Kawamura, & Nakamura, n.d.: 2).

J-BMS supports decisions to fate the deterioration process of existing bridge members, evaluate safety indices (health score) and propose the remaining service life (Emoto, Takahashi, Widyawati & Miyamoto, 2014: 65). It comprises an *inspection module, a maintenance module and an evaluation module and operates at project level instead of network level*. Each element of the bridge is assigned a deficiency rating, and the system processes with analyses of data and elaborates repair plans for each bridge. Also, the application of J-BMS is limited to existing reinforced concrete bridges. Moreover, target members are main girder and slab of these bridges. For existing concrete bridges, the first step in the J-BMS consists of a simple visual inspection of the target bridge (Miyamoto, Kawamura, & Nakamura, n.d.: 2). Miyamoto & Motoshita (2015: 189) added that it is integrated with a concrete bridge rating expert (BREX) system that serves to evaluate the serviceability of existing concrete bridges.

After evaluating the performance of bridge members using inspection data and technical specifications, BREX provides adequate scores for durability on a scale of 0 to 100. These results characterise present deterioration and assist to estimate the remaining life of the bridge using the predicted function of deterioration. Therefore, the rehabilitation strategy results from cost and implications of repairs and strengthening due to the gap between the estimated remaining life and the expected service life. Hence, the rehabilitation strategy contains the various maintenance plans related to cost minimisation or quality maximisation (Miyamoto, Kawamura, & Nakamura, n.d.: 3).

From periodical visual inspections, the J-BMS is used to assess bridge condition and predict the remaining service life (Emoto, Takahashi, Widyawati & Miyamoto, 2014: 65). Subsequently, design plans for repairing and reinforcing the assessed bridge are established. J-BMS breaks the cycle of conflicting data relying on the knowledge and experience of assessors.

2.5.4 United Kingdom

The UK bridge stock, mainly built between the late 1950s and early 1970s, need substantial refurbishment (Flaig & Lark, 2000: 99). In fact, the United Kingdom (UK) had adopted and implemented systems from abroad that could not fairly respond to the needs of the country. At their inception, Structures (Bridge) Management Systems were mere data storage systems developed and implemented to replace awkward manual systems. Data on the inventory and inspections could be stored and statistically processed and produce age distribution of the stock or the type of bridge. These first-generation systems include the National Structures Database (NATS) and Bridgeman developed by Oxfordshire County Council. After these systems, the second-generation BMS, are more advanced and present specific features that systematically assist in prioritising maintenance work.

a. UK NATS

Most systems developed abroad and imported in the UK were not compatible with the UK NATS and requested radical adjustments to be implemented. This UK system performs for more than ten years and mainly comprises an *inventory data and the general and principal inspections data for a noticeable set of bridges* (Flaig & Lark, 2000: 100).

b. Bridgeman

This system is using the whole-life costing techniques from the Transport Research Laboratory (TRL) and the Exor Corporation's `structures manager. Although it is a well-developed database promoted by the TRL, this system is not capable of yielding substantial decision-made outcomes (Flaig & Lark, 2000: 100).

c. Exor's structure manager

This system, similarly to Bridgeman, is using a database technology from Oracle and provides a deterioration prediction model to forecast the future condition of its structures. Subsequently, these condition states are used for maintenance and repair actions. Unfortunately, the deterioration does not always translate the extent of direct link to the structural adequacy of the subject asset (Flaig & Lark, 2000: 100).

d. Highways Structures Management Information System - HiSMIS

This system, introduced since 1990, is the *most widely used BMS in the UK in addition to NATS*. Its modules provide an *input frame for history, inventory, inspection, maintenance. Also, its enquiry and reporting consist of inspection management, maintenance management, replacement/upgrading programme, etc*. It deals with **bridges, tunnels, culverts and causeways, floodways and fords, gantries, lighting systems, and retaining walls**. However, it experiences the challenge of the amount of data collected and high operations costs (Ryall, 2010: 19).

2.5.5 Denmark and Finland

a. Danbro

This Danish BMS is managed by the Danish Road Directorate and has contributed to the improvement of the overall condition of the bridge network (Flaig & Lark, 2000: 100). Through it, an adequate application of repairs and preventive maintenance actions has successfully responded to the goals sets by the Danish Road Directorate.

b. Siha

The Finnish system, Siha, of all the commercially available systems, seems to be the most comprehensive and developed system. Flaig & Lark (2000: 100) described it as comprised of three subsystems that control the whole life of a bridge. This goes from its conceptual phase, through the supervision and quality assurance of its construction, to the management of the completed structure.

2.5.6 Switzerland

a. KUBA

This comprehensive structure management system was developed for the Swiss Federal Roads Authority. It is analogue to other state-of-the-art management systems but has numerous unique characteristics. Hajdin (2008: 47) presented its four components, consisting of a structure inventory (KUBA-DB), a preservation planning tool (KUBA-MS), a reporting tool (KUBA-RP), and a heavyweight transport evaluation tool (KUBA-ST). Its particularity is due to its catalogue of feasible preservation interventions for each condition state of a given element type, characterised by their unit costs and effectiveness (Hajdin, 2008: 53). The following paragraphs describe the components of KUBA.

KUBA-DB is a data collection system and serves as a basis for the other components in KUBA. It masters the inventory, inspection, and intervention data and convivially assists with collection of inventory, preservation, & inspection data (Hajdin, 2008: 57). Indeed, KUBA-DB stores information on resources involved in construction, inspection, and maintenance of structures. Despite KUBA-DB providing relevant information on existing structures, the authorities seem to prefer KUBA-MS over it (Hajdin, 2008: 57).

KUBA-MS, the Management System component, is the kernel of KUBA. Its provides consistent, integrated, and objective decision processes for structures on the Swiss national road system. Additionally, the component KUBA-RP (Reporting) is used for extensive querying and reporting of all data in KUBA (Hajdin, 2008: 58). Finally, the component KUBA-ST (Special Transport) helps the management in deciding whether to clear special transports to pass over a single bridge or over several bridges along a predefined route.

KUBA 5.0 should include two new features: geographic information system (GIS) presentation with linear referencing of road structures, and the capability to collect tunnel data. Moreover, it will include an interface to the core system of the overarching Swiss Road Management and Information System MISTRA. This will facilitate a proper data exchange between KUBA and the core system (Hajdin, 2008: 58). In KUBA 5.0, **comprehensive support for tunnels will be implemented to allow the collection of tunnel data on both the structural and the element level**. Furthermore, other versions of KUBA (5.x) may include a representation of road structures in 3-D (Hajdin, 2008: 59). The following paragraphs provide an overview of the Inventory and Inspection Modules of KUBA.

KUBA system contains elements that are classified by their element type and construction type, while segments are characterised by their extent and by their exposure to environmental influences (Hajdin, 2008: 51). Likewise, an element can contain one or more segments, depending on its geometry, size, structural role, and the prevailing environmental conditions. The example of reinforced concrete column considers the column as the element type and the reinforced concrete as the construction type.

Hajdin (2008: 51) defined the assessment of the condition of a structure as a process of recording damages in terms of their extent and severity. This helps to attribute a predefined condition state to the structure as a whole, or to its structural elements. For example, the assessment units of road structures on Swiss national roads are structural elements. Hajdin (2008: 51) specified that elements are mainly classified using a catalogue of element types and a catalogue of construction types. It is, therefore, necessary to define the elements for each structure prior to first inspection. The inspection consists in identifying damages and grouping them depending on their visual condition in damage areas. Hajdin (2008: 52) recommends that the inspector describes the deterioration process operating in these areas and pigeonholes them into segments. *The frequency of inspections is normally five years, although in certain circumstances more frequent inspection may be required*. However, the interval between the commissioning or inspection ‘zero’ and the first inspection, for newly constructed structures, may be set to 10 years (Hajdin, 2008: 52). Furthermore, local linear coordinates related to the tunnel axis can be used to locate elements, damages and extents of interventions. Also, the use of advanced technology, for example modern laser equipment, for collecting the inspection data will be helpful. The following paragraphs consist of the Condition Rating and Performance Measures as implemented in KUBA.

In this context, a condition rating describes the type, severity, and extent of damage. Type of damage refers to the deterioration process which characterises the look and the propagation of the specific damage. Hajdin (2008: 51) described a scale of five conditions defined, ranging from 1 (perfect condition without any damages) to 5 (needing immediate attention). On the one hand, conditions 1 to 4 reflect states that guarantee the safety and serviceability of the element and hence of the structure. Damage free areas presenting signs of distress are considered condition 1 and, afterward, added to segments. On the other hand, condition 5 mirrors a state of compromised safety and/or serviceability of the element and hence of the structure (Hajdin, 2008: 51). Overall, the severity data expressed by the condition and extent of each damage area are compiled and will serve to establish the condition of the segment, element and the whole structure. The following paragraphs present the Decision – Making Process and Planning Framework of KUBA.

In the decision-making process the goals set are used to attain the optimum decision and these goals are measured in term of money. Hajdin (2008: 51) emphasised that the decision process for preservation interventions should be prioritised as they are deduced from the conditions of the structural elements. And the condition forecast defines preservation projects for any given period in the future. Indeed, the forecast predicts the condition of an element (or segment), given the current condition and the likely environmental influences (Hajdin, 2008: 52). However, the optimum intervention planned for the element does not consider the structure it belongs to. This is obtained by considering a single optimum intervention for a given combination of element type, condition state, and influence indicator. Thus, the optimisation on the element level applies to many combinations of element types, deterioration processes, and influence indicators (Hajdin, 2008: 53).

The emerged preservation projects consist of element interventions. A project emerges for a structure after one of its elements needs an intervention based on the chosen element preservation policy (Hajdin, 2008: 55). The intervention cost is obtained from the extent of an intervention and its unit cost.

2.5.7 Germany

The maintenance activities performed on the German infrastructure assure that its current level of safety will be preserved for the same environmental context. Haardt & Holst (2008: 3) explains that the criteria to assess the failure mechanisms, including agreed thresholds, need the adequate information for management practices. Thus, tools and techniques to steadily apply an effective data management is required. Fortunately, Germany has a Structure Management System that assesses and optimises procedures on object and network level and it is used to respond to future demands.

a. SITRAFFIC International Tunnel Control Centre - ITCC

This system presents three versions comprising a system with one server and two additional systems. The two-server system has one operating as a redundant system in “hot standby” mode. The last system has several operator stations including two redundant servers and controllers with fault tolerance. Also, ATMS/SCADA is a European software platform combined in Telegra Tunnel Systems. It mainly consists of a design support for tunnel subsystems, factory integration, configuration, system testing and delivery of integrated tunnel management system. It also provides a support for field installation, commissioning and acceptance testing, operation and maintenance documentation and training, and a through-life maintenance support.

2.5.8 South Africa

Prior to 2000, *a bridge database and a plan database were used to manage the structures on provincial roads* (Nell, Nordengen, & Newmark, 2008: 63). The former had a *limited inventory information on each bridge* and the latter had only a *listing of as-built drawings of each bridge and condition-based bridge inspection forms*. Unfortunately, this system was not optimal for management of bridge maintenance and rehabilitation. The BMS database is integrated with the Department’s Road Network Information System. Its visual assessment approach uses a 4-point DERU (Degree, Extent, Relevancy and Urgency) system for rating observed defects (Nell, Nordengen, & Newmark, 2008: 63).

a. Station and Tunnel Management System (STMS)

This Tunnel Management System is based on Wonderware Technology and is managed by Kentz Integrated Solutions for Gautrain. It monitors and controls various subsystems like the ventilation and fire detection systems. It also consists of an energy monitoring and control, escalator / lift monitoring and control as well as the management of the Heating Ventilation and Air Conditioning (HVAC). Finally, it has a fire protection and dewatering systems.

b. STRUMAN Bridge Management System

This system was developed by the Roads and Transport Division of the Council for Industrial and Scientific Research (CSIR Built Environment) together with Stewart Scott International

(Nell, Nordengen, & Newmark, 2008: 64). This system mainly focused on the *identification, prioritisation, and planning to enhance the decision-making process*. **It comprises inventory, inspection, condition, budget, and maintenance modules and it exploits visual assessment data to prioritise structure maintenance projects**. From its inception, the inventory and inspection modules were improved to accommodate a culvert module and the integration of the BMS database with the Road Network Information System (RNIS). Moreover, for visual representation of the structure data, additional BMS modules including a map module were integrated using shapefiles from the department's geographical information system (GIS).

To merge bridge rehabilitation and road rehabilitation, the BMS had to be improved to accommodate other management systems including Pavement Management System and Road Maintenance Management System. Also, the system had to pamper extra road structures including culverts and retaining walls, and a culvert module was absorbed into the system. Parallelly, the update of the system facilitated the record of bridge and culvert drawings in electronic format. Finally, the BMS was made available to regional offices and other authorised users via the Internet (Nell, Nordengen, & Newmark, 2008: 64). In 2000 the Provincial Government of Western Cape (PGWC) adopted the STRUMAN BMS. The following paragraph describes the Inventory and Inspection Modules of this BMS.

The Inspection Module of the STRUMAN BMS focuses on observed defects of the various structure elements in place of the overall condition of each element (Nell, Nordengen, & Newmark, 2008: 65). The inspection methodology applied is a *defects-based system and consists of the identification of visual defects on structures and rating these defects in terms of degree, extent of occurrence and relevancy* (Comitee of Transport Officials [COTO], 2016). Using the BMS, the management office elaborates a program of rehabilitation of all bridges and major culverts in the province requiring remedial work and safety-related improvements (Nell, Nordengen, & Newmark, 2008: 64). The following paragraph presents the Condition Rating and Performance Measures of this system.

COTO (2013: D-4) states that the determination of the current structure condition is the first step in supporting the decision-making process. It also explains that the structure condition information is used at network level. It serves to assess the present condition of the structure, ranks the candidate projects and predicts the structure's performance. It is also used to evaluate the change in structure condition over time, to determine maintenance and rehabilitation (M&R) needs, to establish M&R strategies and to optimise M&R funds. The project level requires more data for quality and accuracy. To report the condition or the level of service of structures, COTO (2013: E2) proposes the use of index categories. Hence, the condition and functional indices of the structures should be summarised into one of the five condition categories presented in the following Table 2-3 Additionally, this table provides the colours that should be used when reporting graphically on the information.

Table 2-3: Condition and Functional Categories

Condition Category	Index Range	Condition Category Description	Functional Category Description	Colour Code	Structures
Very Good	85 – 100S	Asset is still like new and no problems are expected.	Good service levels at all times	Blue	Good 70 – 100 Green
Good	70 – 85	Asset is still in a condition that only requires routine maintenance to retain its condition.	Mostly good service levels with isolated problems occurring at certain times.	Green	
Fair	50 – 70	Some clearly evident deterioration and would benefit from preventative maintenance or requires renewal of isolated areas.	Reasonable service but with intermittent poor service.	Orange	Warning 50 – 70 Orange
Poor	30 – 50	Asset needs significant renewal or rehabilitation to improve its structural integrity	Generally poor service levels with occasional very poor service being provided.	Red	Critical 0 – 50 Red
Very Poor	0 – 30	Asset is in imminent danger of structural failure and requires substantial renewal or upgrading with less than 10% of EUL remaining.	Very poor service levels at most times.	Purple	

(Source: COTO, 2013)

The Condition Index for structures considers single very poor elements on the overall condition of the structure. The Structure Priority Condition Index (SPCI) is used to identify those structures with critical defects that should receive urgent attention. In this method, priority indices are calculated at inspection sub-item level. These inspection sub-item priority indices are used to calculate priority indices at inspection item level, which in turn are used to calculate a priority condition index for the structure. Certain inspection items and sub-items are excluded from these calculations.

2.5.9 Australia and New Zealand

a. Bridge Information and Management System - BIMS

This BMS was developed by the Australian Capital Territory Government (ACTG) to assist it for the management of his stock of 730 bridges. Wood & Hutt (1994: 29) describes the system as functioning by regular database updates and inspections, along with maintenance interventions. The importance of the road, the type and condition of its bridges determine the frequency of inspections, and detailed inspections are required for complex problems previously identified. However, in comparison with most of the North American agencies, the bridges managed with BIMS are in small number. The ACTG developed BIMS fundamentally considering the data on the location, characteristics, maintenance history and condition of bridges. Therefore, the information can be easily retrieved from the databases in the form of standard reports, special reports and general queries. Additionally, BIMS automatically schedules cyclic maintenance, general maintenance and inspection cycles based on a condition rating module. This module defines common bridge maintenance activities, their importance and resource requirements (Wood & Hutt, 1994: 29).

b. BRIdge Maintenance and Management System - BRIMMS

This BMS, less developed than BIMS, is used by WORKS Consultancy Services Ltd in New Zealand and it responds adequately to its needs. It can be interpreted as an asset register that reports the bridge inventory and maintenance history details (Wood & Hutt, 1994: 29). Unluckily, it does not contain a ranking bridge condition or performance module. Its ranking is done considering the strength, safety and operational requirements and the importance of the bridge to public use. However, its inventory module is a comprehensive system originating from the 1970s.

2.6 Current Railway Tunnel Management Practice in South Africa

Railway Tunnel Management in South Africa is currently led by the Rail Network Technical Manual for Infrastructure Condition Assessment BBC 8266 (MICA, version 3: August 2017) along with other manuals developed by Transnet Freight Rail (TFR). The additional manuals comprise the Infrastructure Engineering Manual for Track Maintenance BBB 0481 (MTM, version 2: 2012), the Bridge Handbook (Handbook B4: September 1988), the Legend for Inspection Items 2008: BBC 8264 (**Bridges, Culverts, Tunnels and other Structures**). The MICA BBC 8266 provides guidance through detail of numerous condition assessments and promote uniformity and conformity in conducting condition assessment in TFR. It gives the responsibility to maintenance managers in infrastructure to oversee the standard inspections practices and to guarantee the awareness of Depots engineers and Production managers of all unsafe conditions of infrastructure.

2.6.1 Purpose and Scope of Railway Tunnel Inspections

This subsection presents the reason for railway tunnels inspections and their extent. This consists in complying with tunnel maintenance and safety regulations and warranting the structural integrity of tunnel lining, tunnel track slab drainage, tunnel portals, etc.

2.6.2 Method of Inspections

The current condition assessment of railway tunnels in South Africa mainly consists of visual inspection of all tunnel structures.

2.6.3 Frequency of Tunnels Inspections

This subsection provides the occurrence or repetitive sequences in which condition assessments should be done. BBB 0481 (TFR, 2012: 32) recommends that *bridges, culverts and lined tunnels should be inspected at least once a year*. This type of inspections, called Annual Tunnel Inspections are scheduled to be done and completed before the end of April. Therefore, BBC 8266 (TFR, 2017: 17) requests that *the engineers and technical staff, over the year, manage to detect any defects in the railway tunnels and urgently report them to the Central Office*. Moreover, the Central Office does Exception List Inspections annually after the end of April in relation to the exception lists from Depots. Finally, the Central Office does **Principal Tunnel Inspections at least once every five years**.

2.6.4 Competency of Tunnels Inspections Team

This subsection refers to the required qualifications, working experience, training and skills of the principal members of the tunnel inspections team per company policy and by law. Thus, the Annual Tunnel Inspections should be done by the Depot Engineer or his delegate, the Principal and Exception List Inspections should be done by the Senior Engineer (Bridges) or his delegate.

2.6.5 Tunnel Inspection Forms

This subsection specifies the standard documents providing spaces to record adequate information during tunnel inspections (MICA documents). For railway tunnels inspections, the Annual Inspection of Tunnels – BBC 8254 (Figure 2-14) forms are currently in use.

RAILWAY INFRASTRUCTURE ASSET

CONDITION ASSESMENT DOCUMENT

TUNNELS ***MICA REF.: BBC8254 (6.1.1)***

Name/ Description				Depot	
Station to Station					
Nearest Station		Plan Section No.		Plan km	
Inspected By		Functional Location			
Employee No.		Centroid (Lat)		Date	
Designation		Centroid (Lon)			
Inspection Type					
		Lining		Length	m
Signature					

		N/A	U/I	1	2	3	4	Comments	M
Approach Surface	T1								
Tunnel Portal and Foundation	T2								
Embankment Protection Works	T3								
Retaining Wall and Foundation	T4								
Tunnel Drainage	T5								
Kerb/Side Walk	T6								
Tunnel Lining	T7								
Refuge	T8								
Lighting	T9								
Ventilation Shaft	T10								
Miscellaneous	T11								
Track : Geometry	T12								
Rail	T13								
Fastening	T14								
Sleeper	T15								
Ballast	T16								
Track Slab	T17								

					Legend:	
Line Importance/Income	BI 1	High	Medium	Low		
Detour Length	BI 2	200 km	20 km	Zero	N/A	This item does not exist
Structure Usage	BI 3	Daily	Weekly	Not in use	U/I	Unable to inspect this item
Corrosion Factor	BI 4	Severe	Normal	Low	1	Good
Access to Site	BI 5	Difficult	Fair	Easy	2	Minor repairs. Ignore
Replacement Complexity	BI 6	High	Medium	Easy	3	Planned Maintenance
Design Life Cycle	BI 7	End of life	Halfw ay	New	4	Immediate/Emergency repair w ork
Environmental Input	BI 8	High Risk	Medium	Low Risk	M	To be monitored. Show period

Refer to Bridge Office	Yes	No	Photos Taken	
Budget	Yes	No		

	Remarks	Signature
Maintenance Manager		
Depot Engineer		
Senior Engineer, Bridges		

Available on ProjectWise under document number BBC 8254

Figure 2-14: Annual Inspection of Tunnels – BBC 8254

(Source: Transnet Freight Rail, n.d.)

2.7 Summary

This review of the existing literature allowed to navigate through the main concepts of this research. First, with the heavy haul lines in South Africa, it presented the Sishen – Saldanha ore line (ore line at 30 t/axle) and the Richards Bay coal line (coal line at 26 t/axle). The former is the second longest heavy haul line in the world at 861 km, and the latter is 588 km long from Mpumalanga coalfields and has 137 bridges and 37 tunnels. This research presented the Bobbesjaansberg Tunnel, the only tunnel on the Sishen – Saldanha line of 0.787 km long, built in 1975. Also, it briefly introduced the Overvaal rail tunnel that is 3.896 km long and located in Mpumalanga between Ermelo and Piet Relief. Additionally, it introduced the common railway transit tunnel shapes and all TFR current tunnels are oval tunnels with a single track.

Second, this research commented on the most common defects on concrete structural elements of railway tunnels. Among them, it analysed the defects in tunnel liner, the concrete cracking, the corrosion of reinforcing steel, the structural durability, the concrete spalling. Also, this study discussed water leakage that creates more problems to tunnel's concrete liners and reinforced concrete that any combination of tunnel structural problems. In the end, it spoke about differential settlement, presenting a few case studies.

The third section defined and described a structure management system. It mainly recapitulated the maintenance of infrastructure, tunnel deterioration, tunnel inventory, tunnel inspection, tunnel monitoring, tunnel failure. It also distinguished the priority-based management systems from the condition-based management systems. Additionally, it reviewed the existing structures management systems including bridge and tunnel management systems of Canada, USA, Japan, UK, Denmark and Finland, Switzerland, Germany, South Africa, Australia and New Zealand. For each country, it inventoried its structures management systems highlighting the inventory and inspection modules, condition rating and performance measures, decision-making process and planning framework. Particularly for South Africa, a comprehensive description of the procedure to evaluate the condition of defects on tunnel structures has been provided. Moreover, it summarised the current railway tunnels management practices in South Africa. Finally, it highlighted the purpose and scope of these inspections, their methods, their frequencies, the competency of the assessors and the tunnel inspection forms.

In the next chapter, this study develops the Procedures to enhance tunnels management in South Africa. It considers the strengths and the weaknesses of the systems reviewed and proposes an improved version of the current practices in managing railway tunnels in South Africa. The emphasis is given to the tunnels on the heavy haul lines and to their concrete structural elements. Also, the various defects reviewed in this chapter will direct the way inspections will be conducted on these elements and their components. The refined system that is proposed will integrate the inventory and database module, the inspection module and the monitoring module.

3. Procedures to Enhance Tunnels Management

3.1 Introduction

The literature review chapter stressed the current challenges of the structures on the railway lines, especially tunnels on the heavy haul lines in South Africa. It also described the most common defects on concrete structural elements of railway tunnels. Finally, it overviewed the existing structures management systems and the tunnel management practice in South Africa. Considering this relevant information, this chapter of the methods of the management system details the procedures that will be implemented to enhance the management of railway tunnels in South Africa. This research first analysed the current structures management systems reviewed and aligned this analysis to the current railway tunnels management practice in South Africa. Afterwards, it designed the tunnel inventory database that formed the first step of the development of this tunnel management system. It will allow the owner of the tunnel assets to have a big picture of his stock and assist him in retrieving any relevant information concerning those tunnels.

This study discussed tunnel inventory forms, the inventory data and the tunnel inventory reporting. Additionally, it presented the procedures to consider conducting the inspection of railway tunnels. It also emphasised how concrete structural elements of these tunnels should be inspected. Moreover, it described the tunnel evaluation procedures that should assist for an optimum decision-making process. Finally, it recommended the methodology to use to implement monitoring systems for the most critical elements of railway tunnels.

3.2 Railway Tunnel Management Synopsis

The following Figure 3-1 presents the synopsis of the railway tunnel management system adopted, after conducting the comprehensive review of the existing structure management systems in South Africa and abroad.

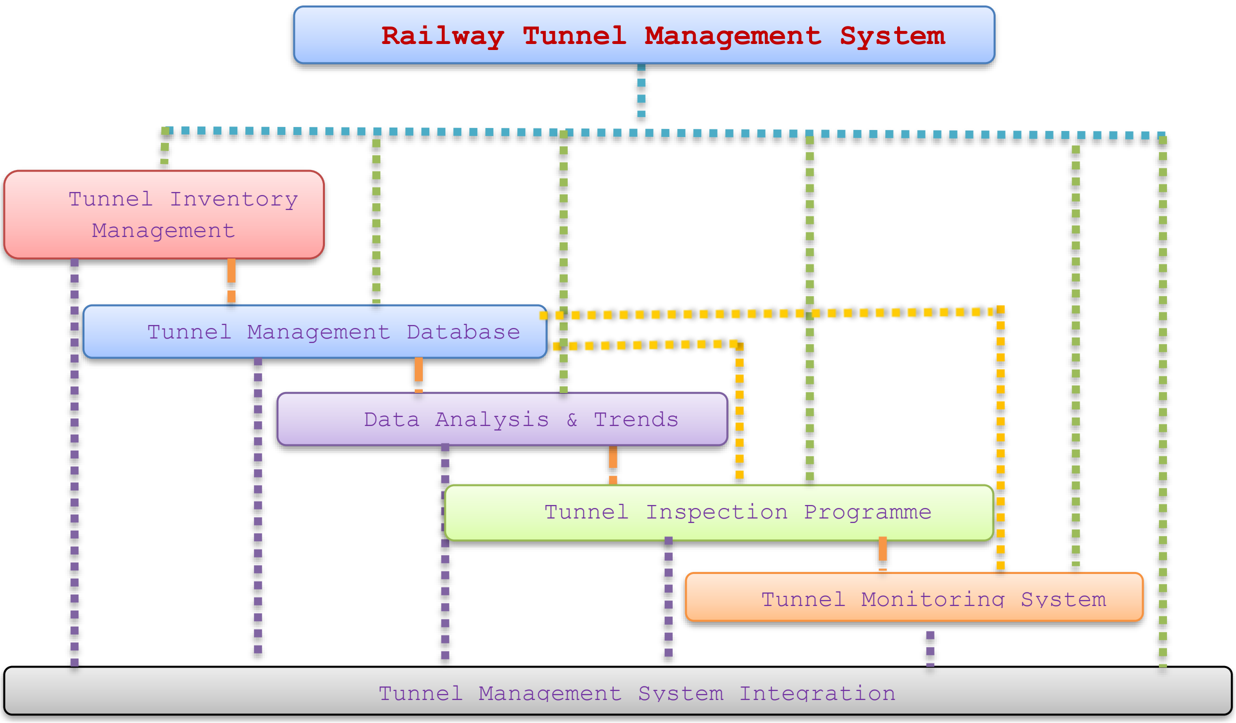


Figure 3-1: Railway Tunnel Management System Synopsis

This synopsis represented the proposed move from a manual system (current management practice in South Africa) to a computerised system (aligned with most of the system reviewed). Additionally, it specified the transition from simple standard inspections practices to a comprehensive system. Explicitly, it expressed the extension of a simplified inventory form to detailed inventory forms considering a tunnel as a structure and its concrete structural elements. Finally, this study linked the data from the monitoring system to the management system.

3.3 Data Analysis

This section outlined the gaps observed in the current railway management practice in South Africa and has enhanced this practice considering the structures management systems reviewed. With the data gathered in inventory and inspection modules, relevant information was obtained that should assist the authority in making consistent decisions on further actions to undertake. This information was obtained through data analysis and manipulation. Generating illustrations condensed the amount of information into single pieces that translated the substantial meaning of the bulk data. Also, important trends came out of the large data stored in the system. The information and trends established led to findings and further planning of remedial measures or prioritising the actions to be taken. Therefore, the combination of the appropriate software including IBM SPSS, MS Access and MS Excel PivotTable and PivotChart helped to use figures (graphs and charts) wherever needed.

The types of figures considered were *line graphs for accurate continuous information, bar graphs to represent discrete information, pie charts to represent percentages of a whole* (English et al., 2013). Moreover, *flow charts have been used for stepwise procedures, mainly in algorithms and Gantt charts and Timelines for planning inspection activities*. From inventory data, the analysis has been conducted and promoted the categorisation of data that provided relevant trends and information. The main parameters considered were the tunnels numbers, tunnels lengths and tunnels locations (regions, sections and areas). Additionally, this study considered tunnels positions on the railway network (kilometres of the beginning and the end of the tunnels), the characteristics of the liners (types and thicknesses). It also scrutinised parallelly a separate analysis for tunnels on the coal lines. Furthermore, it adequately combined and broke down these parameters to identify the simplest relationships between them. Therefore, the information obtained were presented in form of tables or figures (graphs and charts).

3.4 Tunnel Inventory Management

The tunnel inventory database served as a placeholder for all relevant information regarding railway tunnels in South Africa, from the design to the remedial actions, through commissioning and inspections. This database should serve as a platform for tunnel management and automatically update every time additional data should be available and provided through tunnel inventory.

3.4.1 Content and Format of the Inventory Forms

From Tunnel Inventory Forms, each tunnel was recorded and detailed according to its identification items, location items comprising coordinates and geometric data, contract description items and inspection items. Moreover, the concrete structural elements were highlighted in an additional form breaking them down to their components. For this study and future use, Tunnel Inventory Form Templates have been developed and formed part of this report. These templates have been design using Ms Excel or Ms Access Forms and Reports, and they have facilitated and standardised the matching of the procedures to collect data and update the database.

3.4.2 Source of Inventory Data

To obtain relevant information that would constitute the inventory module, the system manager should rely more on existing documents. These are existing drawings (design drawings, as-built drawings), specification documents from the statement of work to project commissioning, site notes and sketches, design reports, previous files and measurements. The inventory file should serve for data analysis to provide relevant information, for planning inspection activities, for designing the monitoring system and should assist in the decision-making process. Further, an Inventory photos form has been designed that would mostly assist when discussing a structure at a distance. It constituted a separate database, due to the size of pictures, that managed inventory and inspection photos. This database has been integrated to the system and worked together with the main database.

Each tunnel should have a tunnel identification number that the authority would assign, and the standard coding should uniformly apply to all tunnels. This number should apply to the whole country and should be considered irrespective of the region. Additionally, each item should have an identification number referring to the category it belongs to. However, this study has considered the coding system used in the existing documents: “Database of Tunnels in Southern Africa” for tunnels. Hence, it recommended some specific coding for a few elements, for example portals that would be numbered numerically, and segments elements would be referred to by their positions in the system and lengths. Also, the position of the segment within the cross-section of the tunnel would be provided. The region where the tunnel is classified should be specified as well, in addition to the chainage. Wherever possible, the GPS coordinates of tunnels should be captured, especially for the beginning and the end of the structure, in the WGS84 format.

3.5 Tunnel Management Database

3.5.1 Structure, Content and Accessibility of the Database

The Tunnel Management System proposed incorporated a set of databases that would be integrated through a programming code written in Microsoft Visual Basic Applications (VBA). The tunnel management database was the core database of the system and comprised the tunnel inventory module, tunnel inspection module and tunnel monitoring module. The tunnel inventory module comprised mainly the record of each tunnel and its features including the identification items, the location items, the geometry items and so on. Any new tunnel commissioned would be added to the tunnel inventory module with all the relevant information from its conception to its commissioning. The tunnel inventory module was linked to the system integration programme that should timely connect it to tunnel inspection module and tunnel monitoring module.

The tunnel inspection module was closely linked to the tunnel inventory module as the latter nurses the former. Indeed, from the inventory data, the subject tunnel was linked to the inspection data that provided the inspection type, date and the inspection team. This would be connected to the inspection files of each element of the specific tunnel inspected on that date. For each element, the details provided consisted of the name, the id number, the dimensions, the unit of measurement, the location (longitudinally along the tunnel and across the cross section). The specific element was linked to a defect file that would assist the tunnel inspector to rate any defects observed and subsequently the element.

Considered as a special inspection type, the tunnel monitoring module interfered closely with the tunnel inspection module. However, the operating mode of tunnel monitoring module was similar to the operating mode of tunnel inspection module. It was nursed from the tunnel inventory module that provided the details of the specific tunnel monitored. Thus, the monitoring file, provided the specific date and time the data should be received on the specific date. It also recorded the name of the expert who observed the defect on the element. The monitoring file linked to all the element files that provided any data at that time, as the system should record only critical data of the defects from the monitoring system. Then the element files connected to the sensory system files that described the parameter monitored. Finally, the sensory system files linked to the defect files that were recorded for their outstanding data observed.

3.5.2 Secondary Database

Railway tunnel management system comprised also a photo database that was mainly an inventory database of inventory photos and inspection photos. In fact, due to the need to record all the relevant photos of the tunnels and the defects observed on their elements, a photos database has been designed. This alleviated the challenge of the size that photos occupy in the memory of computers. The inventory photos file recorded the dates of inventory (beginning and end), the data source, the breakdown of the tunnel and the corresponding photos. Similarly, the inspection photos file recorded the tunnel #, the inspection date, the inspection type, the breakdown of the elements inspected on that tunnel, the inspection outcome and the corresponding photos. This database could also be checked independently, as the reference data was provided.

3.6 Tunnel Inspection Programme

The Tunnel Inspection programme that was compiled described the necessary steps to follow for preparing and carrying out inspections of railway tunnels in South Africa. Therefore, to guarantee the uniformity of the inspections to carry out and the reliability of their outcomes, the following procedures were applied to the development of our tunnel inspection programme. It defined the *inspection frequencies*, promoted certain techniques and described the *expected qualifications of inspectors and their team members*. Referring to the inspection team, it listed a few titles and the equivalent qualifications for each of them. It emphasised on the **knowledge of concrete structures, and the structural behaviour of tunnels**. Also, it considered the *general knowledge of structural analysis and design, coupled with experience of concrete works in harsh environments*. The programme specified as well *general and specific tools and techniques that would appropriately respond to the needs of the inspection team*. It also reviewed the rating system that is commonly used in South Africa, the **DER – U rating system** developed by the Council for Industrial and Scientific Research (CSIR Built Environment).

As a guideline for tunnel inspections, the tunnel inspection programme has developed inspection forms that should direct the inspection team with regard to concrete structural elements. On the concerned items, the common defects observed were listed and the rating of each defect on the corresponding item was defined. These forms also specified the type of inspection carried out, the inspection date, the details of the subject tunnel, and the inspector name.

3.6.1 Inspection Team

That section defined the minimum qualifications for any member of the tunnel inspection team. It emphasised on the *knowledge and experience with concrete materials* (reinforced concrete, precast concrete, prestressed concrete, etc). Also, the *knowledge and experience with tunnel structures would be an advantage for each member, especially the behaviour of tunnel structural systems*. Although the team should comprise a tunnel safety officer that would oversee the daily inductions, members with knowledge of safety regulations and practices were required. The tunnel inspection team should be made of a **chief inspector, tunnel inspectors, tunnel inspection technicians and the tunnel safety officer**. For each position, the requirements for skills and experience were set.

3.6.2 Inspection Tools and Equipment

For tunnel inspections, this study specified two categories of tools and equipment depending on the type of inspection. Therefore, the tools and equipment to be used for routine inspections were listed with the details of their use. Additionally, it made an option where special tools and equipment would be needed for further levels of inspection. However, it could not list all the tools and equipment that would be used for other types of inspections. Finally, this study recommended regular trainings and sessions to update the inspection team on the procedures and use of equipment to efficiently conduct inspections.

3.6.3 Inspection Procedures

In the following chapter, this section described the procedures to be observed and applied to carry out inspections in a uniform and standardised way. Those procedures related to the types of inspections, their frequencies, the specific defects characterising the concrete structural elements of railway tunnels and their components. Also, this study set and made available the primary techniques, mainly non-destructive techniques, in identifying the concrete structural defects and how to apply them during visual inspection. Moreover, it has provided an identical way of taking measurements during the inspection of concrete structural elements of railway tunnels. The unit of measurements, the description of the defects related to the elements and their components were procured in the Tunnel Inspection Forms designed.

3.6.4 DER Rating System and its application to Railway Tunnels Inspections

This study applied the DER rating system, developed in the TMH 19 – Part A, to identify and rate defects on concrete structural elements of railway tunnels in South Africa. DER stands for Degree – severity of the defect, Extent – size of the defect in comparison to the element inspected, Relevancy – impact of the defect to the safety and the structural/functional integrity of the element inspected. D, E, and R are allocated values ranging from 1 to 4, although additional values are specified for D. As TMH 19 recommends the rating only of the worst defect on an inspected item, that is the defect with the highest R-rating, this research suggested the record of any defect identified on a concrete structural element. It considered the need of recording any defect that may develop in an unexpected way and become more critical than the worst defect at the time of inspection.

The outcome of the inspection should be recorded in the system and would be used by the management office to generate and adopt the accurate, optimum and prioritised decision for further interventions. Furthermore, this study considered the "urgency" criterion that was combined to other parameters. The system affected a coefficient to each parameter to minimise the subjectivity of inspectors' judgement on defects. Those coefficients were described in the section presenting the tunnel evaluation system developed.

3.6.5 Tunnel Evaluation System

After rating the defects on the elements of the tunnels, the system evaluated the whole "inspection file". Therefore, the management office would consider the outcome of the evaluation and make informed decisions by interfering with professional judgement to decide on future interventions. The system estimated a score for any given defect, based on evaluation factors defined further. From this score, a relative score was obtained by the ratio of the score to the maximum score on the given element. The unitless relative scores were added for each component and element of the tunnel. Finally, the cumulative value of all the relatives scores of elements of a tunnel was devided by the number of elements and defined the "**health of the tunnel**". This parameter should be combined with the ageing factor and the criticality of the tunnel environment to assist the tunnel management office for final decisions on further intervention actions.

3.6.6 Defects on Concrete Structural Elements of Railway Tunnels

This section designed an easy graphical way of rating defects on the concrete structural elements of railway tunnels and their components. It considered the columns and piles, cross passageways, the interior walls, the liners, the portals, the roof girders, the tunnel ceiling structures and the tunnel invert structures. These graphs should effectively assist the inspectors while on sites and would standardise and promote a uniform way of rating the defects on these elements.

3.7 Tunnel Monitoring System

Condition monitoring should play a crucial role in the management of railway tunnels. Indeed, condition monitoring should detect and identify deterioration in their elements before the deterioration could cause a failure or prevent rail operations. That section detailed the main elements to consider for further development of a consistent Tunnel Monitoring System for the railway tunnel stock in South Africa and specifically the tunnels on the heavy haul lines. The following Figure 3-2 represented a flow chart of the stepwise procedures to decide on the implementation of a monitoring system for a defect on a concrete structural element of the tunnel.

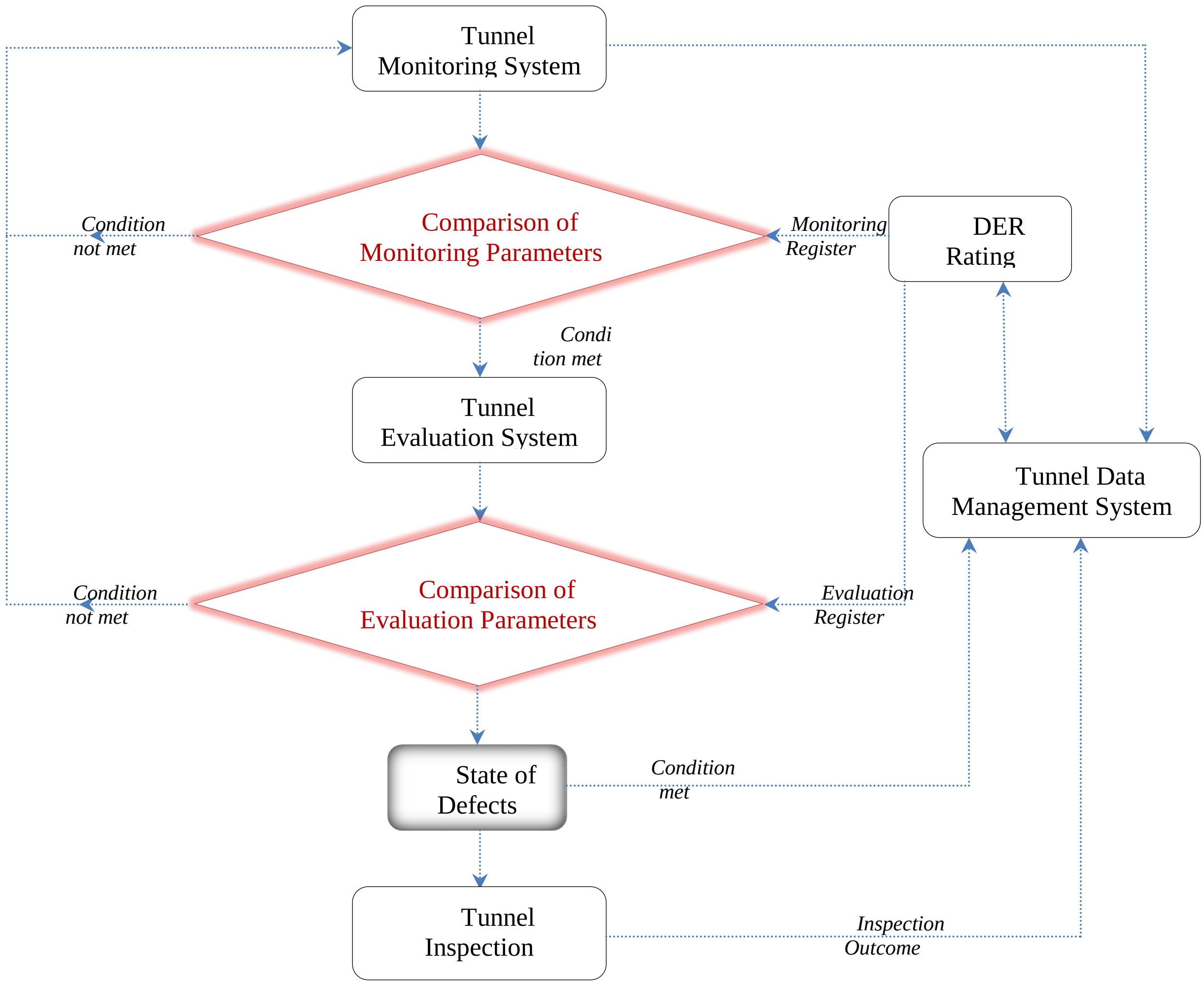


Figure 3-2: Flow Chart of Tunnel Monitoring System

In addition, the following Figure 3-3 presented the sequence of the integrated modules of this Tunnel Monitoring System.

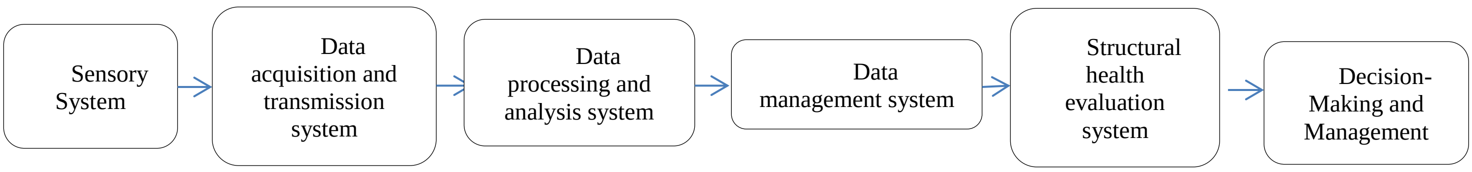


Figure 3-3: Structural Health Monitoring System Integrated Modules

(Source: The Hong Kong Polytechnic University, n.d.)

3.8 Railway Tunnel Management System Integration

After developing various components of Railway Tunnel Management System in South Africa, they were integrated in a manner that optimised their performance as a whole system. This section presented the processes that were developed during the integration of the components of railway tunnel management system. Those processes described the modules that content the steps to undertake and the procedures to pass data. The procedures applied consisted in setting properties and methods and manipulate objects. Additional techniques considered repeating chunks codes with loops, making decisions in the code, importing, exporting, or linking objects. The following set of flow charts summarised the processes developed that were working behind the scenes to integrate all the components and produced the complete management system.

The following Figure 3-4 is a flow chart representing the process that would append new records of data in the Tunnel Inventory Module.

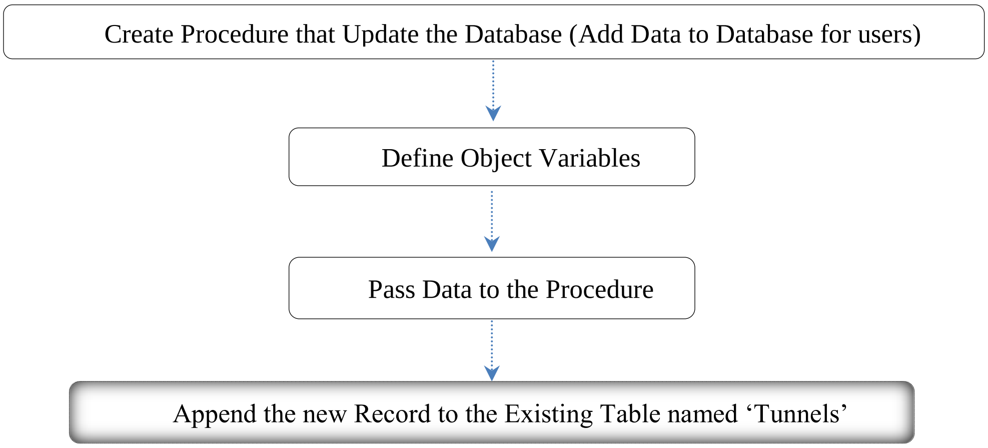


Figure 3-4: Process to Append New Data

Also, the following Figure 3-5 described a flow chart representing the process that generated update Inspection Forms.

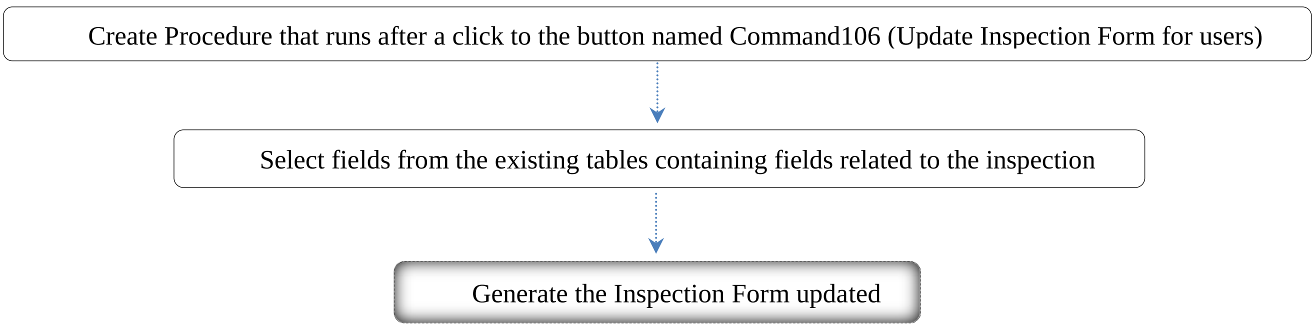


Figure 3-5: Process to Update Inspection Form

The following Figure 3-6 presented the flow chart representing the process that launched the initial inspection planning considering the type of inspection and the tunnel age (year).

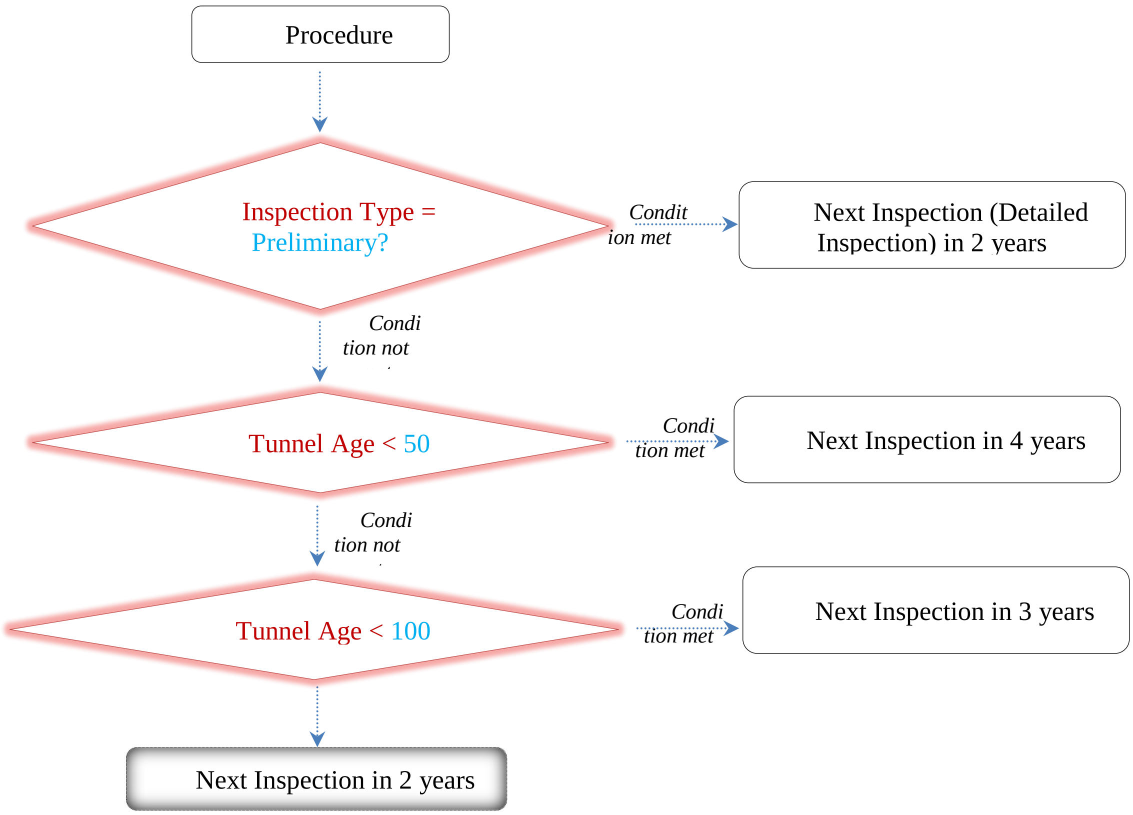


Figure 3-6: Tunnel Inspection Plan Process

3.9 Summary

This chapter of the Procedures to enhance tunnels management has provided a synopsis of the main modules that were developed and formed the components of the Railway Tunnel Management System in South Africa. A data analysis was conducted for the literature reviewed and within the database and a guideline of the analysis will be provided in this report. This guideline provided relevant information regarding the tunnel stock and the tunnels on the heavy haul lines.

The Tunnel Inventory Module served as a placeholder of all the information regarding those tunnels. It comprised two connected tunnel inventory forms that recorded the description of the tunnel as a structure and the description of its concrete structural components. The first form recorded the tunnels' identification, coordinates, contract description, geometric data, inspection and structural features and material items. The second form recorded, for a given tunnel, its concrete structural elements specifying their longitudinal and transversal positions and their measurements. Each inventory form required an identification number for each record. The tunnel management databases comprised a core database serving as a platform to the inventory, inspection and monitoring modules. Additionally, a separate database for inventory and inspection photos was linked to deal only with these types of files.

The Tunnel Inspection Programme set the requirements for the inspection team, defined the types of inspections, their procedures and their frequencies. It also accommodated the DER rating system in the rating and evaluation of railway tunnels in South Africa. However, the introduction of scores and relative scores for defects, final relative scores for elements and the health of each tunnel have simplified the application of DER extended to all defects observed. Tunnels Inspection Forms designed set uniform and standard ways of conducting inspections. A Tunnel Monitoring System was also integrated to the railway tunnel management system to closely monitor the most critical and recurring defects on concrete structural elements. Finally, a set of integration processes were applied to integrate all the modules developed and constitute a unique system.

4. Data Analysis and Findings

4.1 Introduction

The aim of Structure Management Systems is to facilitate the decision-making process through planning, development and implementation stages of the appropriate programs. From the inception of its design and compilation, railway tunnels management system in South Africa provides a set of adequate tools, techniques and processes. These elements will assist the tunnels management authority in South Africa to make informed decisions to sustain the performance of their assets through their service lifespan.

In fact, *tunnel management is how a tunnel stock is cared for from conception to the end of its useful life* (Ryall, 2010: 3). Therefore, **the management of a tunnel is the application of processes to coordinate and carry out a set of operations to prevent or keep tract of its degradation**. These operations consist of *data collection through inventory; inspection and monitoring; assessment of condition and strength; repair, rehabilitation, strengthening, or replacement; optimisation of maintenance strategies* (Ryall, 2010). However, the following factors influence the type and severity of degradation of a tunnel: the atmospheric environment, construction materials, design and detailing, structural form, quality of construction, traffic load, weather, etc. Thus, *a tunnel management system is a tool that assists the authority in obtaining accurate information on the necessity and timeframe to implement one of the above operations*. This will ensure that the tunnel is still performing safely to the level of service required. The following section presents the analysis of the current railway tunnels management practice in South Africa in light of the existing structure management systems. It also conducts an analysis for the tunnel stock and the tunnels on the heavy haul lines.

4.2 Data Analysis

4.2.1 Current Tunnels Management Practice in South Africa

The current tunnels management practice in South Africa consists of *visual inspection to further tunnel maintenance and preserve the structural integrity of the lining, the portals, etc*. The practice is decentralised for annual tunnel inspections performed at regional levels. The central office organises the principal tunnel inspections every five years and the exception list inspections annually in connection with the depots. The Depot Engineer or his delegate carries out the annual tunnel inspections, while the Senior Engineer (Bridges) performs the Principal and Exception List Inspections. The Annual Tunnel Inspections are carried out based on the BBC 8254 forms (previous Figure 2-14). The following section summarises the existing structures management systems that are considered in this study.

4.2.2 Existing Structures Management Systems

From the review of the literature, the following Table 4-1 summarises the structures management systems that enlighten the enhancement of the current tunnels management practice in South Africa that is proposed.

Table 4-1: Existing Structures Management Systems Reviewed

Id #	System Name	Country - Region	System Type
1	BEADS	Canada - Alberta	Bridge
2	Pontis BMS	Canada - Manitoba	Bridge
3	NSBMS	Canada - Nova Scotia	Bridge
4	OBMS	Canada - Ontario	Bridge
5	QBMS	Canada - Quebec	Bridge
6	PEIBMS	Canada - Prince Edward Island	Bridge
7	Pontis BMS	USA	Bridge
8	Bridgit BMS	USA	Bridge
9	Pennsylvania BMS	USA - Pennsylvania	Bridge
10	SIDERA	USA & Others	**Tunnel**
11	J-BMS	Japan	Bridge
12	UK NATS	UK	Bridge
13	Bridgeman	UK	Bridge
14	Exor's Structure Manager	UK	Structure
15	HiSMIS	UK	Bridges, **Tunnels**, Culverts, Retaining Walls
16	Danbro	Denmark	Bridge
17	Siha	Finland	Bridge
18	KUBA	Switzerland	Structure, **Tunnel**
19	SITRAFFIC - ITCC	Germany	**Tunnel**
20	STMS	South Africa	**Tunnel**
21	STRUMAN BMS	South Africa	Structure, Bridge
22	BIMS	Australia	Bridge
23	BRIMMS	New Zealand	Bridge

The above table 4-1 presents twenty-three (23) structures management systems from eleven (11) countries that consist of *bridges, tunnels, culverts, retaining walls and other structures*. These systems have been developed since 1970s and are still improving and relate to varying stock.

4.2.3 Analysis of Current Railway Tunnel Stock

The tunnel stock that was considered in this study is managed by Transnet Freight Rail (TFR), previously called Spoornet. This first section of the analysis will use the data recorded in the inventory file and contained in the database to establish adequate trends and patterns that will lead to relevant information to be used by the authority responsible of railway tunnels in South Africa to make informed decisions regarding their management. The following Figures 4-1 and 4-2 classify the tunnels based on the percentage of their numbers and lengths respectively, relative to their construction methods that will assist the tunnel management office to appropriately classify all tunnels and accurately plan for inspections and further operations.

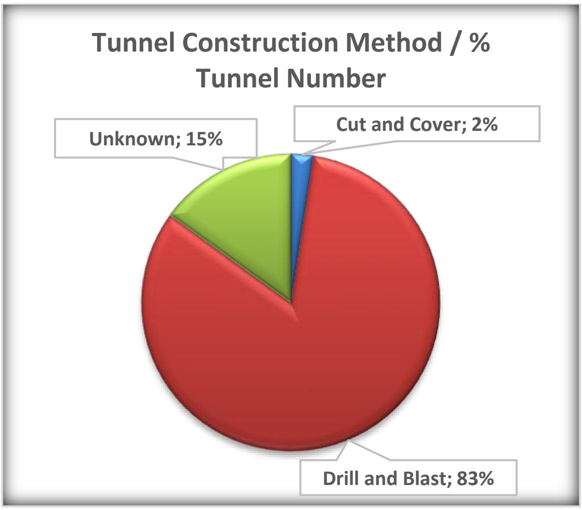


Figure 4-1: Construction Methods – % of Number of Tunnels

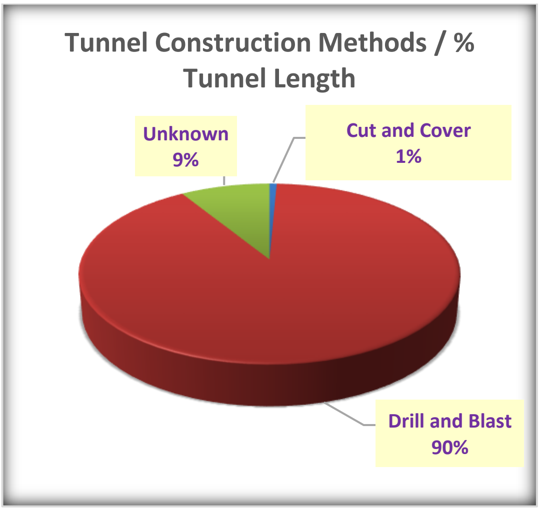


Figure 4-2: Construction Methods – % of Length of Tunnels

The information provided by the above figures tells that *'Drill and Blast' is the most used construction method for railway tunnels in South Africa (83% in term of number of tunnels and 90% in term of their lengths)*. 'Cut and Cover' represents only 2% of the number of tunnels and 1% of their lengths. However, a few tunnels do not have the specified construction methods. The update of this information will improve the current trends. The following Table 4-2 will distribute these construction methods based on the regions the tunnels are located in.

Table 4-2: Number of Tunnels - Region - Method

Region	Construction Method			
	Cut and Cover	Drill and Blast	Unknown	Grand Total
Cape Midlands		25	7	**32**
Eastern Cape		12	4	**16**
North Western Cape			1	**1**
Northern Natal		38	1	**39**
Northern Transvaal		7	4	**11**
Orange Free State		2		**2**
Southern Natal	4	72	13	**89**
Southern Transvaal		8	1	**9**
Western Cape	1	7		**8**
Grand Total	**5**	**171**	**31**	**207**

From table 4-2, most of the tunnels (four out of five or eighty percent) constructed using the 'Cut and Cover' method are located in the Southern Natal. It is also the region with the most number of tunnels (eighty-nine out of two hundred seven). Northern Natal is the second region with the highest number of tunnels (thirty nine). The Western Cape region also has one (out of five) tunnel constructed using 'Cut and Cover' method. The North Western Cape region does have only one tunnel. Orange Free State also has only two tunnels. The following Table 4-3 presents the lengths of tunnels per region and per construction method.

Table 4-3: Length (km) of Tunnels - Region - Method

Region	Construction Method			
	Cut and Cover	Drill and Blast	Unknown	Grand Total
Cape Midlands		9.225	2.18	**11.405**
Eastern Cape		4.943	1.301	**6.244**
North Western Cape			0.787	**0.787**
Northern Natal		33.7271	0.5997	**34.3268**
Northern Transvaal		2.997	1.363	**4.36**
Orange Free State		0.454		**0.454**
Southern Natal	0.631	56.448	6.158	**63.237**
Southern Transvaal		6.738	0.452	**7.19**
Western Cape	0.398	17.015		**17.413**
Grand Total	**1.029**	**131.5471**	**12.8407**	**145.4168**

From table 4-3, on the one hand, Southern Natal is still the region with the highest length of tunnels. On the other hand, Orange Free State is now the region with the shortest length of tunnels, followed by North Western Cape. The following Table 4-4 combines the data from the Table 4-2 and Table 4-3 above.

Table 4-4: Tunnels Numbers and Length (km) - Region

Region	Number of Tunnels	Position / 9	Tunnel Length (km)	Position / 9
Cape Midlands	32	3	11.405	4
Eastern Cape	16	4	6.244	6
North Western Cape	1	9	0.787	8
Northern Natal	39	2	34.3268	2
Northern Transvaal	11	5	4.36	7
Orange Free State	2	8	0.454	9
Southern Natal	89	1	63.237	1
Southern Transvaal	9	6	7.19	5
Western Cape	8	7	17.413	3
Grand Total	**207**		**145.4168**	

Table 4-4 confirms the first position for tunnels numbers and their aggregate length for Southern Natal, followed by Northern Natal. However, the ranking does not match the number of tunnels to their aggregate lengths for the remaining regions. Therefore, when planning for the inspection team and the duration of the inspection, both parameters (number of tunnels and their lengths) should be considered. The following Table 4-5 provides the number of tunnels at the crossroads of the tunnels construction methods and the range of their ages (years).

Table 4-5: Number of Tunnels - Method - Age Range

Construction Method	Range of Tunnels Ages (Year)			
	< 50	50 - 100	>= 100	Grand Total
Cut and Cover		5		**5**
Drill and Blast	55	95	21	**171**
Unknown	6	16	9	**31**
Grand Total	**61**	**116**	**30**	**207**

Table 4-5 tells that all the tunnels constructed using 'Cut and Cover' method are between fifty and hundred years old. Also, thirty (out of two hundred seven or forteen percent) of these tunnels are over hundred years old. As the design life of railway tunnels in South Africa may be considered 100 years, this raises a big concern about the level of service they provide, their structural integrity and public safety. Therefore, optimum inspections and further interventions are key to ensuring that these tunnels still meet the requirements set by the management authority. Similar to this previous table, the following Table 4-6 provides the aggregate lengths of tunnels at the crossroads of the tunnels construction methods and the range of their ages (years).

Table 4-6: Length (km) of Tunnels - Method - Age Range

Construction Method	Range of Tunnels Ages (Year)			
	< 50	50 - 100	>= 100	Grand Total
Cut and Cover		1.029		**1.029**
Drill and Blast	61.4391	65.19	4.91	**131.5471**
Unknown	3.4717	6.175	3.19	**12.8407**
Grand Total	**64.9108**	**72.4**	**8.11**	**145.4168**

The information provided in table 4-6 is interpreted similarly to the comments on the number of tunnels. The following Figure 4-3 and Figure 4-4 specify the percentage of the number and length of tunnels respectively, based on the range of their ages (year).

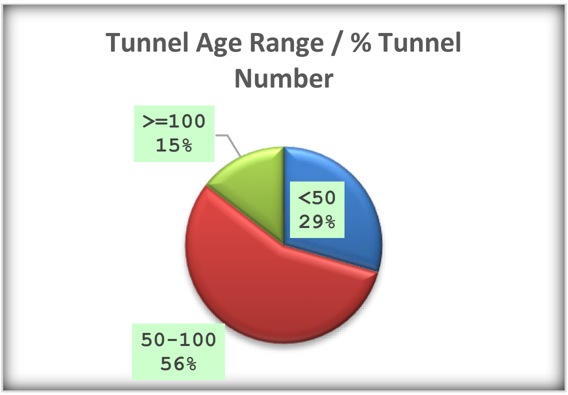


Figure 4-3: Tunnel Age Range - % of Tunnels Number

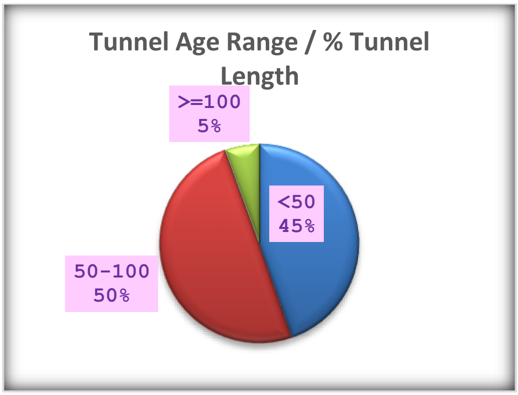


Figure 4-4: Tunnel Age Range - % of Tunnels Aggregate Length

From Figure 4-3 above, only 29% of tunnels (in term of their numbers) are below 50 years old, the remaining are between 50 and 100 years old or over 100 years old. This information makes a call to the management authority to look closely to the current management practices and find ways of improving them. Parallelly, in term of their aggregate lengths, 45% are below 50 years old. The following Table 4-7 presents the number of tunnels matching the regions and the range of tunnels ages.

Table 4-7: Number of Tunnels - Region - Age Range

Region	Tunnel Age Range (Year)			
	<50	50 - 100	>=100	Grand Total
Cape Midlands		20	12	**32**
Eastern Cape		13	3	**16**
North Western Cape	1			**1**
Northern Natal	37	2		**39**
Northern Transvaal	3	6	2	**11**
Orange Free State	2			**2**
Southern Natal	8	70	11	**89**
Southern Transvaal	5	4		**9**
Western Cape	5	1	2	**8**
Grand Total	**61**	**116**	**30**	**207**

From table 4-7, most of the tunnels above 100 years old are located in the Cape Midlands region (twelve out of thirty), followed by the Southern Natal region (eleven out of thirty). Also, the the only one tunnel located in the North Western Cape region et all (two) the tunnels located in Orange Free State region are below fifty years old. Moreover, most of the tunnels located in the Northern Natal region (thrity seven out of thrity nine) are below fifty years old. This information is useful for the location of the tunnel inspection office (team) to reduce the travelling cost and time of the team. In addition, it helps to reduce the cost for accommodation and other related basic needs when planning for inspections and further interventions. Similarly, the following Table 4-8 provides the aggregate lengths of tunnels on the cross-borders of their regions and the range of their ages (years).

Table 4-8: Length (km) of Tunnels - Region - Age Range

Region	Tunnel Age Range (Year)			
	< 50	50 - 100	>= 100	Grand Total
Cape Midlands		9.884	1.521	**11.405**
Eastern Cape		5.865	0.379	**6.244**
North Western Cape	0.787			**0.787**
Northern Natal	33.8498	0.477		**34.3268**
Northern Transvaal	1.781	2.053	0.526	**4.36**
Orange Free State	0.454			**0.454**
Southern Natal	**7.61**	**50.352**	**5.275**	**63.237**
Southern Transvaal	3.821	3.369		**7.19**
Western Cape	16.608	0.398	0.407	**17.413**
Grand Total	**64.9108**	**72.398**	**8.108**	**145.4168**

The information provided in table 4-8 is analogue to the comments made previously. The following Figure 4-5 gives the percentage of the number of tunnels with reference to the regions where they are located.

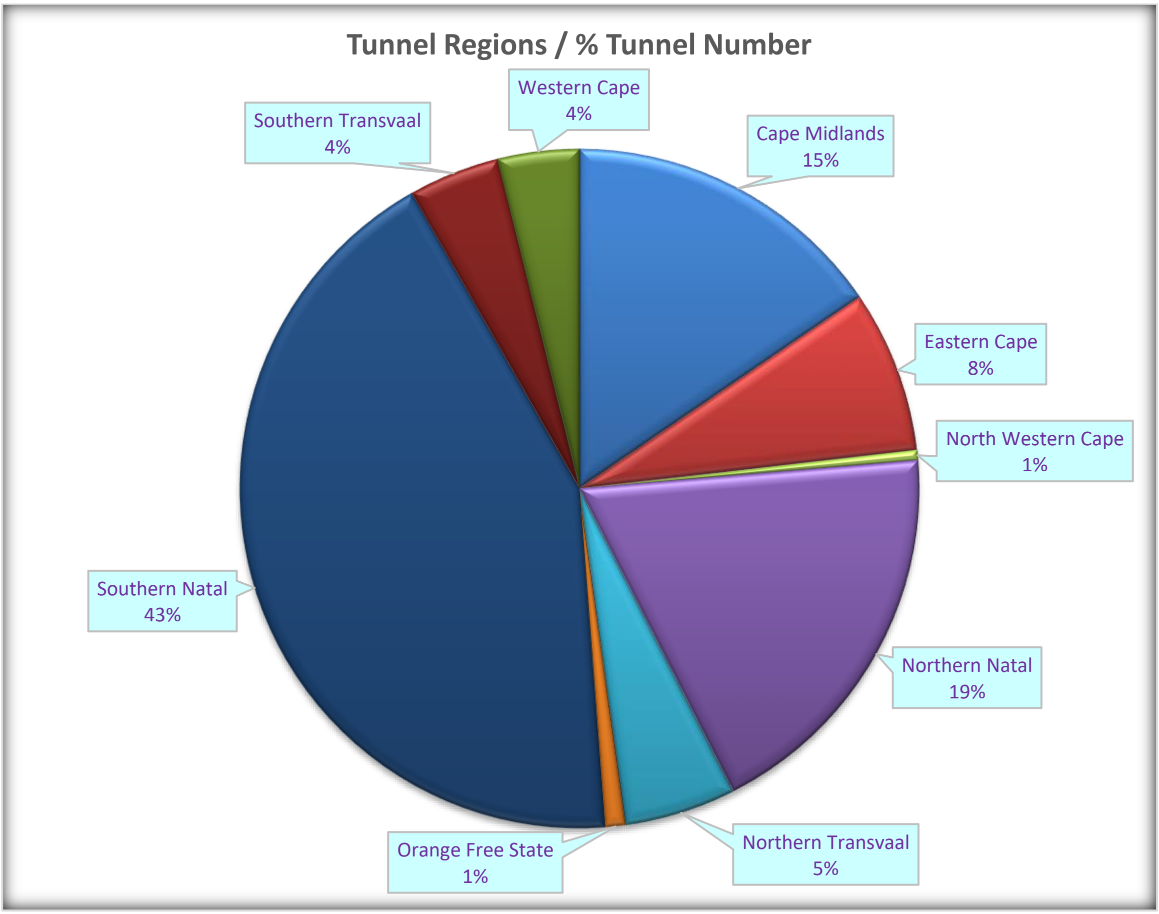


Figure 4-5: Region - % Number of Tunnels

Figure 4-5 tells that most of the tunnels (with reference to their numbers) are in the Southern Natal region followed by the the Northern Natal region.
By contrast, Orange Free State region and North Western Cape region have the fewest numbers of tunnels. This information as well is pertinent to planning inspections and further interventions, regarding the required resources. The following Figure 4-6 presents a similar case to the previous figure, considering the aggregate lengths of tunnels in different regions.

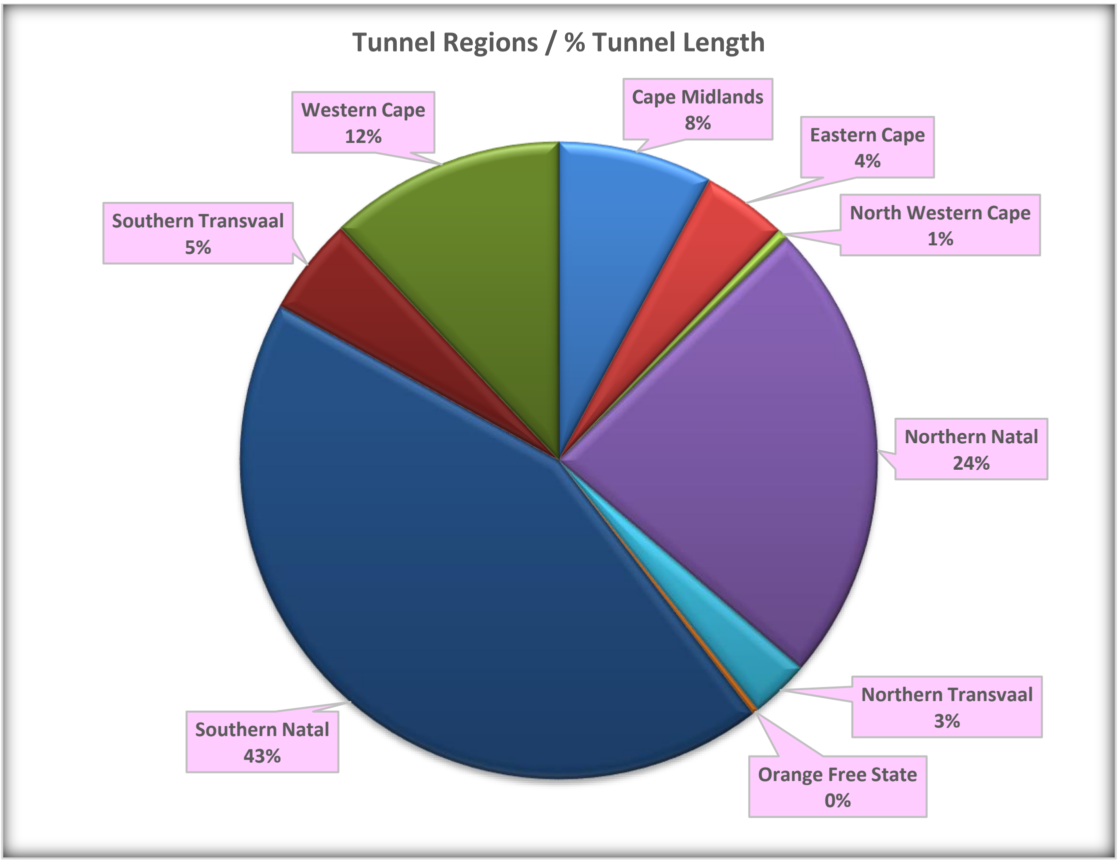


Figure 4-6: Region - % Length of Tunnels

From figure 4-6, Southern Natal is still the region with the highest aggregate length of tunnels, followed by Northern Natal region. This time, Orange Free State region has the lowest aggregate length beside the North Western Cape region. The following Table 4-9 gives the number of tunnels based on their respective regions and the range of their lengths (km).

Table 4-9: Number of Tunnels - Region - Length Range

Region	Tunnel Length Range (Km)				
	< 2.5	2.5 - 5	5 - 7.5	>= 12.5	Grand Total
Cape Midlands	32				**32**
Eastern Cape	16				**16**
North Western Cape	1				**1**
Northern Natal	36	3			**39**
Northern Transvaal	11				**11**
Orange Free State	2				**2**
Southern Natal	85	2	2		**89**
Southern Transvaal	9				**9**
Western Cape	7			1	**8**
Grand Total	**199**	**5**	**2**	**1**	**207**

From table 4-9, the longest tunnel (length ≥ 12.5km) is located in the Western Cape region, followed by the Southern Natal region (all the tunnels whose lengths are between 5km and 7.5km). However, most of the tunnels are relatively short (one hundred ninety nine out of two hundred seven < 2.5km). This information is relevant when planning for the period of inspections and further interventions and the required resources. Similarly, the following Table 4-10 provides the aggregate lengths (km) of tunnels in different regions and based on the range of their individual lengths (km).

Table 4-10: Length (km) of Tunnels - Region - Length Range

Region	Tunnel Length Range (Km)				
	< 2.5	**2.5 - 5**	**5 - 7.5**	**>= 12.5**	**Grand Total**
Cape Midlands	11.405				**11.405**
Eastern Cape	6.244				**6.244**
North Western Cape	0.787				**0.787**
Northern Natal	24.6376	9.6892			**34.3268**
Northern Transvaal	4.36				**4.36**
Orange Free State	0.454				**0.454**
Southern Natal	43.904	7.267	12.066		**63.237**
Southern Transvaal	7.19				**7.19**
Western Cape	4.08			13.333	**17.413**
Grand Total	**103.0616**	**16.9562**	**12.066**	**13.333**	**145.4168**

By linking the two tables (4-9 and 4-10), one of the tunnels in the Western Cape region is longer than 12.5 km. The following Figure 4-7 and Figure 4-8 represent the percentage of the aggregate lengths of tunnels with regard to their numbers and their individual lengths respectively.

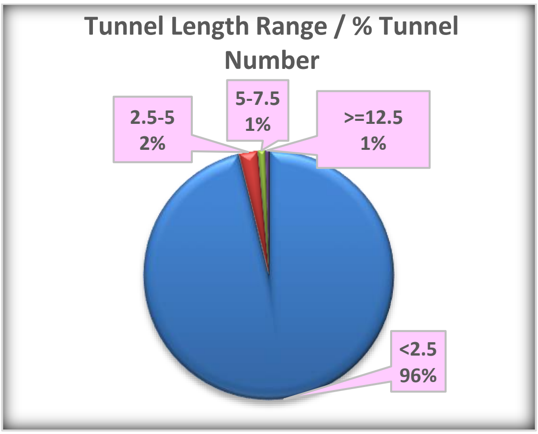


Figure 4-7: Tunnel Length Range - % Number

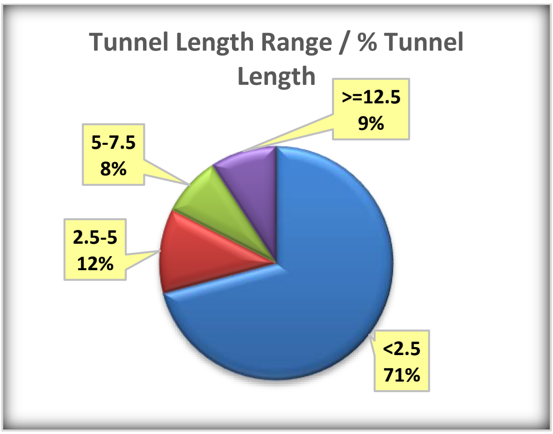


Figure 4-8: Tunnel Length Range - % Length

The combination of Figures 4-7 and 4-8 gives the importance of the individual lengths of the tunnels. The following Table 4-11 gives the number of tunnels in their respective regions and the range of their distances to the ports they link.

Table 4-11: Number of Tunnels - Region - Distance to Port

Region	Range (km) of the Distance of the Tunnel (Beginning) to the Port they link									
	< 25	25 - 50	50 - 75	75 - 100	100 - 125	125 - 150	150 - 175	175 - 200	>= 200	Total
Cape Midlands	5	7	9	5		1		2	3	**32**
Eastern Cape	1	2	2	8	3					**16**
North Western Cape				1						**1**
Northern Natal	3		7	6	7	8	3	1	4	**39**
Northern Transvaal	3		1	4	2	1				**11**
Orange Free State		1			1					**2**
Southern Natal	32	10	21	6	2	6	12			**89**
Southern Transvaal	1		2	2				2	2	**9**
Western Cape	3	5								**8**
Grand Total	**48**	**25**	**42**	**32**	**15**	**16**	**15**	**5**	**9**	**207**

The table 4-11 tells that the Western Cape tunnels are closer to the ports they link. Likewise, the following Figure 4-9 gives the percentage of the number of tunnels in relation to the range of their distances to the ports they link.

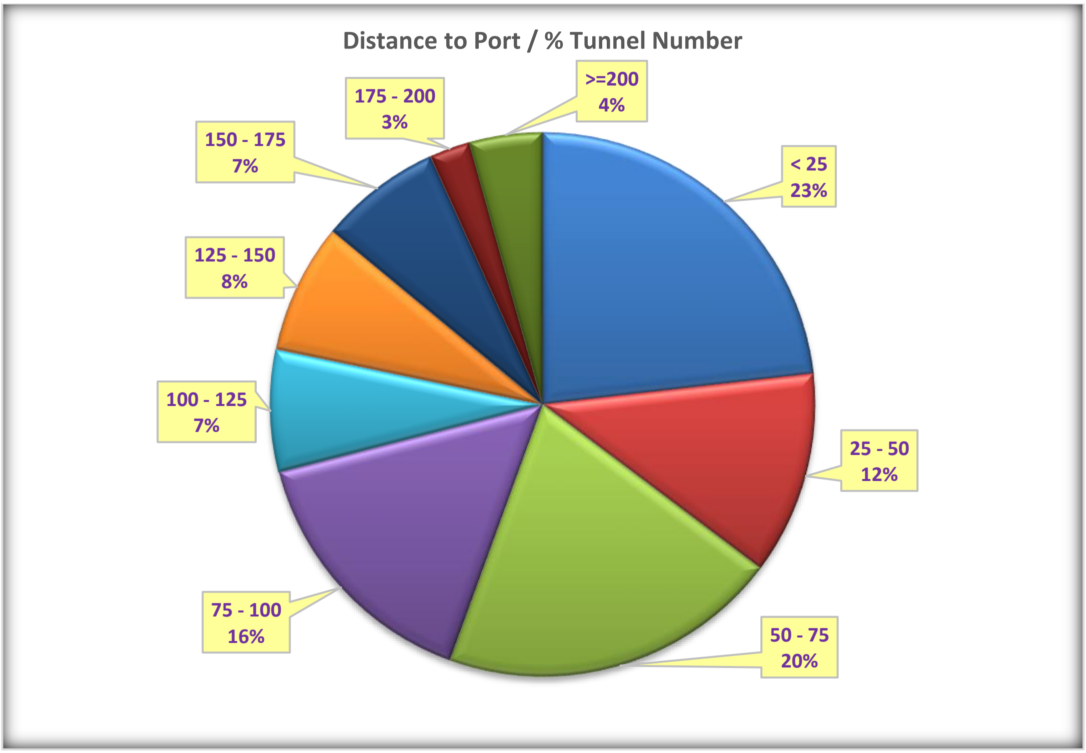


Figure 4-9: Number of Tunnels - Distance to Port

Figure 4-9 tells that most of the tunnels are closer to the ports their link. The following Table 4-12 provides the number of tunnels in relation to their construction methods and the range of their lengths (km).

Table 4-12: Number of Tunnels - Method - Length Range

Construction Method	Tunnel Length Range (Km)				
	< 2.5	2.5 - 5	5 - 7.5	>= 12.5	Grand Total
Cut and Cover	5				**5**
Drill and Blast	163	5	2	1	**171**
Unknown	31				**31**
Grand Total	**199**	**5**	**2**	**1**	**207**

From table 4-12, all the tunnels built using ‘Cut and Cover’ method are short (length < 2.5 km). Likewise, the following Table 4-13 provides the aggregate lengths of tunnels in relation to their construction methods and the range of their individual lengths (km).

Table 4-13: Length (km) of Tunnels - Method - Length Range

Construction Method	Tunnel Length Range (Km)				
	< 2.5	2.5 - 5	5 - 7.5	>= 12.5	Grand Total
Cut and Cover	1.029				**1.059**
Drill and Blast	89.1919	16.9562	12.066	13.333	**131.5471**
Unknown	12.8407				**12.8407**
Grand Total	**103.0616**	**16.9562**	**12.066**	**13.333**	**145.4168**

Table 4-13 is interpreted in a similar way to the previous table. The following Table 4-14 provides the number of tunnels by relating their construction methods and the range of their distances to the ports they link.

Table 4-14: Number of Tunnels - Method - Distance to Port

Construction Method	Range (Km) of Tunnel Distances (Beginning) to the Ports they link									
	< 25	25 - 50	50 - 75	75 - 100	100 - 125	125 - 150	150 - 175	175 - 200	>= 200	Total
Cut and Cover	3	2								**5**
Drill and Blast	33	22	36	26	14	14	13	5	8	**171**
Unknown	12	1	6	6	1	2	2		1	**31**
Grand Total	**48**	**25**	**42**	**32**	**15**	**16**	**15**	**5**	**9**	**207**

From table 4-14, the tunnels constructed using ‘Cut and Cover’ method are closer to the ports they link. The following Table 4-15 provides the number of tunnels by assembling the types of their liners and their construction methods.

Table 4-15: Number of Tunnels - Method - Liner Type

Construction Method	Liner Type			
	C	M	U	Grand Total
Cut and Cover	5			**5**
Drill and Blast	168	2	1	**171**
Unknown	30	1		**31**
Grand Total	**203**	**3**	**1**	**207**

From table 4-15, we realise that all the tunnels using ‘Cut and Cover’ method have their liners of type C. Also, only one tunnel has a liner of type U. The following Table 4-16 provides the number of tunnels by matching the thicknesses (mm) of their liners and their construction methods.

Table 4-16: Number of Tunnels - Method - Liner Thickness

Construction Method	Liner Thickness (mm)							
	300	305	450	457	460	470	500	Grand Total
Cut and Cover		4					1	**5**
Drill and Blast	46	103	9	1	6	4	2	**171**
Unknown	10	17	1	1	2			**31**
Grand Total	**56**	**124**	**10**	**2**	**8**	**4**	**3**	**207**

Table 4-16 tells that most of the tunnels built using 'Cut and Cover' method have the thicknesses of their liners equal to 305 mm (four out of five). However, 1 of them has the thickness of its liner equal to 500 mm. The following Table 4-17 provides the number of tunnels in relation to the range of their ages (year) and the range of their lengths (km).

Table 4-17: Number of Tunnels - Length and Age Ranges

Length Range (Km)	Age Range (Year)			
	< 50	50 - 100	>= 100	Grand Total
< 2.5	57	112	30	**199**
2.5 - 5	3	2		**5**
5 - 7.5		2		**2**
>= 12.5	1			**1**
Grand Total	**61**	**116**	**30**	**207**

Table 4-17 tells that all the oldest tunnels (ages ≥100 years) are among the shortest (length < 2.5 km). And yet, the longest tunnel is among the youngest (age <50 years). The following Table 4-18 gives the number of tunnels in relation to the ranges of their ages (year) and the range of their distances (km) to the ports they link.

Table 4-18: Number of Tunnels - Age & Distance to Port Ranges

Range of Tunnels Positions (km)	Range of Tunnels Ages (Year)			
	< 50	50 - 100	>= 100	Grand Total
< 25	11	31	6	**48**
25 - 50	5	15	5	**25**
50 - 75	9	21	12	**42**
75 - 100	10	17	5	**32**
100 - 125	8	6	1	**15**
125 - 150	8	8		**16**
150 - 175	3	12		**15**
175 - 200	2	3		**5**
>= 200	5	3	1	**9**
Grand Total	**61**	**116**	**30**	**207**

From table 4-18, between 125 and 200 km, on all the links, there is not tunnel that is over 100 years old. The following Table 4-19 gives the number of tunnels in relation to the range of their lengths (km) and the combination of the types of their liners and the ranges of their ages (year).

Table 4-19: Number of Tunnels - Age – Length – Liner Type

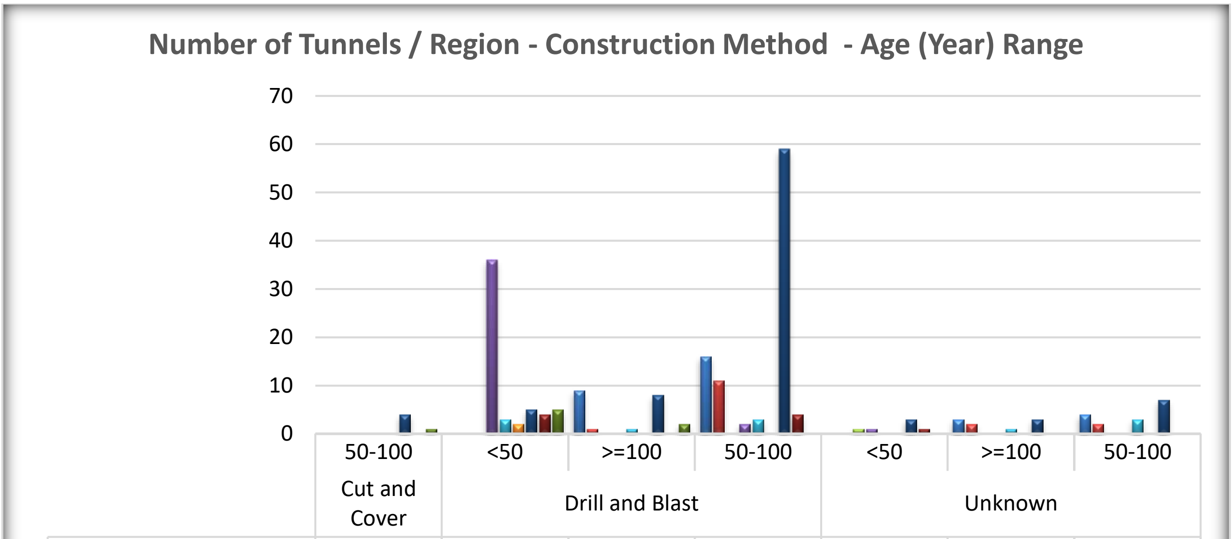
Liner Type / Age Range (Year)	Length Range (Km)				
	< 2.5	2.5 - 5	5 - 7.5	>= 12.5	Grand Total
C					
< 50	57	3		1	**61**
50 - 100	112	2	2		**116**
>= 100	26				**26**
M					
>= 100	3				**3**
U					
>= 100	1				**1**
Grand Total	**199**	**5**	**2**	**1**	**207**

Table 4-19 shows that the liners of types M and U relate only to tunnels that are over hundred years old and are shorter than 2.5 km. However, the liners of type C have been used for tunnels over hundred years old and are still used nowadays. Moreover, the longest tunnels (length ranges between 5 and 7.5 km and beyond 12.5 km) have the liners of type C. Similarly, the following Table 4-20 gives the number of tunnels in relation to the range of their lengths (km) and the combination of the types of their liners and their thicknesses.

Table 4-20: Number of Tunnels - Liner Type & Thickness – Length Range

Liner Type / Liner Thickness (mm)	Length Range (Km)				
	< 2.5	2.5 - 5	5 - 7.5	>= 12.5	Grand Total
C					
300	52	2		1	**55**
305	118	3	2		**123**
450	8				**8**
457	2				**2**
460	8				**8**
470	4				**4**
500	3				**3**
M					
305	1				**1**
450	2				**2**
U					
300	1				**1**
Grand Total	**199**	**5**	**2**	**1**	**207**

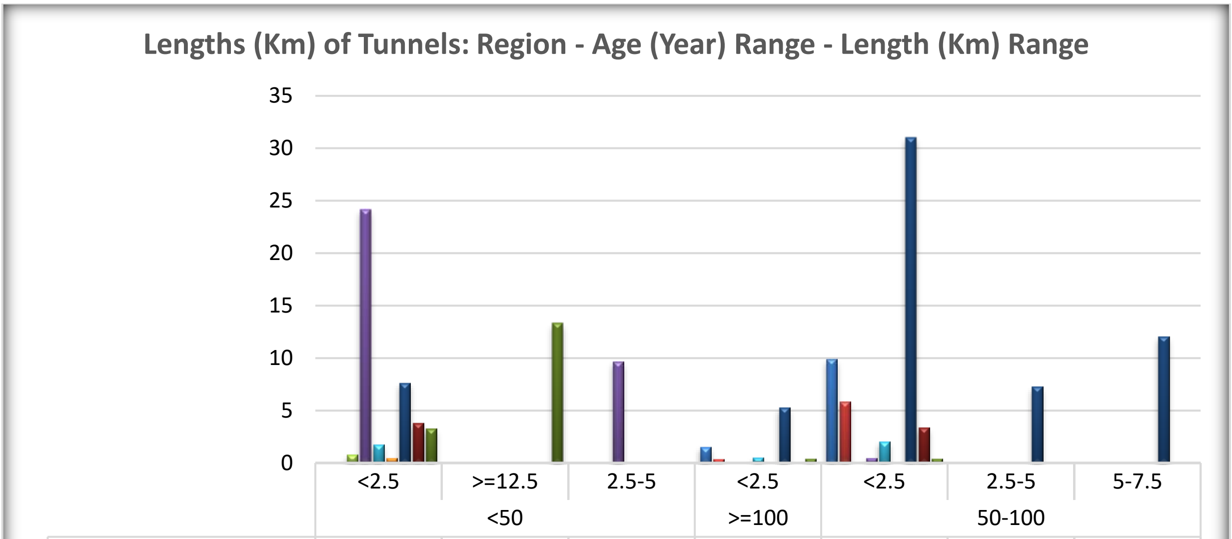
Table 4-20 tells that the liner of type U matched only the thickness of 300 mm while the liner of type M matched the thicknesses of 305 mm and 450 mm. However, the liner of type C matched all the thicknesses (300, 305, 450, 457, 460, 470, 500). The following Figure 4-10 presents in a nutshell the number of tunnels in relation to a combination of parameters including their respective regions, their construction methods and the range of their ages.



	Cut and Cover	Drill and Blast			Unknown		
	50-100	<50	>=100	50-100	<50	>=100	50-100
CAPE MIDLANDS			9	16		3	4
EASTERN CAPE			1	11		2	2
NORTH WESTERN CAPE					1		
NORTHERN NATAL		36		2	1		
NORTHERN TRANSVAAL		3	1	3		1	3
ORANGE FREE STATE		2					
SOUTHERN NATAL	4	5	8	59	3	3	7
SOUTHERN TRANSVAAL		4		4	1		
WESTERN CAPE	1	5	2				

Figure 4-10: Number of Tunnels - Region - Method – Age Range

Figure 4-10 tells that most of the tunnels located in the Southern Natal are between 50 and 100 years old and were constructed using 'Drill and Blast' method. Also, most of the tunnels located in Northern Natal are younger than 50 years old and were constructed using 'Drill and Blast' method. Similarly, the following Figure 4-11 gives the aggregate lengths of tunnels in relation to their regions and the combination of the ranges of their ages and their individual lengths.



	<50			>=100	50-100		
	<2.5	>=12.5	2.5-5	<2.5	<2.5	2.5-5	5-7.5
CAPE MIDLANDS				1,521	9,884		
EASTERN CAPE				0,379	5,865		
NORTH WESTERN CAPE	0,787						
NORTHERN NATAL	24,1606		9,6892		0,477		
NORTHERN TRANSVAAL	1,781			0,526	2,053		
ORANGE FREE STATE	0,454						
SOUTHERN NATAL	7,61			5,275	31,019	7,267	12,066
SOUTHERN TRANSVAAL	3,821				3,369		
WESTERN CAPE	3,275	13,333		0,407	0,398		

Figure 4-11: Length (km) of Tunnels - Region - Age & Length Ranges

From figure 4-11, all the tunnels over 100 years old are shorter (individual lengths less than 2.5 km). Also, all the tunnels whose individual lengths are between 5 and 7.5 km are between 50 and 100 years old and located in the Southern Natal. Finally, the tunnels in the North Western Cape and Orange Free State regions have the shortest aggregate lengths and are among the youngest. The following section conducts a similar analysis, but considers only tunnels on the heavy haul lines.

4.2.4 Analysis of the Tunnels on the Heavy Haul Lines

In the previous section, a comprehensive analysis of the tunnel inventory data has been conducted for all the tunnel stock. In this section, a similar study will consider only tunnels on the heavy haul lines to provide adequate information to the tunnel management authority. The following Figures 4-12 and 4-13 give the percentages of the number of tunnels and their aggregate lengths respectively in relation to their construction methods.

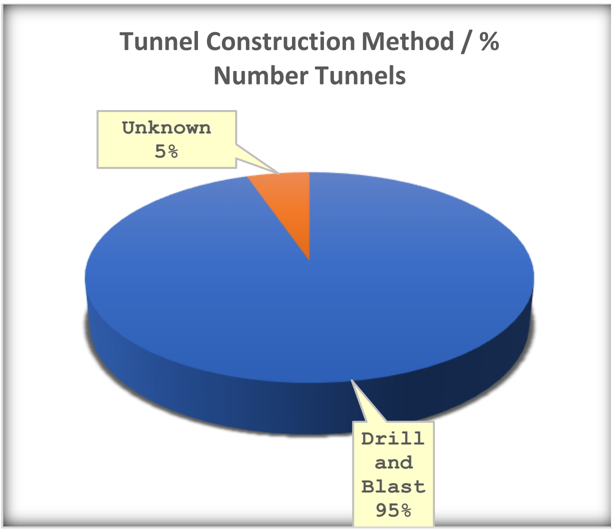


Figure 4-12: HHT Method - Number

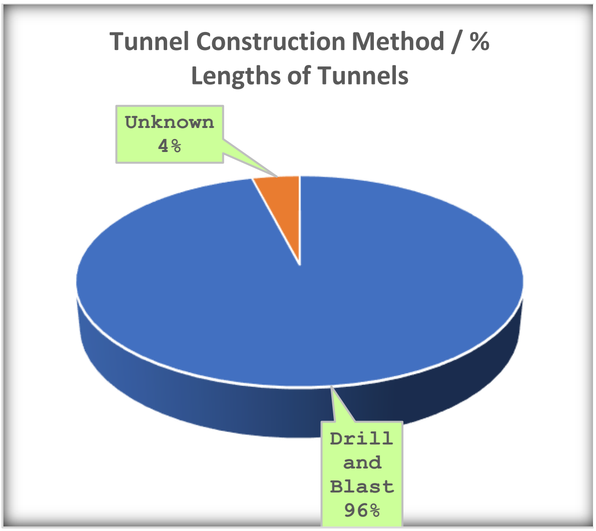


Figure 4-13: HHT Method - Length

Considering Figures 4-12 and 4-13, no tunnel on the heavy haul lines (except those whose construction methods are unknown) has been constructed using 'Cut and Cover' method. However, the literature review revealed that the Overvaal rail tunnel was built (from the eastern and western portals) as 'Cut and Cover' and the blast excavation started in competent rock with adequate cover. The following Table 4-21 presents the number of tunnels on the sections of the heavy haul lines based on their construction methods.

Table 4-21: HHT Number – Region & Section - Method

Region Name *Section Description*	**Construction Method**		
	Drill and Blast	**Unknown**	**Grand Total**
North Western Cape		1	1
Sishen - Saldanha		1	1
Northern Natal	36	1	37
Machadodorp - Piet Retief	1		1
Piet Retief - Vryheid	5	1	6
Vryheid - Empangeni	30		30
Grand Total	**36**	**2**	**38**

From table 4-21, most of the tunnels on heavy haul lines (thirty six out of thirty eight) were constructed using the 'Drill and Blast' method. This can be augmented with the two remaining tunnels whose construction methods are unknown. This table tells as well that most of the tunnels on the heavy haul lines are located in the Northern Natal region (except one of them in the North Western Cape region). The following Figures 4-14 and 4-15 provide the percentages of the number of tunnels and their aggregate lengths based on the ranges of tunnel ages (year).

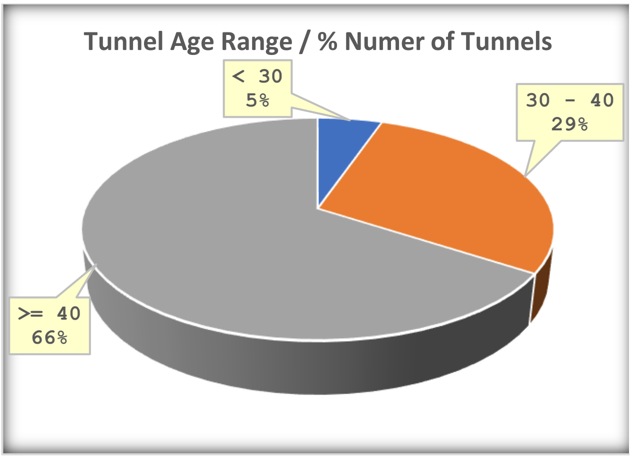


Figure 4-14: HHT Age - Number

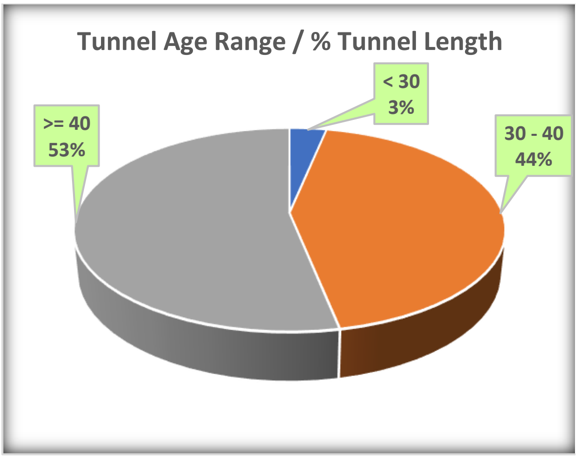


Figure 4-15: HHT Age - Length

From Figures 4-14 and 4-15, the majority of the tunnels are over forty years old. The following Table 4-22 gives the number of tunnels on the heavy haul lines based on the ranges of their ages (year) and their regions and sections of location.

Table 4-22: HHT Number – Region & Section – Age Range

Region Name *Section Description*	**Tunnel Age Range (Year)**			
	< 30	**30 - 40**	**>= 40**	**Grand Total**
North Western Cape			1	1
Sishen - Saldanha			1	1
Northern Natal	2	11	24	37
Machadodorp - Piet Retief			1	1
Piet Retief - Vryheid	2	1	3	6
Vryheid - Empangeni		10	20	30
Grand Total	**2**	**11**	**25**	**38**

The only one tunnel on the Sishen – Saldanha section (ore iron line) is over 40 years old and most of the tunnels on the coal line are also over 40 years old. Remarkably, only 2 tunnels on the heavy haul lines are younger than 30 years old. The following Figures 4-16 to 4-19 provide the percentages of the number and aggregate lengths of tunnels respectively based on their regions and sections.

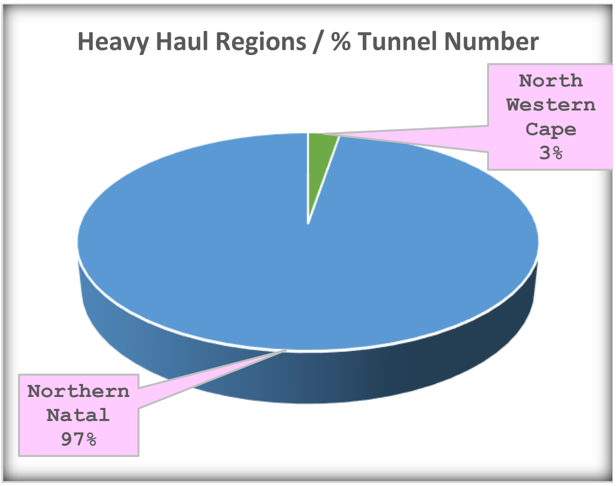


Figure 4-16: HHT Region - Number

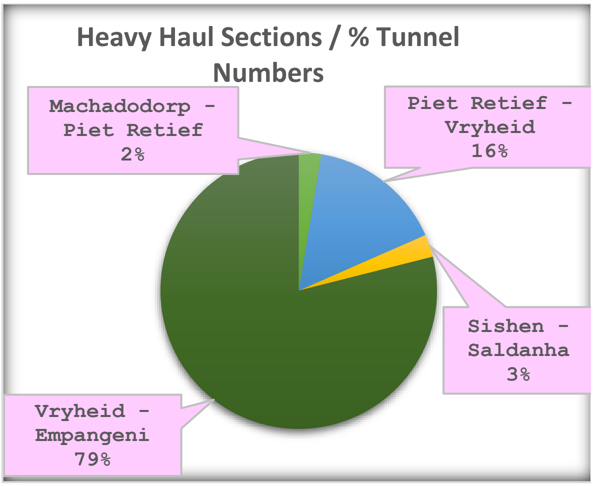


Figure 4-17: HHT Section - Number

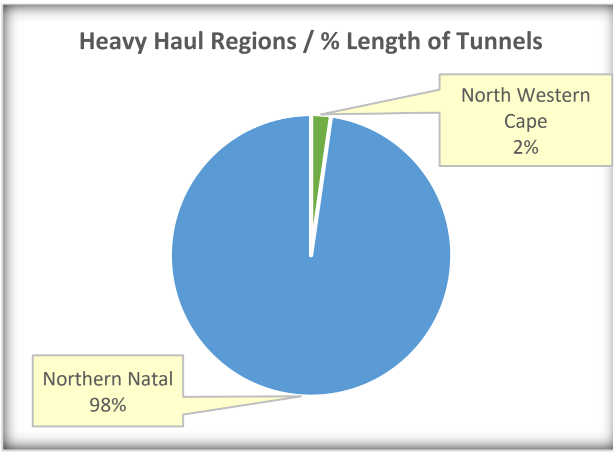


Figure 4-18: HHT Region - Length

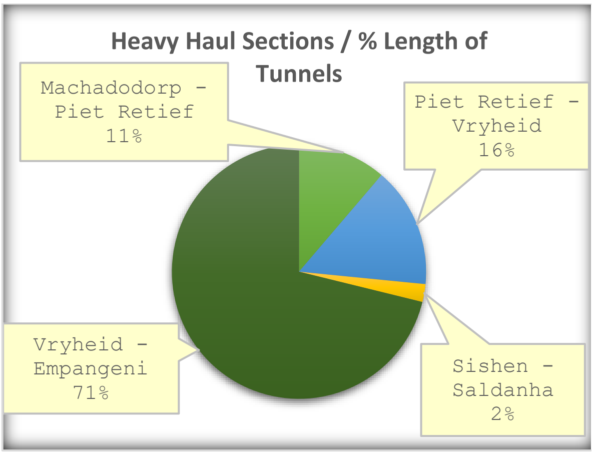


Figure 4-19: HHT Section - Length

From figures 4-16 to 4-19, nearly all the tunnels on the heavy haul lines are in the Northern Natal Region and specifically on the Vryheid – Empangeni section followed by the Piet Retief – Vryheid section. The following Table 4-23 gives the number of tunnels based on the range of their individual lengths and their regions and sections.

Table 4-23: HHT Number – Region & Section – Length Range

Region *Section*	**Tunnel Length Range (km)**				
	< 1.0	**1.0 - 2.0**	**2.0 - 3.0**	**>= 3.0**	**Grand Total**
North Western Cape	1				**1**
Sishen - Saldanha	1				**1**
Northern Natal	27	5	4	1	**37**
Machadodorp - Piet Retief				1	**1**
Piet Retief - Vryheid	5		1		**6**
Vryheid - Empangeni	22	5	3		**30**
Grand Total	**28**	**5**	**4**	**1**	**38**

Table 4-23 demonstrates that only one tunnel is above 3 km and is on the Machadodorp – Piet Retief section of the coal line. Also, it is the only one tunnel on this section. The only one tunnel on the ore iron line is less than 1 km. Of the tunnels on the Piet Retief – Vryheid section, most of them are less than 1 km. The following Figures 4-20 and 4-21 provide the percentages of the number of tunnels based on the ranges of their lengths (km).

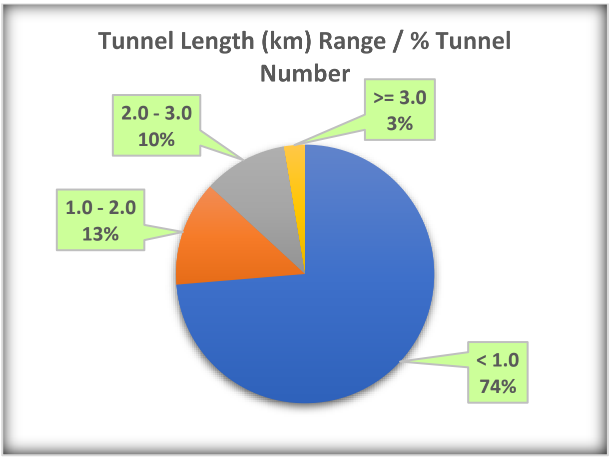


Figure 4-20: HHT Length Range - Number

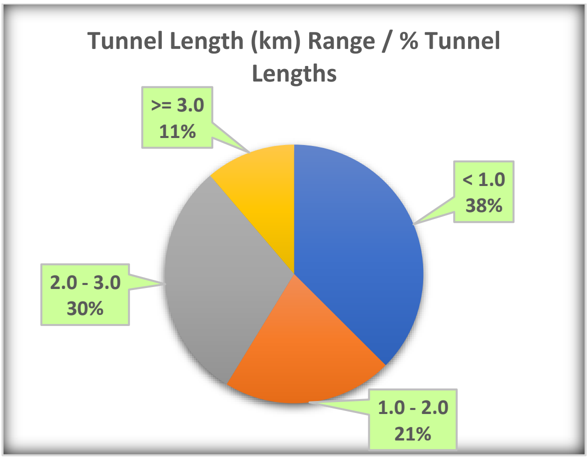


Figure 4-21: HHT Length Range - Length

Figures 4-20 and 4-21 clarify that, with regard to the tunnels numbers, all but the tunnels on the heavy haul lines are less than 1 km long. However, with regard to their aggregate lengths, this trend is largely influenced by the longest tunnels. The following Table 4-24 gives the number of tunnels based on the range of their distances to the ports they link and their regions and sections.

Table 4-24: HHT Number – Region & Section – Distance to Port

Region *Section*	**Range of Tunnel (Beginning) Distance (Km) to the Ports**								
	< 25.0	**50.0 - 75.0**	**75.0 - 100.0**	**100.0 - 125.0**	**125.0 - 150.0**	**150.0 - 175.0**	**175.0 - 200.0**	**>= 200.0**	**Total**
North Western Cape			1						**1**
Sishen - Saldanha			1						**1**
Northern Natal	3	6	5	7	8	3	1	4	**37**
Machadodorp – Piet Retief	1								**1**
Piet Retief – Vryheid						1	1	4	**6**
Vryheid – Empangeni	2	6	5	7	8	2			**30**
Grand Total	**3**	**6**	**6**	**7**	**8**	**3**	**1**	**4**	**38**

From table 4-24, the only one tunnel on the ore iron line is between 75 and 100 km away from the port of Saldanha. On the coal line, the tunnels are located all along the line. The following Figure 4-22 gives the percentage of the number of tunnels in relation to the range of their distances (km) to the ports they link.

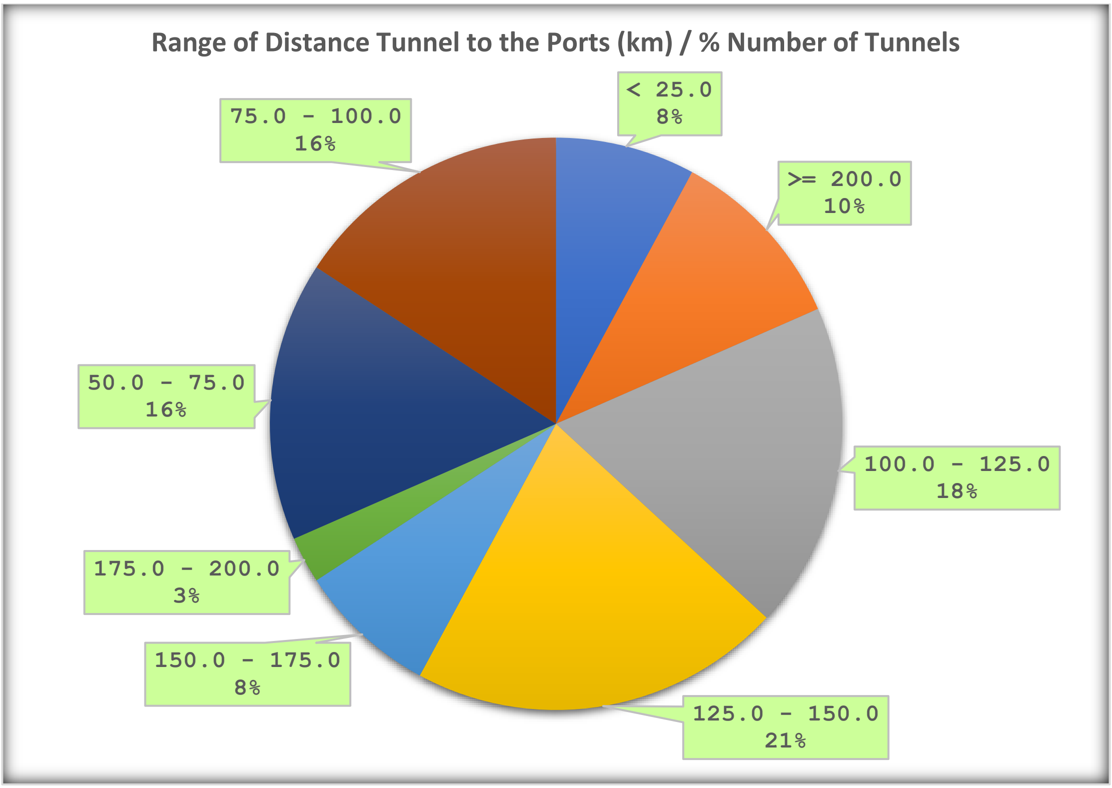


Figure 4-22: HHT Distance to Port - Number

From figure 4-22, a considerable percentage of tunnels are located between 125 and 150 km away from the ports they link against a small percentage between 175 and 200 km. The following Table 4-25 presents the number of tunnels in relation to the ranges of their ages (year) and their lengths (km).

Table 4-25: HHT Length Range – Age Range

Length Range (km)	Age Range (Year)			
	< 30	30 - 40	>= 40	Grand Total
< 1.0	2	5	21	**28**
1.0 - 2.0		2	3	**5**
2.0 - 3.0		4		**4**
>= 3.0			1	**1**
Grand Total	**2**	**11**	**25**	**38**

Table 4-25 tells that the two youngest tunnels (age below 30 years old) are also among the shortest (length shorter than 1 km). Additionally, the longest tunnel (length longer than 3 km) is also among the oldest (over 40 years old). The following Table 4-26 provides the number of tunnels in relation to the ranges of their ages (year) and their distances to the ports they link.

Table 4-26: HHT Distance to Port – Age Range

Range of Tunnels Distances (km) to the Ports	Range of Tunnels Ages (Year)			
	< 30	30 - 40	>= 40	Grand Total
< 25.0		1	2	**3**
50.0 - 75.0		1	5	**6**
75.0 - 100.0		1	5	**6**
100.0 - 125.0		3	4	**7**
125.0 - 150.0		3	5	**8**
150.0 - 175.0		1	2	**3**
175.0 - 200.0		1		**1**
>= 200.0	2		2	**4**
Grand Total	**2**	**11**	**25**	**38**

From table 4-26, the two youngest tunnels (age below 30 years old) are also among the farthest (distances to the ports above 200 km). The following Table 4-27 gives the number of tunnels based on the ranges of their lengths (km) and the combination of the ranges of their ages and the thicknesses of their liners (mm).

Table 4-27: HHT Age & Liner Thickness – Length Range

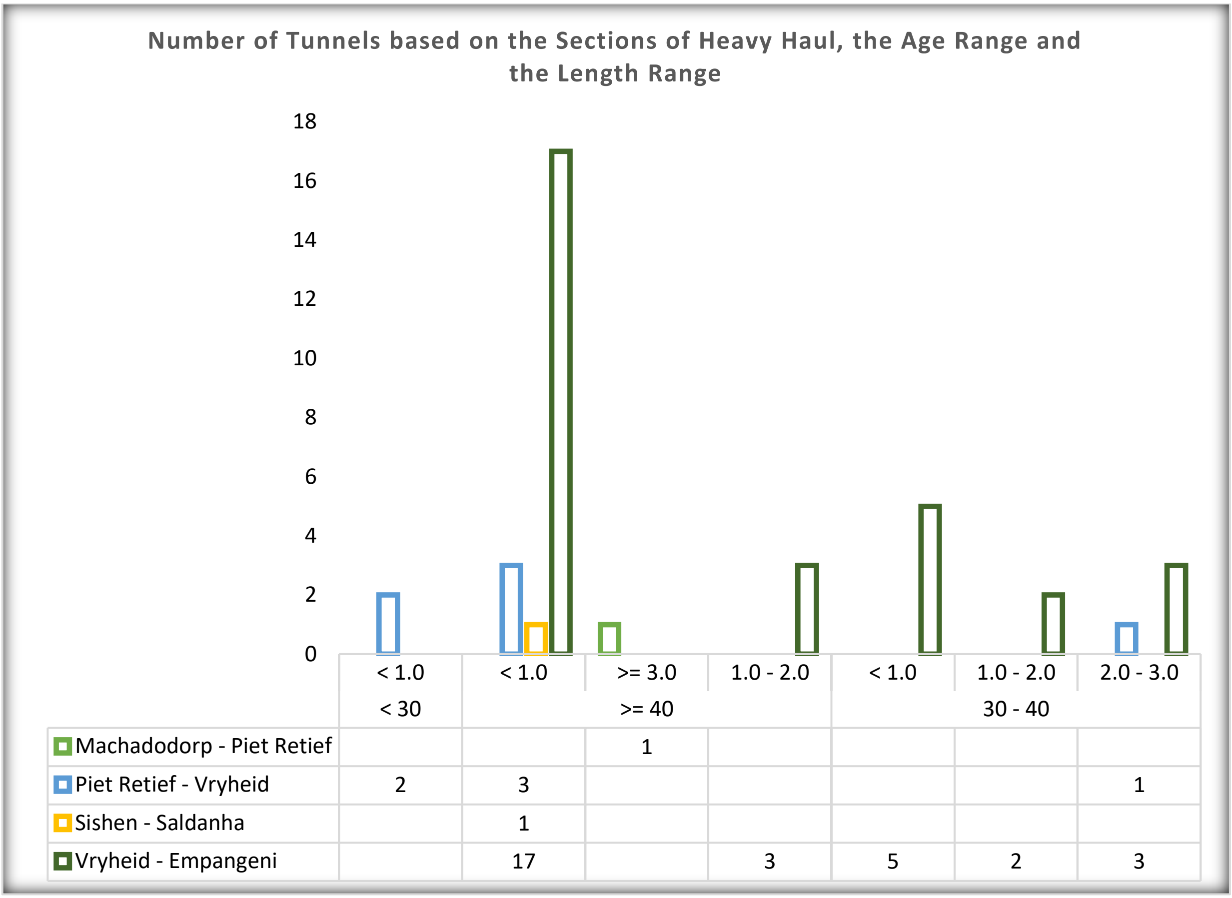
Age (Year) Range *Liner Thickness (mm)*	Length (km) Range				
	< 1.0	1.0 - 2.0	2.0 - 3.0	>= 3.0	Grand Total
< 30	2				**2**
305	2				**2**
30 - 40	5	2	4		**11**
300	5	1	2		**8**
305		1	2		**3**
>= 40	21	3		1	**25**
300	17	2			**19**
305	4	1		1	**6**
Grand Total	**28**	**5**	**4**	**1**	**38**

Table 4-27 shows that all the youngest tunnels have the same thickness of liners (305 mm). Moreover, the longest tunnel has a liner of 305 mm of thickness. Finally, all the tunnels on the heavy haul lines have their liners of thicknesses equal to 300 or 305 mm. The following Table 4-28 presents the lengths (km) of tunnels on the heavy haul lines based on their respective sections and the combination of the ranges of their lengths (km) and their ages (year).

Table 4-28: HHT Length & Age - Section

Length (km) Range *Age (year) Range*	**Sections on the Heavy Haul Lines**				
	Machadodorp - Piet Retief	**Piet Retief - Vryheid**	**Sishen - Saldanha**	**Vryheid - Empangeni**	**Grand Total**
< 1.0		3.1451	0.787	9.0456	**12.9777**
< 30		1.1236			**1.1236**
30 - 40				1.8707	**1.8707**
>= 40		2.0215	0.787	7.1749	**9.9834**
1.0 - 2.0				7.3675	**7.3675**
>= 40				4.5355	**4.5355**
30 - 40				2.832	**2.832**
2.0 - 3.0		2.16		8.2356	**10.3956**
30 - 40		2.16		8.2356	**10.3956**
>= 3.0	3.896				**3.896**
>= 40	3.896				**3.896**
Grand Total	**3.896**	**5.3051**	**0.787**	**24.6487**	**34.6368**

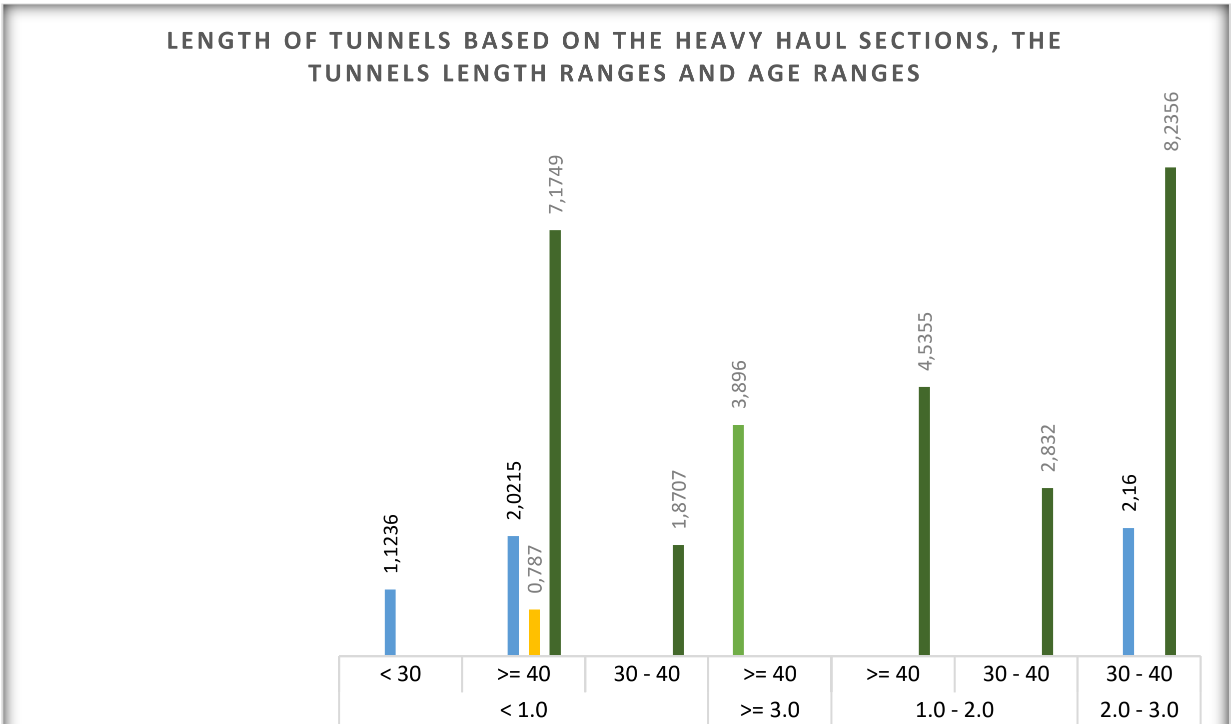
Table 4-28 shows that Vryheid – Empangeni section has the longest aggregate length of tunnels and Sishen – Saldanha has the shortest aggregate length of tunnels. The following Figure 4-23 provides the numbers of tunnels on the heavy haul lines sections in relation to the ranges of their ages (year) and their lengths (km).



	< 30	>= 40			30 - 40		
	< 1.0	< 1.0	>= 3.0	1.0 - 2.0	< 1.0	1.0 - 2.0	2.0 - 3.0
Machadodorp - Piet Retief			1				
Piet Retief - Vryheid	2	3					1
Sishen - Saldanha		1					
Vryheid - Empangeni		17		3	5	2	3

Figure 4-23: HHT Section – Age & Length Ranges

Figure 4-23 tells that the two youngest tunnels are on the Piet Retief – Vryheid section and are among the shortest tunnels. It also tells that both the Sishen – Saldanha section and the Machadodorp – Piet Retief section have only one tunnel each. Similarly, the following Figure 4-24 gives the aggregate lengths of tunnels of the sections of Heavy Haul lines in relation to the ranges of their lengths (km) and their ages (year).



	< 30	>= 40	30 - 40	>= 40	>= 40	30 - 40	30 - 40
	< 1.0			>= 3.0	1.0 - 2.0		2.0 - 3.0
Machadodorp - Piet Retief				3,896			
Piet Retief - Vryheid	1,1236	2,0215					2,16
Sishen - Saldanha		0,787					
Vryheid - Empangeni		7,1749	1,8707		4,5355	2,832	8,2356

Figure 4-24: HHT Section – Aggregate Length

Figure 4-24 can be interpreted similarly to the previous figure. This comprehensive analysis of the railway tunnel stock and the tunnels on the heavy haul lines in South Africa unveils important trends and provides critical information. This information will be considered when planning for inventory, inspection and monitoring of railway tunnels in South Africa.

4.3 Findings

4.3.1 Tunnel Inventory Management

Ryall (2010: 5) stipulated that any basic management system entails an initial logging of the basic data relating to the object of interest in the form of a database. This should be followed by the regular collection and recording of information through inspections to appraise the condition of the object of interest and the rate of deterioration. This research designed, in light of the current form (Figure 2-14) and with emphasis on the concrete structural elements, Tunnel Inventory Forms for railway tunnels in South Africa. These forms will be used to record the available data on the tunnel stock and to record the data for any new tunnel, from its conception to its commissioning. Therefore, as-built drawings, design reports and site measurements constitute the most reliable source of information for inventory of railway tunnels.

a. Content and Format of Tunnels Inventory Forms

This research proposed two categories of railway tunnels inventory forms. The first form described the tunnel as a structure and provided a list of its *identification, coordinates, contract description, geometric data, inspection, structural features and materials respective items* (Table 4-29). *The format of an item comprised the item id#, the name of the item and its value*. The portal beginning kilometres and portal end kilometres referred to their distances to the port. The relative distance of any element of the tunnel to the portal located to the side of the port should serve to locate the element with referring to the port.

The second form provided a list of the concrete structural elements and requested their names, id#, distances to P1 (longitudinal positions), positions (transversal positions), values and units (Table 4-30). It has been noted that the longitudinal positions provided with reference to the first portal were relative positions. Therefore, the position of the element to the port should be obtained after adding to it the distance of the portal to the port. The transversal positions were pre-defined and referred to the position within the cross-section as left - bottom: L-B, left - top: L-T, right - top: R-T, right - bottom: R-B.

Table 4-29: Railway Tunnels Inventory Form a

Tunnel Name ☐ Tunnel Number: ☐ Inspector Name: ☐
<u>Data Source</u> ↓: Inventory Date: ☐
Site Measurement: ☐ As Built Drawing: ☐ Design Documents: ☐ Existing Data: ☐

Item ID	Item	Value
1	**Identification Items**	
1.1	Tunnel Number	
1.2	Tunnel Name	
1.3	Tunnel status	
1.4	Asset Number	
1.5	Record Number	
1.6	Section Description	
1.7	Section Name	
1.8	Area Status	
1.9	Region Number	
1.10	Province Name	
1.11	Location Code	
1.12	Portal Beginning Kilometres	
1.13	Portal End Kilometres	
1.14	Route Number	
1.15	Route Name	
2	**Coordinates Items**	
2.1	Survey System	
2.2	Elevation	
2.3	Tunnel Orientation	
2.4	Tunnel Portal’s Latitude (South)	
2.5	Tunnel Portal’s Longitude (East)	

Item ID	Item	Value
2.6	Geological System	
3	**Contract Description Items**	
3.1	Contract Number	
3.2	Contract Price	
3.3	Owner	
3.4	Designer	
3.5	Builder	
3.6	Construction Method	
3.7	Year Completed	
3.8	Operator	
4	**Geometric Data Items**	
4.1	Tunnel Length	
4.2	Tunnel Width	
4.3	Tunnel Height	
4.4	Tunnel cross-sectional area (m^2)	
4.5	Left sidewalk width	
4.6	Right sidewalk width	
4.7	As built details	
4.8	Other details	
5	**Inspection items**	
5.1	Preliminary inspection	
5.2	Detailed inspection	
5.3	Impact inspection	
5.4	Critical inspection	
6	**Structural features and material items**	
6.1	Description of bores	
6.2	Tunnel shape	
6.3	Portal shape	
6.4	Rock description	

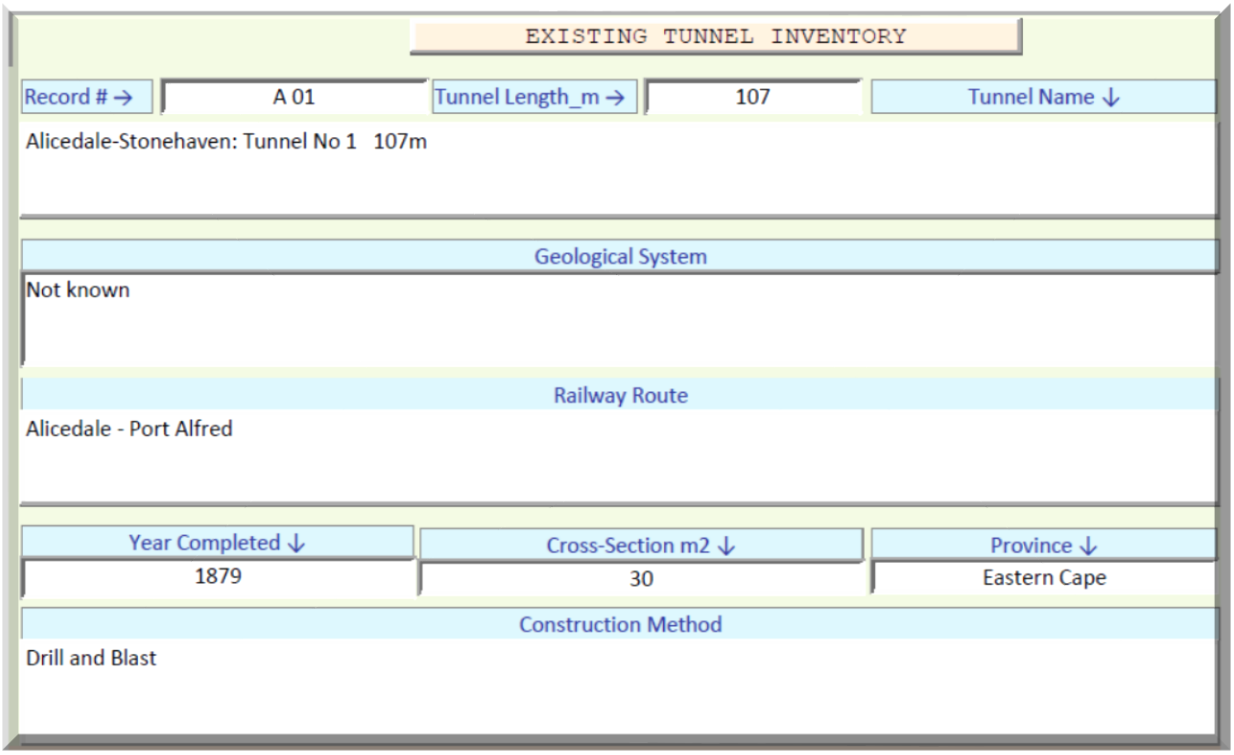
Table 4-29 considered the inventory items proposed in the “Specifications for the National Tunnel Inventory” of the U.S. Department of Transport (USA. U.S. Department of Transportation, 2015: 2-2). However, it mainly focused on the South African’s model proposed in the “Database of Tunnels in Southern Africa” (First edition: 2000; second edition: 2001; third edition: 2002) developed and published by the South African National Council on Tunnelling.

Table 4-30: Railway Tunnels Inventory Form b

ID #	Component	No	Distance P1 (km)	Position L-B, L-T, R-T, R-B	Value	Unit
1	**Columns and Piles**					
1.1	Concrete Column/Pile					Each
2	**Cross Passageway**					
2.1	Concrete Cross Passageway					m
3	**Interior Walls**					
3.1	Concrete Interior Walls					m^2
4	**Liners**					
4.1	Cast-in-Place Concrete Tunnel Liner					m^2
4.2	Precast Concrete Tunnel Liner					m^2
5	**Portals**					
5.1	Concrete Portal					m^2
6	**Roof Girders**					
6.1	Concrete Tunnel Roof Girder					m
6.2	Prestressed Concrete Tunnel Roof					m
7	**Tunnel Ceiling Structures**					
7.1	Ceiling Slab					
7.1.1	*Concrete Ceiling Slab*					m^2
7.2	Ceiling Girder					
7.2.1	*Concrete Ceiling Girder*					*m*
7.2.2	*Prestressed Concrete Ceiling Girder*					*m*
7.3	Ceiling Panels					
7.3.1	*Concrete Ceiling Panels*					m^2
8	**Tunnel Invert Structures**					
8.1	Invert Slab					
8.1.1	*Concrete Invert Slab*					m^2
8.2	Slab-on-Grade					
8.2.1	*Concrete Slab-on-Grade*					m^2
8.3	Invert Girder					
8.3.1	*Concrete Invert Girder*					*m*
8.3.2	*Prestressed Concrete Invert Girder*					*m*

b. Existing Inventory Data

The following Figure 4-25 represented the screenshot of inventory data of railway tunnels (a single page of the existing inventory data).


EXISTING TUNNEL INVENTORY

Record # → A 01 Tunnel Length_m → 107 Tunnel Name ↓

Alicedale-Stonehaven: Tunnel No 1 107m

Geological System

Not known

Railway Route

Alicedale - Port Alfred

Year Completed ↓	Cross-Section m2 ↓	Province ↓
1879	30	Eastern Cape

Construction Method

Drill and Blast

Figure 4-25: Screenshot of the Existing Inventory Data

Figure 4-25 gave three identification items: "Record #" corresponding to the Tunnel Number, Tunnel Name, Province Name and "Railway Route" corresponding to the Route Name. It also provided the Geological System as a coordinates item, Tunnel Length and Cross-Section as a Geometric Data items, Year Completed and Construction Method as Contract Description items. The tunnel stock recorded consisted of 207 tunnels comprising 38 tunnels on the heavy haul lines (1 on the ore iron line and 37 on the coal line). In addition to the tunnel elements presented in the previous Table 4-30, extra inventory data were recorded. They have been presented in the Inventory Data Description section below. Finally, all the data recorded in the inventory forms should be sent to the tunnel data management office to feed and update the database.

c. Inventory Data Description

The Table A-1 in appendix A presented a comprehensive categorisation and description of tunnel elements. For each concrete structural element, that table provided the element name, its function, its description, how to measure its dimensions and its unit.

d. Photographic File and Photos Database

"Inventory photos form an important part of the inventory database and are very useful when discussing a structure at a distance" (Nordengen, Humphries & Moyo, 2017:7). As explained in the Procedures to enhance tunnels management Chapter, a separate database that managed inventory (and inspection) photos has been developed. That database was integrated to the system and worked together with the main database. The tunnel inventory photos module of the tunnel photos database was directly linked to the tunnel inventory file and recorded the id # of the tunnel and the Tunnel Number. It also included the beginning of the inventory, the end of the inventory, the data source, the numbers of the part, component and element inspected. The photos recorded presented the element, the component, the part and the tunnel.

4.3.2 Tunnel Management Database

The Tunnel Management Database is the platform that includes the various modules developed to manage the tunnel stock. For railway tunnels in South Africa, the proposed core database for management was bonded with the inventory module and served to analyse data for adequate trends and relevant information. That database also nursed the tunnel inspection programme and the tunnel monitoring system. In fact, the inspection and monitoring files were linked to the inventory file within the database. The following section presented the design of the tunnel inspection programme for railway tunnels in South Africa.

4.3.3 Tunnel Inspection Programme

After recording valuable data through inventory, feeding up the database and establishing relevant trends, the study designed a Tunnel Inspection Programme (TIP). This programme considered the health of all the structures to be managed and the development of their conditions. In fact, the understanding of the course, effect, and aftermath of defects to the function and structural integrity of tunnel systems require conducting a productive inspection. Therefore, the knowledge of common deficiencies that can be identified on tunnel structural systems will assist the inspection team to respond adequately to their tasks. This section described the design of a Tunnel Inspection Programme appropriate to the South African Railway Tunnels and targeted specifically the tunnels on the heavy haul lines.

Basic steps should be properly considered and applied for the results of the inspection of tunnels to be useful to the office responsible for planning maintenance, repairs, strengthening and rehabilitation. The first of these steps related to the *qualification of inspection team members*. Their ability to properly identify elements of the tunnel, the defects that occur and make a professional judgment in assessing and reporting them is critical. As a team, each member should be able, at a defined level, to contribute positively and timely to the completion of inspection tasks. This subsection describes the core positions required to conduct the inspections of tunnels and defines for each position the requirements of skills and experience.

a. Composition of the Inspection Teams

Personnel conducting inspection tasks should have minimum qualifications related to concrete materials and understand the basics of the behaviour of tunnel structural systems. For practicality, the study mainly considered the *chief inspector, tunnel inspectors, tunnel inspection technicians and the tunnel safety officer* in the accomplishment of inspection tasks for structural systems of railway tunnels. The chief inspector should prepare a programme for inspecting a specific set of tunnels, determine the resources needed regarding personnel, equipment/tools, and materials. He should also oversee the whole team and all activities involved during inspection. Moreover, the chief inspector should define the level and type of inspections to carry out, and finally present the inspection report after evaluating all deficiencies.

The remaining team members should follow instructions from the chief inspector, prepare the documents, equipment and materials required, and execute the inspection tasks according to the programme. Particularly, the technicians should oversee taking photographs and making sketches. *Depending on the length of the tunnel and the programme set by the chief inspector, tunnel inspectors and tunnel safety officers might be required*. They should be part of the inspection team or, in some circumstances, the chief inspector might delegate the responsibility to a tunnel inspector to oversee the inspection and report to him. The tunnel safety officer should provide the safety measures to be considered and conduct some induction with the inspection team. He should also attend the inspection activities on recommendation of the chief inspector.

The proposed required qualifications for chief inspector, tunnel inspectors, tunnel safety officer, and tunnel inspection technicians were presented as follows:

Chief Inspector:

- Be a registered professional engineer or;
- Possess a degree in structural/ civil engineering with a minimum of two years' experience in tunnel management or tunnel engineering or;
- Have a minimum of ten years' experience in tunnel inspection or tunnel engineering;
- Be trained and certified in the identification and assessment of structural defects that occur and threaten the integrity of a structural element;
- Have knowledge of applicable standards, codes and guidelines for concrete structural elements;
- Be trained and certified in the assessment of concrete structures, especially the mechanisms of deterioration of concrete structures.

Tunnel Inspectors:

- Possess a degree in structural/ civil engineering;
- Have a minimum of five years' experience in tunnel inspection or tunnel engineering;
- Have knowledge of applicable standards, codes and guidelines for concrete structural elements;
- Be trained and certified in the identification and assessment of structural defects that occur and threaten the integrity of a structural element.

Tunnel Inspection Technicians:

- Be trained in general tunnel inspection procedures and methods;
- Possess a minimum of two years' experience with concrete structures;
- Be able to work with drawings and technical reports;
- Be familiar with previous inspection reports.

Tunnel Safety Officer:

- Be trained and certified in Safety Management;
- Possess a minimum of 3 years as Safety Officer or an equivalent position;
- Have knowledge of safety practices in the underground structures and environment.

After defining the qualified inspection team, the tunnel management office should identify a set of tools and equipment relevant to tunnel inspections. The chief inspector should be in charge of setting the list, including the number of items for each type, of the tools and equipment for a specific tunnel.

b. Inspection Tools and Techniques

The following Table 4-31 provided the list and description of tools and equipment to be used for tunnel inspection:

Table 4-31: Tunnel Inspection Tools and Equipment

ID #	Instrument Name	Instrument Use
1	Fire Extinguisher	Response to fire incident
2	GPS Navigation Device	To provide the geographical position of tunnels
3	Digital Camera with flash	To take photographs of defects, elements, and the structure
4	Binoculars	To view objects at distance
5	Access equipment: Ladder, removable scaffolding	To access elements and components in height above the ground level of the tunnel
6	Crack width gauge	To measure the width of cracks
7	Laser distance meter	To measure objects in places hard to access
8	Hammer	To sound the concrete
9	Spray paint, Chalk or markers	To mark the identified areas of concern
10	Inspection forms	To record the details of inspection
11	Torch	To provide light in dark areas of the tunnel
12	Measuring tapes and wheel	To take measurements of the defects and tunnel elements
13	Screw drivers	To be used wherever needed.
14	Safety equipment: harnesses, first aid kit, gloves, safety vests, safety boots…	To help the inspection team work safety

Additional tools and equipment might be required for further levels of inspections, and they should be specified under the description of the types of inspection. As the inspection team was equipped, they needed to understand the procedures to undertake to conduct inspections.

c. Inspection Procedures

This subsection presented the types of inspection to carry out, their frequencies, their underlying processes, and the specific defects characterising the concrete structural elements of railway tunnels. The primary techniques to identify concrete structural defects to apply during inspection are visual inspection and non-destructive techniques. Firstly, carry out a visual inspection on all accessible areas of concrete structural elements, measure and document any identified defects. Bergeson and Ernest (2015: 4-38) emphasised that non-destructive testing (NDT) technology could also be used to characterise the extent of deficiencies in structural elements. Therefore, baseline readings from NDT technologies should be used to monitor defects over time. NDT methods were considered effective for evaluating:

- Concrete permeability;
- Delamination and spalling of concrete liners due to reinforcing steel corrosion;

- Problems with integrity of ceiling systems and connections to the tunnel lining;
- Voids behind and within tunnel linings;
- Water leakage.

Figures D-1 to D-8 (Common Defects on Tunnels Concrete Elements) and Table E-1 (Description of Defects) in the appendices should serve as guides for inspection procedures. After understanding the inspection procedures, the chief inspector and the tunnel inspectors were required to get used to the rating system that they will apply for tunnel inspections. The study considered the DER Rating System that is widely applied in South Africa, although it slightly differentiated its applicability as the study related to concrete structural elements only.

d. DER Rating System (Committee of Transport Officials [COTO], 2016)

The DER rating system, presented in TMH 19 – Part A, has been presented earlier in this study, in the review of the literature chapter. It was applied to identify and rate defects on concrete structural elements of railway tunnels in South Africa. To recall the basics, DER stands for:

- D – Degree: the severity of the defect;
- E – Extent: the size of the defect compared to the element inspected;
- R – Relevancy: the impact of the defect to the safety and the structural / functional integrity of the element inspected.

D, E and R were allocated values ranging from 1 to 4, although additional values were considered for D. The following Table 4-32 presented the meaning of each value to be considered.

Table 4-32: DER Rating System

Rating	D (Degree)	E (Extent)	R (Relevancy)	
X	Not applicable			
U	Unable to inspect			
0	No visible defects			
1	Minor	Local	Minimum	No structural integrity or safety issues
2	Moderate	More than local	Moderate	Some possible structural integrity or safety issues
3	Warning	Less than general	Major	Structural integrity or safety compromised
4	Severe	General	Critical	Serious impact on structural integrity and/or user safety

(Committee of Transport Officials [COTO], 2016)

However, TMH 19 prevents a certain number of combinations between D and R, specifying that “R-rating cannot be more than one point higher than the D-rating”. Although COTO recommended the rating only of the worst defect on an inspected item (defect with the highest R-rating), this study proposed the rating of any defect identified on an element as all the elements considered were structural elements of tunnels, and for recording purposes.

e. Application of DER Rating System to the Defects on Elements of Tunnels

DER Rating System should be applied to the defects on concrete structural elements of railway tunnels in a way to fully report the state of any defect on these elements. The reporting should specify also the implication of the defect rated to the structural integrity of the element and its functionality. The input from the inspection team would assist the management office to generate and adopt accurate, optimum and prioritised decision in relation to the future intervention needed. Additionally, the study considered the “urgency” parameter, while assessing the previous parameters, that estimated the timeframe to be set for intervention on the defect observed. Therefore, it translated, in plain words, the DER Rating System and the “Urgency” parameter as per the following Table 4-33:

Table 4-33: DER and Urgency in Plain Words

Id#	Parameter	Pronoun	Interpretation
1	Degree	What?	What problem do we have on this element?
2	Extent	Where?	“Where (in term of proportion on the element size) is the defect observed on this element?” or “How widespread is the defect on the inspection item being inspected?”
3	Relevancy	How?	“How tolerant can we be to the defect affecting the element considered?”
4	Urgency	When?	“When will the defect be dealt with?”

The following Table 4-34 summarised, for tunnels inspection, those timeframes considered before any remedial actions could be implemented.

Table 4-34: Timeframe for Intervention on Defect Observed

Urgency	Timeframe	Description
1	Routine	Will be decided based on the routine inspections
2	Within 2 years	To be monitored during a period of 2 years and decide further
3	Within 1 year	To be monitored during a period of 1 year and decide further
4	As soon as possible	Call to immediate or urgent intervention.

For decision making purpose, the rating of tunnel defects led to the evaluation of the entire system before planning for inspection.

f. Scoring of the Condition of the Tunnel Elements

As the elements considered for this study were concrete structural elements, any defect on one of them might have catastrophic consequences to the structural integrity of the element or the whole tunnel, or to the safety of the public. Therefore, this study defined a “Scoring of the Condtion System” that considered the overall level of a specific defect affecting a concrete structural element of the tunnel. It was based on coefficients applied to the parameter considered as presented in the following Table 4-35:

Table 4-35: Evaluation Factors for Defects on Tunnel Elements

ID#	Inspection Parameter	Evaluation Factor
1	Degree – what is the problem on this element	2
2	Extent - where is the defect observed on this element	3
3	Relevancy – how critical is the defect for the element	4
4	Urgency – when to fix it	1

The application of the evaluation factor led to the definition of several “scenarios” representing a given rated value for each parameter, and the translation of a “score” for every defect observed. Subsequently, the study defined a “relative score”, obtained by dividing the score corresponding to a given scenario by the highest score of the system. Equation 4-1 expressed the value of a score for a given defect on an element.

$$\text{Score} = D * 2 + E * 3 + R * 4 + U \qquad \text{Equation 4-1}$$

After determining the score of a given defect, the relative score was determined by applying the following Equation 4-2:

$$\text{Relative Score} = \frac{\text{Score}}{\text{Maximum Score}} \qquad \text{Equation 4-2}$$

Table B-1 in appendix B represented all the possible combinations that could be presented for a given defect. The final relative score would be obtained by the aggregate of all related relative scores of a given element and is given by the following Equation 4-3. Therefore, the final relative score of an element would represent its health called health of each element of the tunnel in relation with the defects observed on it.

$$\text{Final Relative Score} = \sum_{i=1}^{i=n} \text{Relative Score}_i \qquad \text{Equation 4-3}$$

n is the number of defects on the element j.

The health of the tunnel was obtained by the ratio of the cumulative result of all the final relative scores of its elements by the number of elements and was given by the following Equation 4-4. That final parameter of the tunnel should be considered with additional information from the monitoring system and the considerations of tunnel age and tunnel length to decide on further interventions.

$$\text{Tunnel Health} = \frac{1}{m}\sum_{j=1}^{j=m} \text{Final Relative Score}_j \qquad \text{Equation 4-4}$$

m is the number of elements of the tunnel inspected

The details relating to the type of inspection and the timeframe (planning) were given in the following paragraph.

g. Tunnel Inspection Plan

The specifications relating to tunnel inspection team, inspection tools and equipment, and the inspection procedures were given in the previous subsection. These specifications were integrated and applied to the definition of tunnel inspection types summed up in the following Table 4-36. That table described several components to consider for a given inspection type and related it to tunnels ages and tunnels lengths for setting inspection intervals and resources allocation.

Table 4-36: Tunnel Inspection Description

<table>
<tr><th>ID #</th><th>Inspection Type</th><th>Inspection Process</th><th>Inspection Team</th><th>Inspection Time and Frequency</th></tr>
<tr><td>1</td><td>Preliminary Inspection</td><td>First to be carried out;
Identification of defects related to the construction;
Establishment of inspection file for tunnel;
Set a baseline of the condition of concrete structural elements of the tunnel.</td><td>One chief inspector;
one tunnel inspector;
one tunnel safety officer;
two tunnel technicians.</td><td>After tunnel cleaned;
After tunnel commissioned;
After initial inventory of the tunnel;
Before operations.</td></tr>
<tr><td>2</td><td>Detailed Inspection</td><td>Routine comprehensive inspection scheduled at regular time intervals;
To be performed two years after preliminary inspection</td><td>One chief inspector;
two tunnel inspectors;
one tunnel safety officer;
three technicians.</td><td><table><tr><th>ID #</th><th>Tunnel age (years)</th><th>Interval (years)</th></tr><tr><td>1</td><td>< 50</td><td>4</td></tr><tr><td>2</td><td>50 ≤ age ≤ 100</td><td>3</td></tr><tr><td>3</td><td>> 100</td><td>2</td></tr></table></td></tr>
<tr><td>3</td><td>Impact Inspection</td><td>Due to an unstable event to the tunnel;
Performed after damage caused by accident, blast, earthquake, fire, flood, etc.
Assess the ceiling and the liner for an accident, use a hammer and check exposed reinforcement after a fire, inspect for cracks and the vicinity of the portals after an earthquake</td><td>chief inspector;
one tunnel inspector;
one tunnel safety officer;
two technicians;
a geotechnical engineer after a flood.</td><td>Immediately following an incident to the tunnel;
May necessitate the closure of the tunnel based on the severity of the damage</td></tr>
<tr><td>4</td><td>Critical Inspection</td><td>Performed after a set relatively lengthy period of time to identify hidden defects;
Provide missing data on a defect identified during detailed inspection;
To monitor an identified default.</td><td>One chief inspector;
two tunnel inspectors;
one tunnel safety officer;
three technicians.</td><td>Every twelve years following the preliminary inspection;
One month following a request from the chief inspector for missing data;
Whenever needed to install monitoring devices.</td></tr>
</table>

The applicability of the requirements for the type of inspection considered basically a tunnel that is less than 2.5 km in length. For every 2.5 km of the tunnel, the Chief Inspector should adjust the team, the tools and equipment needed. Professionally, the timing of tunnel inspections was set from a system that considered previous inspection results, tunnels ages, their lengths and other parameters. Therefore, a tunnel inspection plan was defined that decided on the timeframe and the needs of any inspections. The following Table 4-37 provided an Initial Tunnel Inspection Plan that should apply to each tunnel.

Table 4-37: Tunnel Inspection Planning

Id#	Task Id	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1	**Tunnel Inspection Programme**						
2	1	Initial Inventory	Tunnel Length (km) / 2	To be defined	Start 1 + Duration 1		Based on Tunnel Length
3	2	Preliminary Inspection	Tunnel Length (km) / 2	Finish1 +1/12 years	Start 2 + Duration 2	2FS+1/12 years	Based on Tunnel Length
4	*3*	*Detailed Inspection*					
5	3.1	Tunnel Age < 50	Tunnel Length (km) / 2	Finish 2 + 4 years	Start 3.1 + Duration 3.1	3FS+4 years	Based on Tunnel Length
6	3.2	50 ≤ Tunnel Age ≤ 100	Tunnel Length (km) / 2	Finish 2 + 3 years	Start 3.2 + Duration 3.2	3FS+3 years	Based on Tunnel Length
7	3.3	Tunnel Age > 100	Tunnel Length (km) / 2	Finish 2 + 2 years	Start 3.3 + Duration 3.3	3FS+2 years	Based on Tunnel Length
8	4	Impact Inspection	To be defined	To be defined	Start 4 + Duration 4		To be defined
9	5	Critical Inspection	To be defined	To be defined	Start 5 + Duration 5		To be defined

The resources that would form part of the inspection should be considered based on the length of the tunnel, and the main idea was to keep a single inspection team per tunnel for a given inspection. However, for tunnels whose lengths are more than 2.5 km, the Chief Inspector might organise two separate teams supervised each by a tunnel Inspector. The tunnel inspection team would use a formal Tunnel Inspection

Form that required a set of relevant data. The following paragraph details a "Tunnel Inspection Form" template designed for railway tunnels in South Africa.

h. Content and Format of Tunnel Inspection Forms

The following Figure 4-26 gave a template form that should assist in conducting tunnel inspections on site, and the filled in forms should form a physical part of the inspection records, while they would also serve to nurse and update the management system.

Tunnel Name:		Tunnel Number:		
Inspection Date:		Inspection Type:	Preliminary Inspection	
			Detailed Inspection	
Inspector Name:			Impact Inspection	
			Critical Inspection	

Element Name	**Element #**	**Distance to Portal No 1**	**Position L-B, L-T, R-T, R-B**	**Value Measured**	**Unit**
Cast-in-Place Concrete Tunnel Liner					m^2
Defect on the Element		*Degree*	*Extent*	*Relevancy*	*Urgency*
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking (Liners)					
Distortion					
Leakage					
Exposed Rebar					
Precast Concrete Tunnel Liner					m^2
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking (Liners)					
Distortion					
Leakage					
Exposed Rebar					

Element Name	Element #	Distance to Portal No 1	Position L-B, L-T, R-T, R-B	Value Measured	Unit
Concrete Tunnel Roof Girder					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Rebar					
Prestressed Concrete Tunnel Roof Girder					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Prestressing					
Exposed Rebar					
Concrete Column/Pile					Each
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Rebar					
Concrete Cross Passageway					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking (Liners)					
Distortion					
Leakage					
Exposed Rebar					
Concrete Interior Walls					m^2
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking (Liners)					
Exposed Rebar					
Concrete Portal					m^2
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					

Element Name	Element #	Distance to Portal No 1	Position L-B, L-T, R-T, R-B	Value Measured	Unit
Cracking (Liners)					
Settlement					
Exposed Rebar					
Concrete Ceiling Slab					m^2
Delamination/Spall/Patched area					
Efflorescence					
Cracking					
Exposed Rebar					
Concrete Ceiling Girder					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Rebar					
Prestressed Concrete Ceiling Girder					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Prestressing					
Exposed Rebar					
Concrete Ceiling Panels					m^2
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Rebar					
Concrete Invert Slab					m^2
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Rebar					
Concrete Slab-on-Grade					m^2
Delamination/Spall/Patched area					

Element Name	Element #	Distance to Portal No 1	Position L-B, L-T, R-T, R-B	Value Measured	Unit
Cracking					
Settlement					
Exposed Rebar					
Concrete Invert Girder					m
Delamination/Spall/Patched area					
Efflorescence					
Cracking					
Exposed Rebar					
Prestressed Concrete Invert Girder					m
Delamination/Spall/Patched area					
Efflorescence/Rust Staining					
Cracking					
Exposed Prestressing					
Exposed Rebar					

Figure 4-26: Railway Tunnels Inspection Form

The design of Figure 4-26 found its roots in the "Elements" section in the "Specifications for the National Tunnel Inventory" of the U.S. Department of Transport (USA. U.S. Department of Transportation, 2015: 3-1). It also considered some recommendations from "Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual" from the same department. Before conducting a Tunnel Inspection, the Tunnel Safety Officer should conduct a health and safety "Inspection Team Induction". That should present the emergency exit plan for the given tunnel, highlight the easiest way of accessing fire extinguishers and make the team aware of any potential risks related to the specific tunnel to be inspected. Also, the Chief Inspector would brief the inspection team on common defects that could be expected on concrete structural elements of railway tunnels.

i. Defects on concrete structural elements of railway tunnels

To ensure uniform and standardised inspection rating, the set of figures (Figure D-1 to Figure D-8) and Table E-1 in the Appendices presented an approach of rating the common defects on concrete structural elements of railway tunnels. The reference to these figures should serve as a guideline to minimise the subjectivity of the inspectors' judgments. After several inspections and the knowledge of the most critical elements of railway tunnels structures, the management office should identify the defects that can be regularly monitored on those most critical elements. Therefore, the adoption of an adequate monitoring system would be needed. The following section described the tunnel monitoring system that could be used as a reference to consider the monitoring of any defects on a concrete structural element of the railway tunnel.

4.3.4 Tunnel Monitoring System

Tunnel monitoring will apply in this system for condition-based inspection and for adequate planning of maintenance, repair and other tunnel management system's activities. Indeed, CIRIA (2007: 1188) stressed that *a regular structural monitoring programme is needed to evaluate structures for safety, condition, performance and functionality, and is useful to predict failure mechanisms and damage trends*. Fundamentally, **the performance of a structure is assessed by comparing measures of its condition and performance at given intervals in time**. Specifically, tunnel monitoring will help dealing with the damages of the system about their extent, location, nature and the prediction of their futures. Therefore, this study oversaw *the evolution and behaviour of corrosion of reinforcement, cracks, spalls and other defects that may be identified on concrete structural elements of railway tunnels in South Africa using sensors*.

a. Tunnel Monitoring Strategies

The implementation of a Tunnel Monitoring System (TMS) would *improve the management of the tunnels by reducing unnecessary interventions through the monitoring of any changes in the behaviour of tunnels or their environments*. In fact, the **understanding of the failure modes and deterioration mechanisms of individual structural components of a tunnel is crucial to design their monitoring systems**. This should also consider the behaviour of the whole structure. Another crucial parameter is the *understanding of the physical signs of impending failure associated with each damage mode*. Therefore, the monitoring programme should provide pre-failure symptoms, and determine the way to quantify any changes. This study considered a condition-based monitoring over other available options: failure-based monitoring, periodic monitoring, use-based monitoring, load-based monitoring, etc. *Condition-based monitoring is the source of information needed to evaluate the structure's integrity, either periodically or after extreme events*. Additionally, it looked absolutely at structural condition measures instead of other measures as functional performance, environmental loading conditions, etc.

The main steps in the development of this tunnel monitoring system were the definition of parameters of evaluation of the processes and the determination of methods of measurement for each of them. Additionally, the selection of appropriate instrument and techniques based on the reliability and the accuracy was required. The following section described the *critical parameters to monitor and their related methods of measurement based on the tunnel concrete structural defects that could be identified*. A comprehensive description of the characteristics of each defect should be given, for example, the length, width, and depth for spalls in concrete; length and width for cracks, etc. Also, the position of the defect should be specified in the longitudinal direction of the tunnel and within the tunnel cross-section (perpendicular to the tunnel axis). Finally, the setting up of the monitoring system should be described.

b. Sensory System for Tunnels Elements

A sensor refers to an accelerometer or strain gauge and a node refer to a whole sensor unit that comprises the sensor, a power supply, a data transmitter/receiver, and a microcontroller (Hodge et al. 2014). The following Table 4-38 presented the parameters to be monitored and the method to be applied describing the sensors to be used on concrete structural elements of railway tunnels.

Table 4-38: Elements of the Tunnel Sensory System

ID#	Parameter to Monitor	Sensor	Description
1	Crack	Optical fibre	continuous remote surveillance of the damage data: the grade and positions of damages, the progress of cracks and exfoliation of **tunnel lining**; allow the detection and monitoring of multiple cracks without requiring prior knowledge of crack locations; optimum as the location of cracks in a concrete structure is not known in a-priori, making conventional ‘point’ sensors (e.g., strain gauges) ineffective in the sensing of cracks.
		Displacement Transducer	converts a linear or angular displacement into a signal suitable for recording; can monitor movement across cracks and joints in *precast concrete panels in a railway tunnel to ensure the tunnel structure is stable*.
2	Strain	Optical fibre	highly likely incorporated in disaster prevention systems, which cover various ground structures including **tunnels**; installed within the *primary liner of the sprayed concrete lining which forms the structural support to the underground caverns and tunnels*; data generated to show the internal strains within the lining; strain data relevant for structural verification purposes.
3	Structure Distortion	Inclinometer (Tilt Meters)	can detect *distortion of railway structures* by detecting changes in incline.
4	Structure Movement	Displacement Transducer	In **mountain tunnels**, considerable ground deformations are deliberately permitted, while in **urban tunnels**, the main objective is limiting ground deformations around the tunnel and thus causing the minimum possible movement and disturbance at ground surface and the structures founded there.

ID#	Parameter to Monitor	Sensor	Description
		Optical fibre sensing system	⦚ structural displacement monitoring applied to measure the **displacement of a tunnel lining**; ⦚ sensitive: rotational movement of 0.5° and lateral movement of 0.1mm of the fixings.
		Differential FBG strain sensor	monitoring the *stability of the tunnel during the backfilling and traffic-operating periods*.
5	Transverse Deformation	Pressure Transducer	Tunnel sections generally take long time to stabilise. These time-dependent deformations effect the **tunnel lining** along with the modulus of deformation of the rock mass.
6	Settlement	Settlement Probe	*measure large settlement*
7	Joint	Displacement Transducer	monitor *movement across cracks and joints* in *precast concrete panels in a railway tunnel* to ensure the tunnel structure is stable.
8	Leakage	Piezometer	*measure the positive water pressure in the ground water of rail beds*
		Tensiometer	measure *negative water pressure* (water tension) in the soil to quantify the soil moisture status
		Vibrating Wire Piezometer	⦚ measure *changes in ground water pressure* and *monitoring the vibrations;* ⦚ are suited to long-term monitoring.
9	Rebar Corrosion	C4 Probe	⦚ *monitor the corrosion rate and condition of existing reinforced concrete structures*; ⦚ optimised for use with *tunnel elements*; ⦚ For tunnels, verify both *along the tunnel route and radially around the tunnel*.
		Sense Probe	detect 'internally' generated *stray currents found in rail system tunnels*.

c. Non-Destructive Testing

Non-destructive testing (NDT) methods prove to be more efficient in areas not easily accessible or when in-depth evaluations are required. Also, to determine the extent of deficiencies in structural elements, this study proposed the use of baseline readings from NDT technologies to monitor defects over time. For this study, NDT methods would be mainly used to evaluate *water leakage, delamination and spalling of concrete liners due to the corrosion of reinforcing steel, concrete permeability*. Additional evaluations consisted of the *voids behind and within tunnel linings, the integrity of steel liners underneath concrete linings, the integrity of ceiling systems and connections to the tunnel lining*. Some common NDT technologies that were recommended consisted of the air and ground coupled GPR, impact echo, scanners, ultrasonic echo and surface waves. Other various imaging techniques could be used to verify the tunnel geometry and identify changes that occur with the tunnel surface over time. Also, infrared imagery is useful for identifying water leaks in the liner. Additional information on NDT technology could be found at: http://www.ndtoolbox.org/content/tunnels.

The following section described the processes of integration of the components of the railway tunnel management system developed. It considered the 'life' of the database et its connections and interactions with other modules.

4.3.5 Tunnel Management System Integration

After developing various components of Railway Tunnel Management System in South Africa, they had to be integrated in a manner that optimised their performance as a whole system. This section presented a set of algorithms that were adopted and applied to the Railway Tunnels Management System that was developed (Appendix I). The first set of procedures appended new data, the second updated the inspection form, the third evaluated the inspection data and the final planned for further inspections.

a. Append Data to the Database

This set of procedures worked with the Tunnel Inventory Management and manipulated the Inventory Form to "Add Data to Database". It added the new records to the existing database and operated as described in the Procedures to enhance tunnels management chapter (Figure 3-4). Those procedures were executed by the set of codes provided in Appendix I-1. Once the database contained the record of the new tunnel inventoried, the system was updated and gave the user the opportunity to add additional data. The next code updated the inspection form.

b. Update Inspection Form

This set of procedures worked with the Tunnel Inspection Programme and the Tunnel Monitoring System. After updating the Tunnel Inventory File, it made it available to the inspection and monitoring forms that would be updated once new data was recorded. These procedures applied the steps described in Figure 3-5 of the Procedures to enhance tunnels management chapter to update the Inspection and Monitoring Files. Those procedures were executed by the set of codes presented in Appendix I-2. Once the inspection form was updated, the system could evaluate the result of inspections for a given period. This was detailed in the following section.

c. Tunnel Inspection Evaluation

The first component of this set of procedures opened the 'Tunnel Inspection Evaluation' form. Subsequently, it evaluated the inspection file after the manager defined the required options. The process to evaluate the inspection files has been described in the Procedures to enhance tunnels management chapter. Those procedures were executed by the set of codes initiated in Appendix I-3. The step following Tunnel Inspection Evaluation was to elaborate further inspections. 'Tunnel Inspection Plan' was the tool developed to respond to that need.

d. Tunnel Inspection Plan

This set of procedures considered the inspection type and the previous inspection data, if any, and determined the period the next inspection of a given tunnel should be carry out. For the first time a tunnel was evaluated, the system planned for its preliminary inspection during the next two years. After the preliminary inspection, the system considered tunnel age and the previous inspection file to set the timeframe for the upcoming inspection. Those procedures aligned with the process described in the Procedures to enhance tunnels management chapter (Figure 3-6). Those procedures were executed by the set of codes listed in Appendix I-4.

4.4 Summary

This chapter of 'Data Analysis and Findings' considered the current tunnel management practice in South Africa and the best practice from existing structures management systems. The current tunnel management practice in South Africa consists of a visual inspection of three types. The Depot Engineer performs the annual inspections using the BBC 8254 forms and the Senior Engineer performs the Principal inspection every 5 years, the Exception List Inspections every year. It also summarised 23 existing structures management systems, from 11 countries, that relate to bridges, tunnels, culverts, retaining walls and other structures. Thus, it applied the relevant methods defined to develop a railway tunnels management system that would improve the current management practice in South Africa presented.

That system comprised firstly a *Tunnel Inventory Module managing the records of new tunnels and their concrete structural elements through uniform and standardised forms*. It also comprised *management databases constituting platforms for different modules developed and serving for analysis and support for decisions*. The Tunnel Inspection Module defined the *requirements of the qualifications for the inspection team, specified the inspection procedures and designed inspection forms for uniformity and conformity*. The Tunnel Monitoring Module designed *targeted the most critical and recurring defects on concrete structural elements of railway tunnels*. It also described a few non-destructive testing techniques that could be referred to complement visual inspections. Finally, the Tunnel Integration Module interacted with other modules and integrated the whole system.

The analysis of the current tunnel stock and the tunnels on the heavy haul lines revealed that there are *207 tunnels with a total length of 145.417 km*. It also revealed that only 2% of the tunnels were built using the 'Cut and Cover' method against 83% using the 'Drill and Blast'. However, the information for the 15% remained was incomplete. When considering the aggregate lengths of tunnels, these figures become 1% for 'Cut and Cover' against 90% for 'Drill and Blast' and 9% unknown. The analysis revealed also that only *29% of the tunnels are below 50 years against 15% over 100 years*. The remained 56% are between 50 and 100 years old. Moreover, *43% of tunnels are in the Southern Natal* followed by *19% in the Northern Natal*, against 1% in the North Western Cape and 1% in the Orange Free State. And 96% of tunnels are less than 2.5 km long and 1% are over 12.5 km long.

A similar analysis was conducted on the *38 tunnels on the heavy haul lines (1 on the ore iron line and 37 on the coal line) with a total length of 34.637 km*. It revealed that 95% of them were built using the 'Drill and Blast' method and it is unknown for the remaining 5%. Also, 66% of them are over 40 years old against only 5% under the age of 30. Additionally, 97% of these tunnels are in the Northern Natal, of them *79% are on the Vryheid – Empangeni section*, and only 3% in the North Western Cape, on the Sishen – Saldanha section. With regard to their lengths, 3% are above 3 km against 74% below 1 km.

5. Conclusion and Recommendations

5.1 Conclusion

In relation to the precedent chapter, the following are the conclusions that align with the data analysis and findings translating the attainment of the objectives set for this research. After scrutinising the current railway tunnels management practice in South Africa, this research proposes **a consistent computerised management system that optimises the current management practice**. This is due to the tunnel stock and their valuable contribution to improving the economic and social well-being of this country. The current management practice consists in a simple and easy visual inspection applying condition assessment to identify unsafe conditions of these tunnels. However, it is a reactive and curative approach that prioritises the functionality of the tunnels over its structural integrity as most of the items frequently inspected are not structural elements. it is also subjective as it relies more on the level of competency of the assessor. Finally, the current management practice suffers for defects not easily identifiable and increases the risk of failure for leaving them to the loop of principal tunnel inspections.

From the 23 systems overviewed, this study unveils that *many organisations*, *regions and countries are adopting computerised structures management systems targeting the size and the specificity of their infrastructure*. Without plenty of complexities, these fitted systems respond efficiently and adequately to their management needs. Also, these computerised systems assist better the authorities in making informed decisions on future planning and interventions.

The proposed railway tunnels management system in South Africa sets *uniform and straightforward procedures of inspecting concrete structural elements of these tunnels*. It is a proactive and preventive system that links the data of the tunnel stock recorded to the inspection and monitoring modules and makes available the various components of the tunnels and their history. From its comprehensive inventory module, this system assists the management authority and the inspection team through the whole process to successful planning of further inspections. Through its tunnels inventory forms, this system identifies all the tunnels and their respective items and links them to their concrete structural elements. With the suitable inspection resources (team members, tools and equipment) and techniques, the planned inspections activities are conducted through the guidance of inspection forms. These forms specify for each concrete structural element the corresponding defects that can be observed and rated using the DER rating system.

To emphasise the benefits of Exception List Inspections, the proposed system considers a *monitoring module that deals with the most critical and vulnerable elements and the most recurring defects*. This module serves particularly to monitor the tunnels on the heavy haul lines that are subjected to increase of axle load and higher frequency of flow.

In a nutshell, the proposed railway tunnels management system provides a *big picture of the tunnel stock, their conditions, their inspection needs and history*. It also assists the authority to easily update the tunnel inventory file, plan further inspections and subsequent remedial actions (if required) and monitor the most critical and vulnerable elements. Thus, this system equips the authority and the inspection team with all the necessary tools to conduct objectively the inspections of concrete structural elements of railway tunnels. Finally, it efficiently sustains the evaluation of the tunnels inspected, the planning of further inspections and resources.

5.2 Recommendations

Based on the findings and the preceding conclusions, the following recommendations are made to *enforce the soundness of the proposed tunnel management system*. We recommend to the management authority to further adopt a monitoring system for each tunnel on the heavy haul lines. Thus, we recommend to the management authority to make available the information on all current monitoring systems installed in these tunnels and the most critical data collected. Also, to gradually and progressively integrate the use of the proposed system to its current management practice. Additionally, we recommend to the authority to make available all the previous railway tunnels inspection files to be uploaded to the proposed system. Apart from this, we recommend a further comprehensive study to integrate the inspection of non-structural elements to the proposed system. Finally, we recommend to the management authority to organise a comprehensive study of the water leakage issues on railway tunnels to better understand and adequately respond to them.

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Appendix A: Description of Tunnel Elements

Table A-1: Tunnel Elements

ID #	Element	Function	Description	Measurement	Unit
1	*Columns and Piles*	*Vertical load bearing elements usually comprised of concrete or steel components.*	*Piles are embedded into the ground. Columns are free standing members located above the ground level.* *Lateral bracing may be incorporated to stiffen the columns.*		
1.1	Concrete Column/Pile	The columns support the roof girders, ceiling girders, invert girders. The piles support the columns.		Total number = sum of all the number of columns and piles.	Each
2	*Cross Passageway*	*They consist in linking parallel tunnels.*	*Should ideally be slightly pressurised to maintain positive air flow to prevent smoke from entering the escape route, which helps to maintain a tenable environment for evacuees & emergency responders.*		
2.1	Concrete Cross Passageway	Oriented transverse to the tunnel bores, & comprised of doors to allow egress between separated tunnel bores.		Total Length = sum of all the lengths of each cross passageway.	m
3	*Interior Walls*	*Separate opposing traffic, the travel way from the ventilation plenum or from the emergency egress corridor.*	*While the tunnel liner is in contact with the ground, the interior walls are not.*		
3.1	Concrete Interior Walls	Define those internal walls in tunnels placed to separate traffic travelling in opposite directions. Barrier between tunnel segments in an emergency.		Area = Length (along centerline) * height (of the tunnel).	m^2
4	*Liners*	*Support the ground around the tunnel and restricts groundwater infiltration into the tunnel.*	*Many tunnels have a two-pass liner system: an initial liner (temporary support: shotcrete & rock bolts, ribs & lagging, & slurry walls) and a final liner (permanent support: cast-in-place concrete liners or bolted & assembled precast concrete segments). Installed in all types of tunnel projects (available, easy to use, durable, relatively low cost). The roof of a tunnel is*		

ID #	Element	Function	Description	Measurement	Unit
			considered part of the tunnel liner.		
4.1	Cast-in-Place Concrete Tunnel Liner	Functions as a shell for the exterior of the tunnel and as a divider between different bores of the tunnel.	In most cases it consists of a reinforced concrete ceiling slab of 100mm≤ thickness ≤ 150mm spanning transversely between the tunnel walls and supports.	Area = Length (along the centerline) (of the tunnel) * perimeter (of the liner).	m^2
4.2	Precast Concrete Tunnel Liner	Functions as a shell for the exterior of the tunnel and as a divider between different bores of the tunnel.		Area = Length (along the centerline) (of the tunnel) * liner perimeter	m^2
5	*Portals*		*Located at the entrances and exits of the tunnel.*		
5.1	Concrete Portal	Define the portal facades comprising the architectural/structural elements above the track bed at the opening of the tunnel bore.		Area = Width * height (of the portal) - area of the track bed opening	m^2
6	*Roof Girders*	*Main horizontal support for a flat tunnel roof. They support the tunnel roof & the loads from the backfill, surcharge, and traffic above.*	*Used to support deck system, can be steel or concrete.*		
6.1	Concrete Tunnel Roof Girder	Supports the tunnel roof liner or exposed rock which constitutes the tunnel roof.		Total Length = sum of all the lengths of each tunnel roof girder.	m
6.2	Prestressed Concrete Tunnel Roof Girder	Supports the tunnel roof liner or exposed rock which constitutes the tunnel roof.		Total Length = sum of all the lengths of each tunnel roof girder.	m
7	*Tunnel Ceiling Structures*		*They consist of slabs or panels that are supported by girders or hangers and anchorages. They include either reinforced concrete ceiling slabs or precast concrete ceiling panels that are supported by either girders or hangers and anchorages.*		
7.1	Ceiling Slab	Slabs are cast-in-place concrete elements.	Ceiling Slabs and Ceiling Panels serve the same function in the ceiling system.		
7.1.1	Concrete Ceiling Slab	Defines the structural slabs that separate the space above the track bed from the upper plenum.		Area = Width * Length (of the slab)	m^2

ID #	Element	Function	Description	Measurement	Unit
7.2	Ceiling Girder	Main horizontal support for the ceiling panels or slabs.	These structural elements are used in place of hangers and anchorages.		
7.2.1	Concrete Ceiling Girder	Support the structural ceiling slabs separating the space above the track bed from the upper plenum.		Total Length = Sum of the lengths of each tunnel ceiling girder.	m
7.2.2	Prestressed Concrete Ceiling Girder	Support the structural ceiling slabs separating the space above the track bed from the upper plenum.		Total Length = Sum of all the lengths of each tunnel ceiling girder.	m
7.3	Ceiling Panels	Panels are precast concrete elements.	Ceiling Slabs and Ceiling Panels serve the same function in the ceiling system.		
7.3.1	Concrete Ceiling Panels	Separate the upper plenum from space above the tunnel track bed. They are typically supported by hangers.		Area = Width * Length (of the panel).	m^2
8	*Tunnel Invert Structures*	*They consist of slabs that are supported by girders or on grade.*	*When the railroad is a structurally supported slab, then the space below the supported railroad is used for ventilation & drainage. The supported invert slab acts like a bridge deck that carries traffic loads.*		
8.1	Invert Slab	The slab evaluation is three dimensional with the defects observed on the top surface, bottom surface, or both, and being captured using the defined criteria.	Slab top or bottom surfaces that are not visible for inspection shall be assessed based on the available visible surface. If both top & bottom surfaces are not visible, use destructive & non-destructive testing.		
8.1.1	Concrete Invert Slab	Structural slabs that support the track bed and traffic loads.		Total Area = Width * Length (of the slab)	m^2
8.2	Slab-on-Grade				
8.2.1	Concrete Slab-on-Grade	Defines a slab supported continuously on a subbase material.		Area = Width * Length (of the slab).	m^2
8.3	Invert Girder	Main horizontal support for the slabs.			
8.3.1	Concrete Invert Girder	Defines the invert girders that support the invert slabs.		Total Length = sum of all the lengths of each invert girder.	m
8.3.2	Prestressed Concrete Invert Girder	Defines the invert girders that support the invert slabs.		Total Length = sum of all the lengths of each invert girder.	m

Appendix B : Tunnel Inspection Evaluation

Table B-1: Inspection Scores and Relative Scores

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
1	1	*1*	*1*	*1*	*1*	10	25.0
2	65	*1*	*1*	*1*	*2*	11	27.5
3	2	*2*	*1*	*1*	*1*	12	30.0
	129	*1*	*1*	*1*	*3*		
4	5	*1*	*2*	*1*	*1*	13	32.5
	66	*2*	*1*	*1*	*2*		
	193	*1*	*1*	*1*	*4*		
5	3	*3*	*1*	*1*	*1*	14	35.0
	17	*1*	*1*	*2*	*1*		
	69	*1*	*2*	*1*	*2*		
	130	*2*	*1*	*1*	*3*		
6	6	*2*	*2*	*1*	*1*	15	37.5
	67	*3*	*1*	*1*	*2*		
	81	*1*	*1*	*2*	*2*		
	133	*1*	*2*	*1*	*3*		
	194	*2*	*1*	*1*	*4*		
7	4	*4*	*1*	*1*	*1*	16	40.0
	9	*1*	*3*	*1*	*1*		
	18	*2*	*1*	*2*	*1*		
	70	*2*	*2*	*1*	*2*		
	131	*3*	*1*	*1*	*3*		
	145	*1*	*1*	*2*	*3*		
	197	*1*	*2*	*1*	*4*		
8	7	*3*	*2*	*1*	*1*	17	42.5
	21	*1*	*2*	*2*	*1*		
	68	*4*	*1*	*1*	*2*		
	73	*1*	*3*	*1*	*2*		
	82	*2*	*1*	*2*	*2*		
	134	*2*	*2*	*1*	*3*		
	195	*3*	*1*	*1*	*4*		
	209	*1*	*1*	*2*	*4*		
9	10	*2*	*3*	*1*	*1*	18	45.0
	19	*3*	*1*	*2*	*1*		
	33	*1*	*1*	*3*	*1*		
	71	*3*	*2*	*1*	*2*		
	85	*1*	*2*	*2*	*2*		
	132	*4*	*1*	*1*	*3*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	137	*1*	*3*	*1*	*3*		
	146	*2*	*1*	*2*	*3*		
	198	*2*	*2*	*1*	*4*		
10	8	*4*	*2*	*1*	*1*	19	47.5
	13	*1*	*4*	*1*	*1*		
	22	*2*	*2*	*2*	*1*		
	74	*2*	*3*	*1*	*2*		
	83	*3*	*1*	*2*	*2*		
	97	*1*	*1*	*3*	*2*		
	135	*3*	*2*	*1*	*3*		
	149	*1*	*2*	*2*	*3*		
	196	*4*	*1*	*1*	*4*		
	201	*1*	*3*	*1*	*4*		
	210	*2*	*1*	*2*	*4*		
11	11	*3*	*3*	*1*	*1*	20	50.0
	20	*4*	*1*	*2*	*1*		
	25	*1*	*3*	*2*	*1*		
	34	*2*	*1*	*3*	*1*		
	72	*4*	*2*	*1*	*2*		
	77	*1*	*4*	*1*	*2*		
	86	*2*	*2*	*2*	*2*		
	138	*2*	*3*	*1*	*3*		
	147	*3*	*1*	*2*	*3*		
	161	*1*	*1*	*3*	*3*		
	199	*3*	*2*	*1*	*4*		
	213	*1*	*2*	*2*	*4*		
12	14	*2*	*4*	*1*	*1*	21	52.5
	23	*3*	*2*	*2*	*1*		
	37	*1*	*2*	*3*	*1*		
	75	*3*	*3*	*1*	*2*		
	84	*4*	*1*	*2*	*2*		
	89	*1*	*3*	*2*	*2*		
	98	*2*	*1*	*3*	*2*		
	136	*4*	*2*	*1*	*3*		
	141	*1*	*4*	*1*	*3*		
	150	*2*	*2*	*2*	*3*		
	202	*2*	*3*	*1*	*4*		
	211	*3*	*1*	*2*	*4*		
	225	*1*	*1*	*3*	*4*		
13	12	*4*	*3*	*1*	*1*	22	55.0
	26	*2*	*3*	*2*	*1*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	35	*3*	*1*	*3*	*1*		
	49	*1*	*1*	*4*	*1*		
	78	*2*	*4*	*1*	*2*		
	87	*3*	*2*	*2*	*2*		
	101	*1*	*2*	*3*	*2*		
	139	*3*	*3*	*1*	*3*		
	148	*4*	*1*	*2*	*3*		
	153	*1*	*3*	*2*	*3*		
	162	*2*	*1*	*3*	*3*		
	200	*4*	*2*	*1*	*4*		
	205	*1*	*4*	*1*	*4*		
	214	*2*	*2*	*2*	*4*		
	15	*3*	*4*	*1*	*1*		
	24	*4*	*2*	*2*	*1*		
	29	*1*	*4*	*2*	*1*		
	38	*2*	*2*	*3*	*1*		
	76	*4*	*3*	*1*	*2*		
	90	*2*	*3*	*2*	*2*		
	99	*3*	*1*	*3*	*2*		
14	113	*1*	*1*	*4*	*2*	23	57.5
	142	*2*	*4*	*1*	*3*		
	151	*3*	*2*	*2*	*3*		
	165	*1*	*2*	*3*	*3*		
	203	*3*	*3*	*1*	*4*		
	212	*4*	*1*	*2*	*4*		
	217	*1*	*3*	*2*	*4*		
	226	*2*	*1*	*3*	*4*		
	27	*3*	*3*	*2*	*1*		
	36	*4*	*1*	*3*	*1*		
	41	*1*	*3*	*3*	*1*		
	50	*2*	*1*	*4*	*1*		
	79	*3*	*4*	*1*	*2*		
	88	*4*	*2*	*2*	*2*		
15	93	*1*	*4*	*2*	*2*	24	60.0
	102	*2*	*2*	*3*	*2*		
	140	*4*	*3*	*1*	*3*		
	154	*2*	*3*	*2*	*3*		
	163	*3*	*1*	*3*	*3*		
	177	*1*	*1*	*4*	*3*		
	206	*2*	*4*	*1*	*4*		
	215	*3*	*2*	*2*	*4*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	229	*1*	*2*	*3*	*4*		
16	16	*4*	*4*	*1*	*1*	25	62.5
	30	*2*	*4*	*2*	*1*		
	39	*3*	*2*	*3*	*1*		
	53	*1*	*2*	*4*	*1*		
	91	*3*	*3*	*2*	*2*		
	100	*4*	*1*	*3*	*2*		
	105	*1*	*3*	*3*	*2*		
	114	*2*	*1*	*4*	*2*		
	143	*3*	*4*	*1*	*3*		
	152	*4*	*2*	*2*	*3*		
	157	*1*	*4*	*2*	*3*		
	166	*2*	*2*	*3*	*3*		
	204	*4*	*3*	*1*	*4*		
	218	*2*	*3*	*2*	*4*		
	227	*3*	*1*	*3*	*4*		
	241	*1*	*1*	*4*	*4*		
17	28	*4*	*3*	*2*	*1*	26	65.0
	42	*2*	*3*	*3*	*1*		
	51	*3*	*1*	*4*	*1*		
	80	*4*	*4*	*1*	*2*		
	94	*2*	*4*	*2*	*2*		
	103	*3*	*2*	*3*	*2*		
	117	*1*	*2*	*4*	*2*		
	155	*3*	*3*	*2*	*3*		
	164	*4*	*1*	*3*	*3*		
	169	*1*	*3*	*3*	*3*		
	178	*2*	*1*	*4*	*3*		
	207	*3*	*4*	*1*	*4*		
	216	*4*	*2*	*2*	*4*		
	221	*1*	*4*	*2*	*4*		
	230	*2*	*2*	*3*	*4*		
18	31	*3*	*4*	*2*	*1*	27	67.5
	40	*4*	*2*	*3*	*1*		
	45	*1*	*4*	*3*	*1*		
	54	*2*	*2*	*4*	*1*		
	92	*4*	*3*	*2*	*2*		
	106	*2*	*3*	*3*	*2*		
	115	*3*	*1*	*4*	*2*		
	144	*4*	*4*	*1*	*3*		
	158	*2*	*4*	*2*	*3*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	167	*3*	*2*	*3*	*3*		
	181	*1*	*2*	*4*	*3*		
	219	*3*	*3*	*2*	*4*		
	228	*4*	*1*	*3*	*4*		
	233	*1*	*3*	*3*	*4*		
	242	*2*	*1*	*4*	*4*		
19	43	*3*	*3*	*3*	*1*	28	70.0
	52	*4*	*1*	*4*	*1*		
	57	*1*	*3*	*4*	*1*		
	95	*3*	*4*	*2*	*2*		
	104	*4*	*2*	*3*	*2*		
	109	*1*	*4*	*3*	*2*		
	118	*2*	*2*	*4*	*2*		
	156	*4*	*3*	*2*	*3*		
	170	*2*	*3*	*3*	*3*		
	179	*3*	*1*	*4*	*3*		
	208	*4*	*4*	*1*	*4*		
	222	*2*	*4*	*2*	*4*		
	231	*3*	*2*	*3*	*4*		
	245	*1*	*2*	*4*	*4*		
20	32	*4*	*4*	*2*	*1*	29	72.5
	46	*2*	*4*	*3*	*1*		
	55	*3*	*2*	*4*	*1*		
	107	*3*	*3*	*3*	*2*		
	116	*4*	*1*	*4*	*2*		
	121	*1*	*3*	*4*	*2*		
	159	*3*	*4*	*2*	*3*		
	168	*4*	*2*	*3*	*3*		
	173	*1*	*4*	*3*	*3*		
	182	*2*	*2*	*4*	*3*		
	220	*4*	*3*	*2*	*4*		
	234	*2*	*3*	*3*	*4*		
	243	*3*	*1*	*4*	*4*		
21	44	*4*	*3*	*3*	*1*	30	75.0
	58	*2*	*3*	*4*	*1*		
	96	*4*	*4*	*2*	*2*		
	110	*2*	*4*	*3*	*2*		
	119	*3*	*2*	*4*	*2*		
	171	*3*	*3*	*3*	*3*		
	180	*4*	*1*	*4*	*3*		
	185	*1*	*3*	*4*	*3*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	223	*3*	*4*	*2*	*4*		
	232	*4*	*2*	*3*	*4*		
	237	*1*	*4*	*3*	*4*		
	246	*2*	*2*	*4*	*4*		
22	47	*3*	*4*	*3*	*1*	31	77.5
	56	*4*	*2*	*4*	*1*		
	61	*1*	*4*	*4*	*1*		
	108	*4*	*3*	*3*	*2*		
	122	*2*	*3*	*4*	*2*		
	160	*4*	*4*	*2*	*3*		
	174	*2*	*4*	*3*	*3*		
	183	*3*	*2*	*4*	*3*		
	235	*3*	*3*	*3*	*4*		
	244	*4*	*1*	*4*	*4*		
	249	*1*	*3*	*4*	*4*		
23	59	*3*	*3*	*4*	*1*	32	80.0
	111	*3*	*4*	*3*	*2*		
	120	*4*	*2*	*4*	*2*		
	125	*1*	*4*	*4*	*2*		
	172	*4*	*3*	*3*	*3*		
	186	*2*	*3*	*4*	*3*		
	224	*4*	*4*	*2*	*4*		
	238	*2*	*4*	*3*	*4*		
	247	*3*	*2*	*4*	*4*		
24	48	*4*	*4*	*3*	*1*	33	82.5
	62	*2*	*4*	*4*	*1*		
	123	*3*	*3*	*4*	*2*		
	175	*3*	*4*	*3*	*3*		
	184	*4*	*2*	*4*	*3*		
	189	*1*	*4*	*4*	*3*		
	236	*4*	*3*	*3*	*4*		
	250	*2*	*3*	*4*	*4*		
25	60	*4*	*3*	*4*	*1*	34	85.0
	112	*4*	*4*	*3*	*2*		
	126	*2*	*4*	*4*	*2*		
	187	*3*	*3*	*4*	*3*		
	239	*3*	*4*	*3*	*4*		
	248	*4*	*2*	*4*	*4*		
	253	*1*	*4*	*4*	*4*		
26	63	*3*	*4*	*4*	*1*	35	87.5
	124	*4*	*3*	*4*	*2*		

Group No	Scenario No	Degree	Extent	Relevancy	Urgency	Score	Relative Score %
	176	*4*	*4*	*3*	*3*		
	190	*2*	*4*	*4*	*3*		
	251	*3*	*3*	*4*	*4*		
27	127	*3*	*4*	*4*	*2*	36	90.0
	188	*4*	*3*	*4*	*3*		
	240	*4*	*4*	*3*	*4*		
	254	*2*	*4*	*4*	*4*		
28	64	*4*	*4*	*4*	*1*	37	92.5
	191	*3*	*4*	*4*	*3*		
	252	*4*	*3*	*4*	*4*		
29	128	*4*	*4*	*4*	*2*	38	95.0
	255	*3*	*4*	*4*	*4*		
30	192	*4*	*4*	*4*	*3*	39	97.5
31	256	*4*	*4*	*4*	*4*	40	100.0
Grand Total							**256**

Appendix C: Railway Operators in South Africa

Table C-1: Railway Operators

Id #	Railway Operator
1	**Class A**
1.1	Access Freight International Limited
1.2	AFGRI Handling and Storage
1.3	African Explosives Holdco Limited T/A African Explosives Limited (AEL)
1.4	African Rail and Traction Services
1.5	AFRISAM
1.6	Anglo American Platinum T/A Rustenburg central Services Ltd
1.7	Anglo American Thermal Coal
1.8	Anglogold Ashanti - The South Africa Region Metallurgy
1.9	Arcelormittal Newcastle
1.10	Arcelormittal Vanderbijilpark
1.11	Assmang Limited: Iron Ore Beeshoek Mine
1.12	Assmang Limited T/A Khumani Iron Ore Mine
1.13	Assmang Limited - Managnese Ore - Black Rock
1.14	Assmang Managnese: Cato Ridge Works
1.15	BHP Billiton Energy Coal SA Ltd T/A Phola Coal Processing Plant
1.16	BHP Billiton T/A BECSA Coal Processing (Middelburg Mines)
1.17	Bidfreight Port Operations (Proprietary) Limited
1.18	Black Mountain Mining P/L
1.19	Bombela Operating Co (Pty) Ltd
1.20	Bosveld Phosphates
1.21	BP Southern Africa T/A BPSA
1.22	Cape Point Partnership
1.23	Chevron Oil SA (Pty) Ltd
1.24	City of Cape Town
1.25	City of Tshwane Metropolitan Municipality
1.26	City of Umhlathuze Municipality
1.27	Delmas Coal (Pty) Ltd
1.28	Dorstfontein Coal Mine (Pty) Ltd
1.29	Droogvallei Rail Siding Company P/L
1.30	Duferco/ Vanchem Vanadium Products (Pty) Ltd
1.31	Durban Coal Terminal Co T/A Bulk Connections
1.32	Ekurhuleni Metropolitan Municipality
1.33	Engen Petroleum Limited - Bethlehem
1.34	Engen Petroleum Limited - Bloemfontein
1.35	Engen Petroleum Limited - Kroonstad
1.36	Engen Petroleum Limited - Langlaagte

Id #	Railway Operator
1.37	Engen Petroleum Limited - Montague Gardens
1.38	Engen Rafinery
1.39	Eskom Generation T/A Majuba Power Station
1.40	Eskom Holdings SOC Limited T/A Eskom Generation - Camden Power Station
1.41	Ethekwini Municipality
1.42	Evraz Highveld Steel and Vanadium Corporation Ltd
1.43	Evraz Highveld Steel and Vanadium Ltd - Mapochs Mine Division
1.44	Exxaro Coal (Pty) Ltd - Inyanda Coal
1.45	Exxaro Leewpan Coal
1.46	Exxaro Resources (Pty) Ltd - Grootegeluk Coal
1.47	Exxaro Resources (Pty) Ltd T/A New Clydesdale Coal
1.48	Forbes Coal Trading as Manhattans
1.49	Forzando Coal Mines (Pty) Ltd
1.50	Foskor (Pty) Limited - Phalaborwa
1.51	Foskor (Pty) Limited - Richards Bay
1.52	Fransrail Cc T/A Franschhoek Valley Wine Tram
1.53	Friends of the Rail
1.54	Glencore Operations Coal SA P/L T/A Glencore Operations Coal SA
1.55	Grindrod Terminals Richards Bay (A Division of Grindrod (SA) (Pty) Ltd
1.56	Harmony Gold Mine
1.57	Hotazel Manganese Mines (Pty) Ltd
1.58	Impala Platinium Holdings Ltd T/A Implats
1.59	Island View Storage Ltd, Durban
1.60	Island View Storage Ltd, Richards Bay
1.61	Kangra Coal (Pty) Ltd T/A Savmore Colliery
1.62	Karbochem (Pty) Ltd
1.63	Lafarge Industries SA
1.64	Locomotive, Engines & General Engineering Cc
1.65	Mactransco (Pty) Ltd
1.66	Mafube Coal Mining (Pty) Ltd
1.67	Mashala Resources (Pty) Ltd
1.68	Mbombela Local Municipality
1.69	Moqhaka Municipality
1.70	Misobo Coal P/L
1.71	NATREF T/A (National Petroleum Refiners of SA P/L)
1.72	NPC - Cimpor (Pty) Ltd
1.73	Omnia Fertilizer (A Division of Omnia Group (Pty) Ltd)
1.74	Optimum Coal Holdings P/L T/A Koornfontein Mine P/L
1.75	Optimum Coal Mine (Pty) Ltd
1.76	Outeniqua Power Van
1.77	Palabora Mining Company

Id #	Railway Operator
1.78	Patons Country Narrow Gauge Railway
1.79	PetroSA (Petroleum Oil & Gas Corporation of SA P/L)
1.80	Pioneer Foods T/A Sasko Grain
1.81	PPC Ltd T/A PPC Cement
1.82	Passenger Rail Agency of SA Rail
1.83	Reefsteamers
1.84	Richards Bay Coal Terminal Company Limited
1.85	Richards Bay Minerals
1.86	Rovos Rail Tours (Pty) Ltd
1.87	RRL Grindrod (Pty) Ltd
1.88	SA Coal Mine Holdings T/A Voorslag Coal Handling P/L
1.89	SA Coal Mine Holdings Ltd T/A SACM Operations (Pty) Ltd
1.90	SA Freight Logistics T/A SAFLOG
1.91	SABT T/A Durban Bulk Management And Logistics (Pty) Ltd
1.92	Sandstone Estates
1.93	Sappi Southern Africa (Pty) Ltd T/A SAICCOR Mill
1.94	Sappi Southern Africa Limited
1.95	Sasol Infrachem Ammonia & Explosives Operations
1.96	Sasol Secunda Rail Operations
1.97	Sasol Shared Services, Division of Sasol Group Services P/L
1.98	Senwes Ltd
1.99	Shanduka Coal (Pty) Ltd
1.100	Shell SA Marketing (Pty) Ltd
1.101	Sheltam (Pty) Ltd
1.102	Sibanye Gold Limited T/A Driefontein Operation
1.103	Sishen Iron Ore Company (Pty) Ltd T/A Kolomela Mine
1.104	Sishen Iron Ore Company (Pty) Ltd T/A Thabazimbi Iron Ore Mine
1.105	Sol Plaatje Municipality
1.106	Tongaat Hulett Limited
1.107	Total SA (Pty) Ltd - Nelspruit
1.108	Total SA (Pty) Ltd - Ladysmith
1.109	Total SA (Pty) Ltd T/A Total Island View Terminal
1.110	Total SA (Pty) Ltd Polokwane
1.111	Total South Africa - Waltloo (Pty) Ltd
1.112	Trains Planes & Automobiles Cc T/A Atlantic Rail
1.113	Transnet Freight Rail, Division of Transnet Ltd
1.114	Transnet Ltd T/A Transnet National Ports Authority
1.115	Transnet Ltd T/A Transnet Port Terminals
1.116	Transnet SOC Ltd T/A Transnet Engineering
1.117	Transnet SOC Ltd T/A Transnet Pipelines
1.118	Tshipi e Ntle Manganese Mining (Pty) Ltd - Tshipi Borwa Mine

Id #	Railway Operator
1.119	Umfolozi Sugar Planters Ltd T/A UCOSP
1.120	Umgeni Steam Railway
1.121	United Manganese of Kalahari (Pty) Ltd T/A UMK
1.122	Vopak Terminal Durban P/L
1.123	Woestalleen Colliery (Pty) Ltd
2	**Class B**
2.1	African Realty Trust (Pty) Ltd
2.2	Allem Brothers (Pty) Ltd
2.3	Anglo Welsh Coal Mines
2.4	Aplorox Cc
2.5	Arcelormittal Vereeniging
2.6	Ash Resoures (Pty) Ltd
2.7	Assmang Chrome: Machadodorp Works
2.8	Astral Operations Ltd T/A Meadow Feeds
2.9	Auto Commodities (Pty) Ltd
2.10	AVENG Africa Ltd T/A Manufacturing Infraset (Brakpan)
2.11	AVENG Trident Steel
2.12	Bakara Engineering (Pty) Ltd
2.13	Barloworld Logistics Africa (Pty) Limited
2.14	Bayfibre Central Timber Cooperative
2.15	Benicon Coal (Pty) Ltd
2.16	Billiton Aluminium SA Ltd T/A Bayside Aluminium
2.17	BMW (SA) (Pty) Ltd
2.18	Botswana Ash (Pty) Ltd
2.19	Brandywine Vallery Investments (Pty) Ltd T/A Uitkomst Colliery
2.20	Breede Valley Municipality (BVM)
2.21	Bridge Intermodal (A Division of Bridge Shipping P/L)
2.22	Buffalo City Municipality
2.23	Columbus Stainless (Pty) Ltd
2.24	Consol Glass (Pty) Ltd
2.25	Crowe Brothers T/A Fairfield Estate JV
2.26	Crown Chickens (Pty) Ltd T/A Sovereign Foods
2.27	CTC Timber Products (Pty) Ltd
2.28	CTE Investments (Pty) Ltd
2.29	DCD Rolling Stock (A Division of DCD Group (Pty) Ltd)
2.30	Delta (E.M.D.) (Pty) Ltd
2.31	Dept of Defence T/A DOD Logistics Division
2.32	Distell Wadeville
2.33	Easigas (Pty) Ltd
2.34	Eastern Chrome Mines
2.35	Elandsfontein Colliery (Pty) Ltd

Id #	Railway Operator
2.36	Emnambithi/Ladysmith Municipality
2.37	Engen Petroleum Limited - Engen Witbank
2.38	Engen Petroleum Limited - Klerksdorp
2.39	Engen Petroleum Limited - Mokopane
2.40	Engen Petroleum Ltd - Rustenburg
2.41	Engen Petroleum Ltd T/A Zenex Blend Plant
2.42	Ensign Shipping & Logistics (Pty) Ltd
2.43	Epol A Division of Rainbow Farms (Pty) Ltd - Berlin
2.44	Epol A Division of Rainbow Farms (Pty) Ltd - Pietermarizburg
2.45	Epol A Division of Rainbow Farms (Pty) Ltd - PTA West
2.46	Epol A Division of Rainbow Farms (Pty) Ltd - Worcester
2.47	Ethekwini Cold Stores
2.48	Everite Building Products (Pty) Ltd
2.49	Exxaro North Block Complex T/A Exxaro Mpumalanga Glisa Colliery
2.50	Feltex Holdings P/L T/A Brenner Mills P/L
2.51	Ferrometals (A Division of Samancor Chrome Ltd Kermas)
2.52	Flamite (Pty) Limited
2.53	Foodcorp Consumer Brands Milling Division
2.54	Ford Motor Company Of Southern Africa (Manufacturing) (Pty) Ltd
2.55	FPT Group P/L (Durban)
2.56	FPT Group P/L (PE)
2.57	FPT Group P/L (Cape Town)
2.58	General Motors SA P/L T/A GMSA
2.59	George Municipality
2.60	Gledhow Sugar Co P/L
2.61	Glen Douglas Dolomite Mine (Pty) Ltd
2.62	Glencore Operations Alloys Lydenburg Works
2.63	Glencore Operations South Africa (Pty) Ltd Rustenburg Works
2.64	Glencore Operations South Africa (Pty) Ltd Wonderkop Smelter
2.65	Golfview Mining (Pty) Ltd
2.66	Gordonia Mills (Pty) Ltd
2.67	Greystones Enterprises
2.68	Grindrod Intermodal
2.69	Grindrod SA (Pty) Ltd T/A Grindrod Terminals (Maydon Wharf)
2.70	GWK Limited
2.71	Mister Bread Milling P/L
2.72	Moorreesburgse Koringboere (Pty) Ltd
2.73	Mpact Paper Ltd - Felixton Mill
2.74	MSC Depots
2.75	Msunduzi Municipality
2.76	Naledi Rail Engineering

Id #	Railway Operator
2.77	National Department of Public Works
2.78	NCT Durban Woodchips (Pty) Ltd
2.79	Nelson Mandela Bay Municipality
2.80	Newcastle Municipality
2.81	Nissa SA (Pty) Ltd
2.82	Nitrophoska (Pty) Ltd
2.83	Nkomazi Municipality
2.84	Northern Coal (Pty) Ltd
2.85	NTK Limpopo Agric (Pty) Ltd
2.86	NWK Limited
2.87	Nzenga Investments P/L
2.88	Omnia Group (Pty) Ltd T/A Protea Chemicals Cape
2.89	OMV Crushers
2.90	Otgcterminals (Pty) Ltd
2.91	Overberg Agri Bedrywe P/L
2.92	OVK Bedryf Beperk
2.93	Paramount Mills (Pty) Ltd
2.94	Plasser South Africa (Pty) Ltd
2.95	Premier Foods Limited
2.96	Pretoria Metal Pressing (A Division of Denel SOC Ltd)
2.97	Profile Feeds P/L
2.98	Protank (Pty) Ltd T/A Indian Ocean Terminals
2.99	Puregas (Pty) Ltd
2.100	Racec Rail (Pty) Limited
2.101	Reatile Timrite T/A Reatile Timrite Mine Support Products
2.102	Rheinmetall Denel Munition (Pty) Ltd
2.103	Rhino Minerals P/L T/A Rhino Andalusite Mine
2.104	Royal Salt Company (Pty) Ltd
2.105	RRL Grindrod Locomotives P/L
2.106	SA Bulk Commodity Trading And Storage Services (Pty) Ltd
2.107	SA Container Depot Freigth - City Deep
2.108	SA Container Depot Freigth - Durban
2.109	SA Feed Phosphates (Pty) Ltd
2.110	Safripol (Pty) Ltd
2.111	Saint-Gobain Construction Products SA (Pty) Ltd
2.112	Saint-Gobain Gyproc SA (Pty) Ltd T/A Gyproc
2.113	Samancor Tubatse Chrome
2.114	Samancor Western Chrome Mines T/A Samancor Ltd
2.115	Samquarz (Pty) Ltd
2.116	SATI Container Services (Pty) Ltd - Cape Town
2.117	SATI Container Services Jhb (Pty) Ltd

Id #	Railway Operator
2.118	SCAW South Africa (Pty) Ltd
2.119	Seawind Investments 15 (Pty) Ltd
2.120	Senmin International (Pty) Ltd
2.121	Sentraal Suid Co-Operative Ltd - Swellendam
2.122	Shell & BP SA Petroleum Refineries (Pty) Ltd - SAPREF
2.123	Shincel (Pty) Ltd
2.124	Siyazi Technology (Pty) Ltd
2.125	South African Breweries: Prospecton
2.126	South African Breweries: Ibhayi -Brewery
2.127	South African Breweries: Maltings - Alrode
2.128	South African Breweries: Newlands Brewery
2.129	Sturrock & Robson Industries T/A Martin And Robson
2.130	Suidwes Landbou (Edms) BPK
2.131	Sumo Coal (Pty) Limited
2.132	The New Reclamation Group P/L
2.133	The South African Breweries Limited: Rosslyn
2.134	The South African Breweries Limited: Nelspruit
2.135	The South African Breweries Maltings
2.136	The South African Breweries: Bloemfontein
2.137	The South African Breweries: Kimberley
2.138	The South African Breweries: Polokwane
2.139	Transalloys (Pty) Ltd
2.140	Tronox Mineral Sands Pty Ltd T/A Tronox Namakwa Sands - (Mineral Separation Plant)
2.141	Tronox Mineral Sands Pty Ltd T/A Tronox Namakwa Sands - (Smelter)
2.142	TSB Sugar RSA Limited
2.143	TWK Agriculture Limited
2.144	KLK Petroleum Verspreiders (EDMS) Park
2.145	Kynoch Fertilizer (A Division of Farmisco (Pty) Ltd)
2.146	Lafarge Industries South Africa
2.147	Lanxess CISA (Pty) Ltd
2.148	Lanxess Merebank
2.149	Lennings Rail Services (Pty) Ltd
2.150	Lesotho Milling Co P/L
2.151	Lime Distributors (Pty) Ltd
2.152	Lion Match Products (Pty) Ltd
2.153	Lukhanji Municipality
2.154	Lyttelton Dolomite (Pty) Ltd
2.155	Macdonald's Transport Upington T/A Macdonald's Transport & Warehousing
2.156	Macsteel Service Centers SA P/L
2.157	Manganese Metal Company (Pty) Ltd
2.158	Masonite Africa Limited

Id #	Railway Operator
2.159	McPhail Distributors (Pty) Ltd
2.160	MGK Operating Company T/A Prodsure
2.161	Middelburg Ferrochrome (MFC) (A Business Unit of Samancor Chrome Ltd)
2.162	Tzaneng Treated Timbers (Proprietary) Limited
2.163	Umtshezi Local Municipality
2.164	Unilever South Africa P/L
2.165	Union Carriage & Wagon (Pty) Ltd T/A UCW
2.166	Validtrade 2013 Cc
2.167	Veekos (Pty) Ltd Now Feedmaster
2.168	VKB Landbou Ltd
2.169	Voestalpine VAE SA P/L
2.170	Wictra Holdings P/L
2.171	Witkop Fluospar Mine (Pty) Ltd
2.172	Xstrata-Merafe Venture Boshoek Works
2.173	Yeastpro
2.174	Zululand Anthracite Colliery
2.175	A.M. Alberts (Pty) Ltd T/A Progress Milling
2.176	Afgri Operations Ltd T/A Afgri Animal Feeds
2.177	African Hide Trading (Pty) Ltd
2.178	African Oxygen Limited T/A Afrox
2.179	Heartland Leasing (Pty) Ltd
2.180	Hernic Ferrochrome P/L
2.181	Hulamin Limited
2.182	Idwala Industrial Holdings (Pty) Ltd
2.183	Illovo Sugar Ltd SA Ltd - Noodsberg
2.184	Impala Platinum Refineries
2.185	Industrial Locomotive Services Cc
2.186	Jindal Mining
2.187	JLR Services And Warehousing Cc
2.188	Kaap Agri (Pty) Ltd
2.189	Keaton Energy T/A Vaalkrantz Colliery
2.190	Kelvin Power (Pty) Ltd
3	**Crossborder (Class A Operators)**
3.1	Botswana Railways
3.2	Mozambique Ports & Railways T/A CFM
3.3	Swaziland Railways

Appendix D : Common Defects on Tunnels Concrete Elements

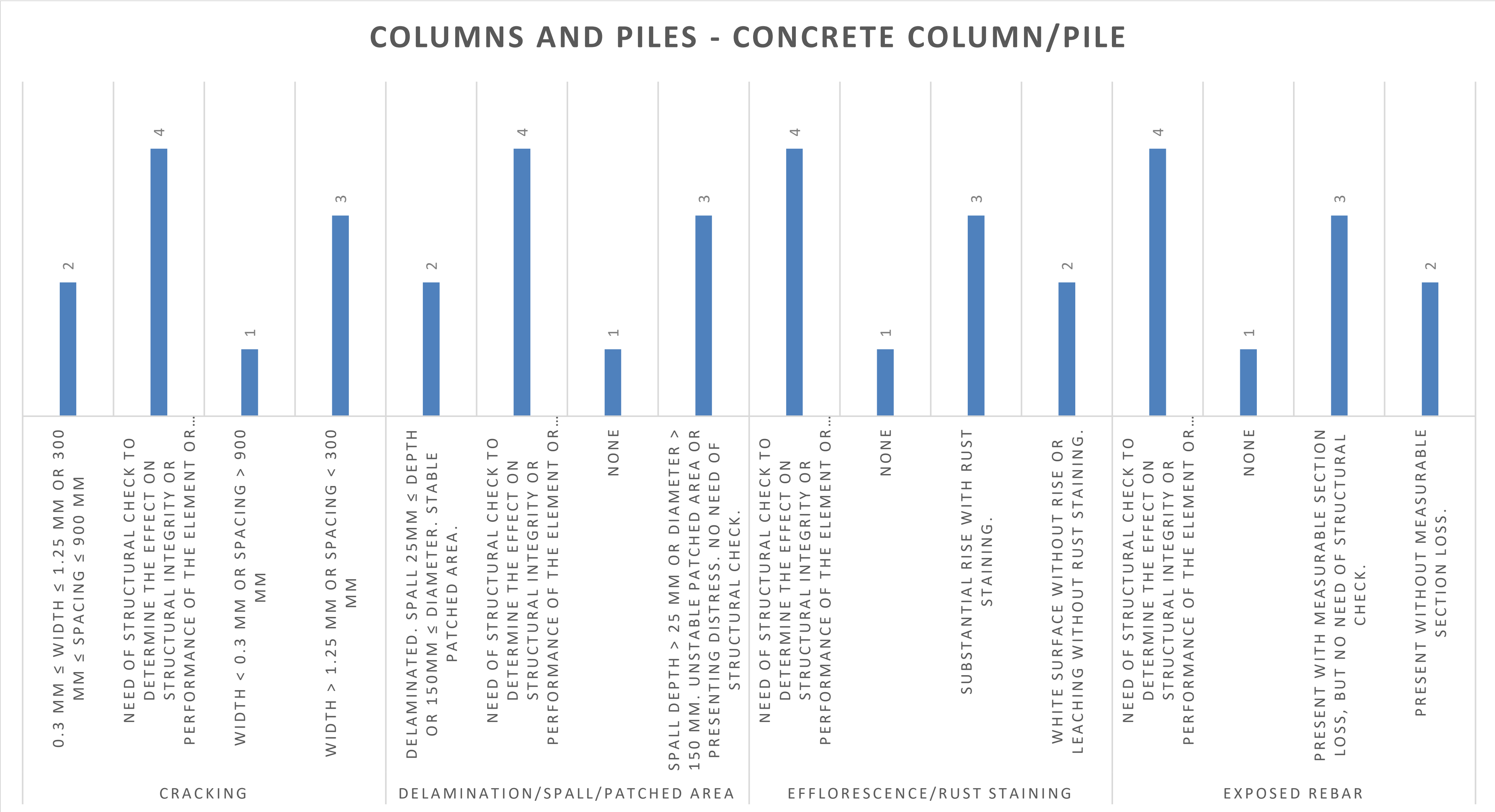

Figure D-1: Common Defects on Tunnel Concrete Columns/Piles

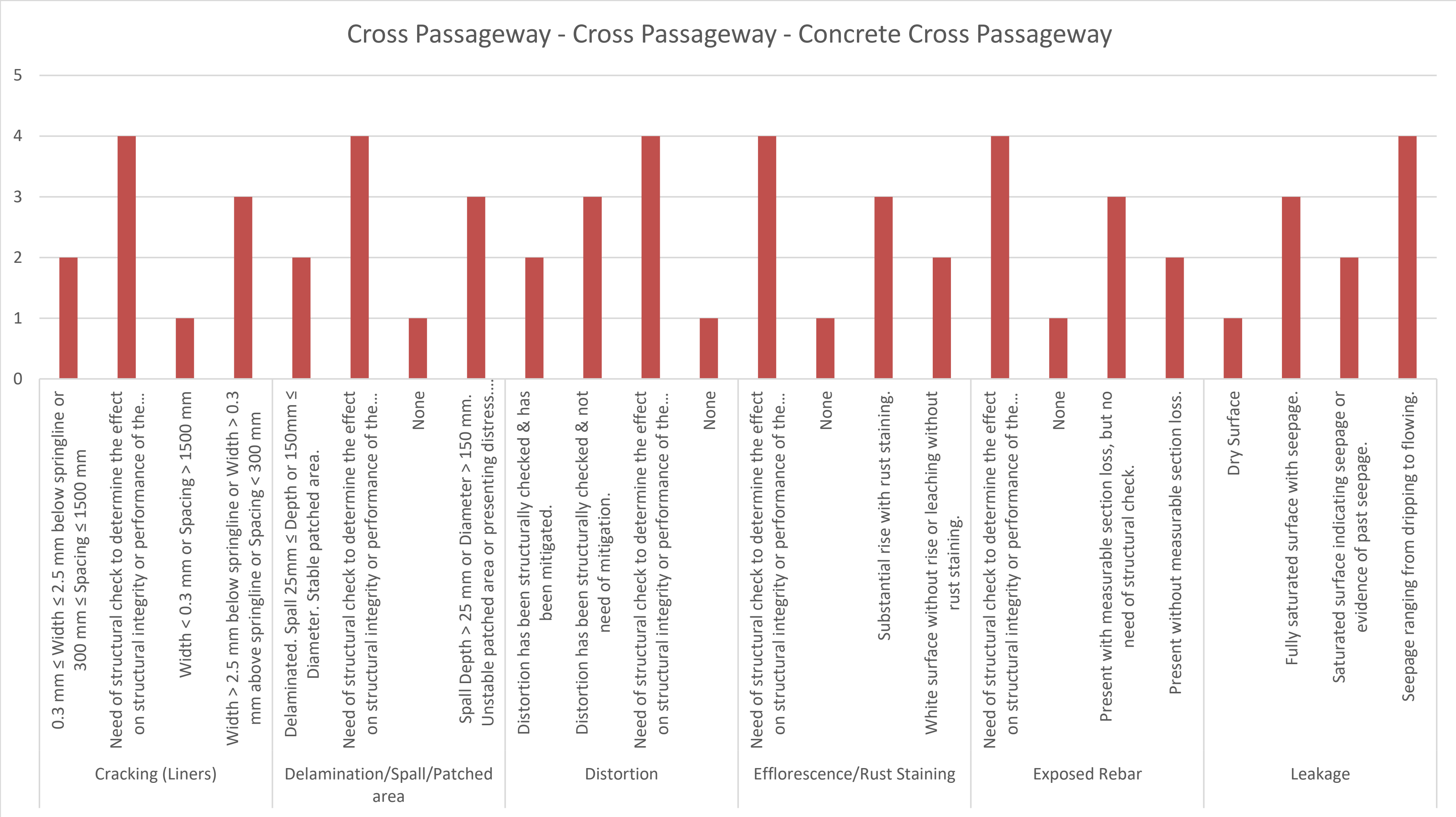

Figure D-2: Common Defects on Tunnel Concrete Cross Passageways

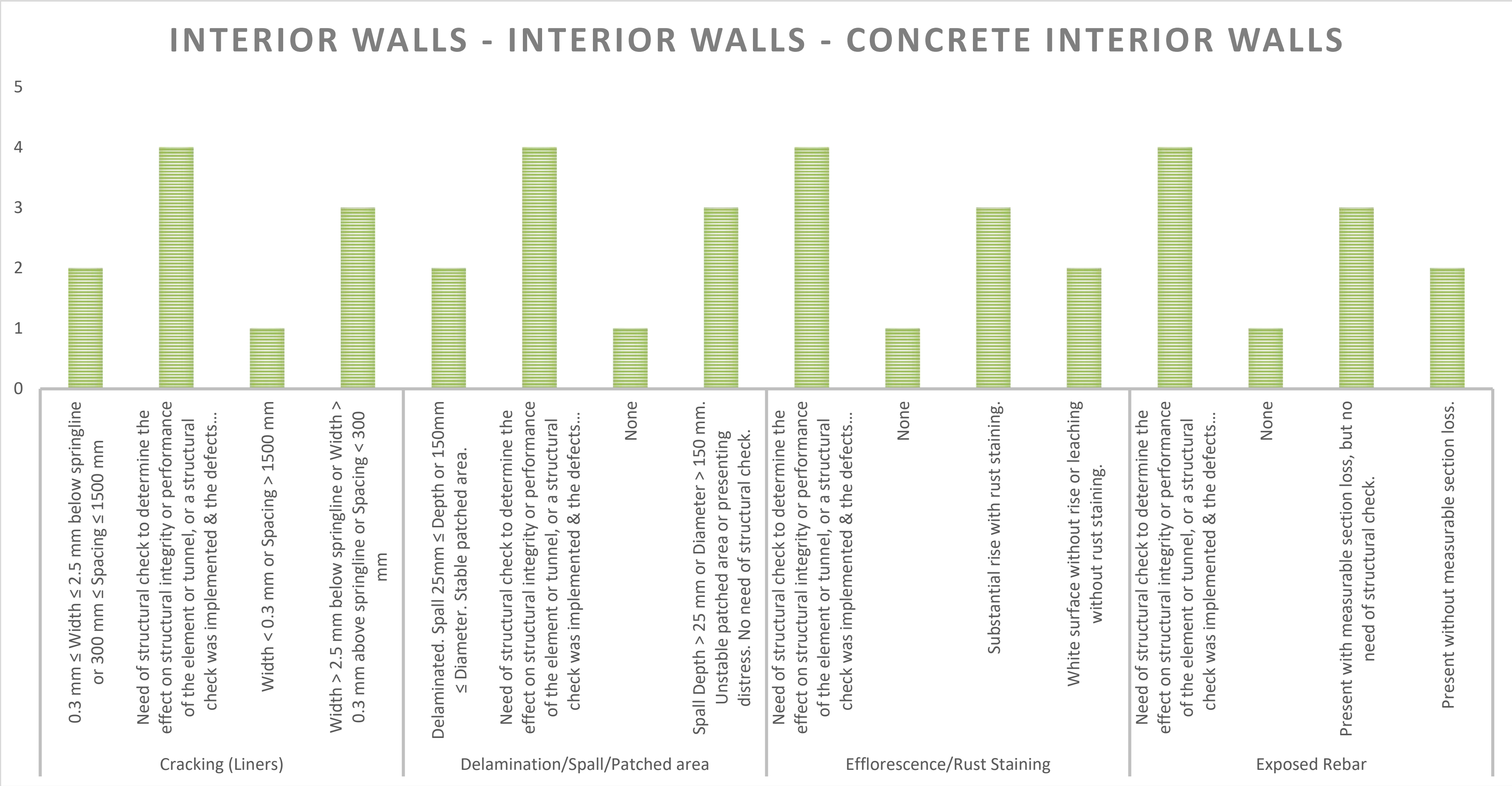

Figure D-3: Common Defects on Tunnel Concrete Interior Walls

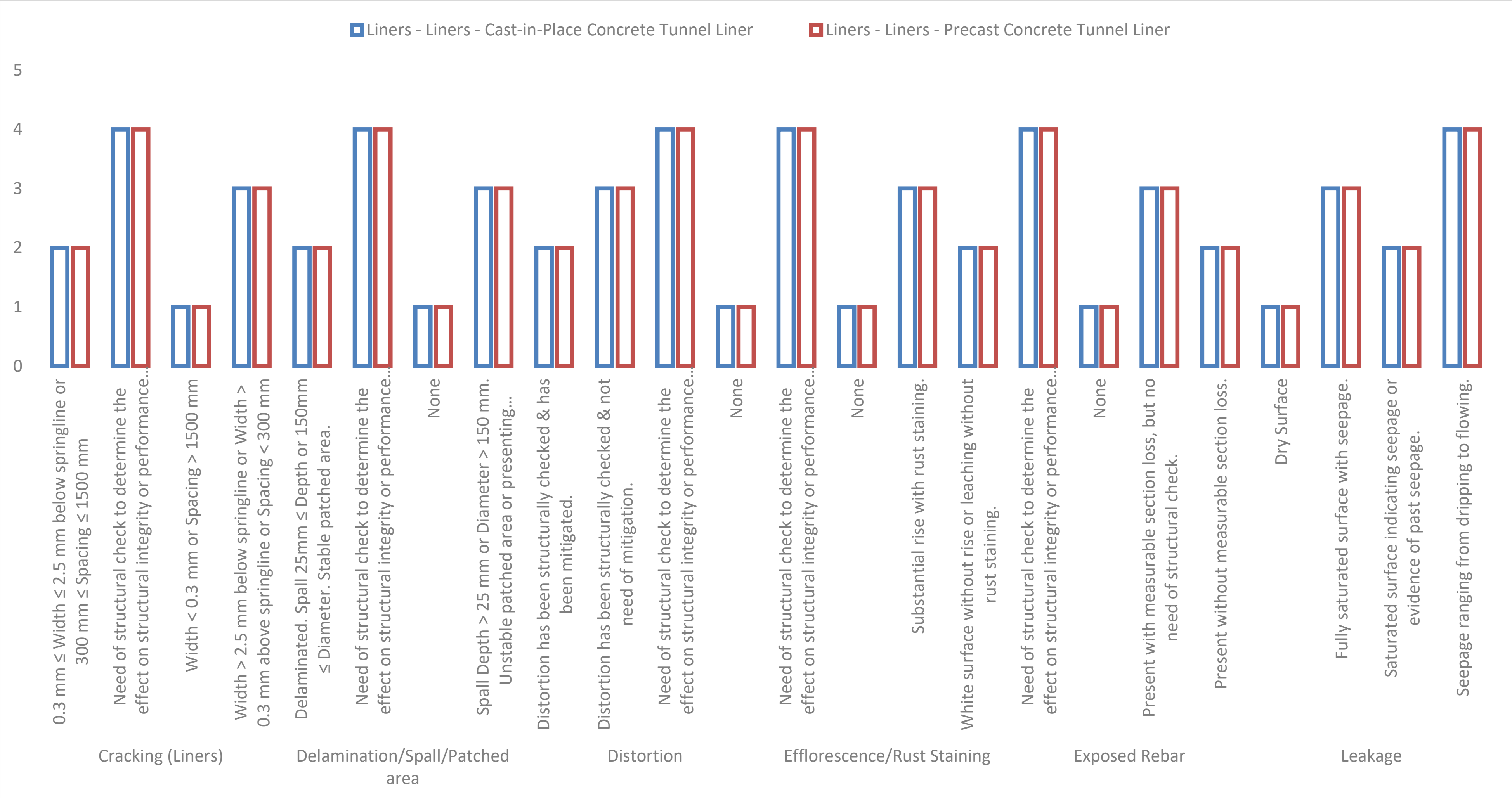

Figure D-4: Common Defects on Tunnel Cast-in-Place / Precast Concrete Tunnel Liners

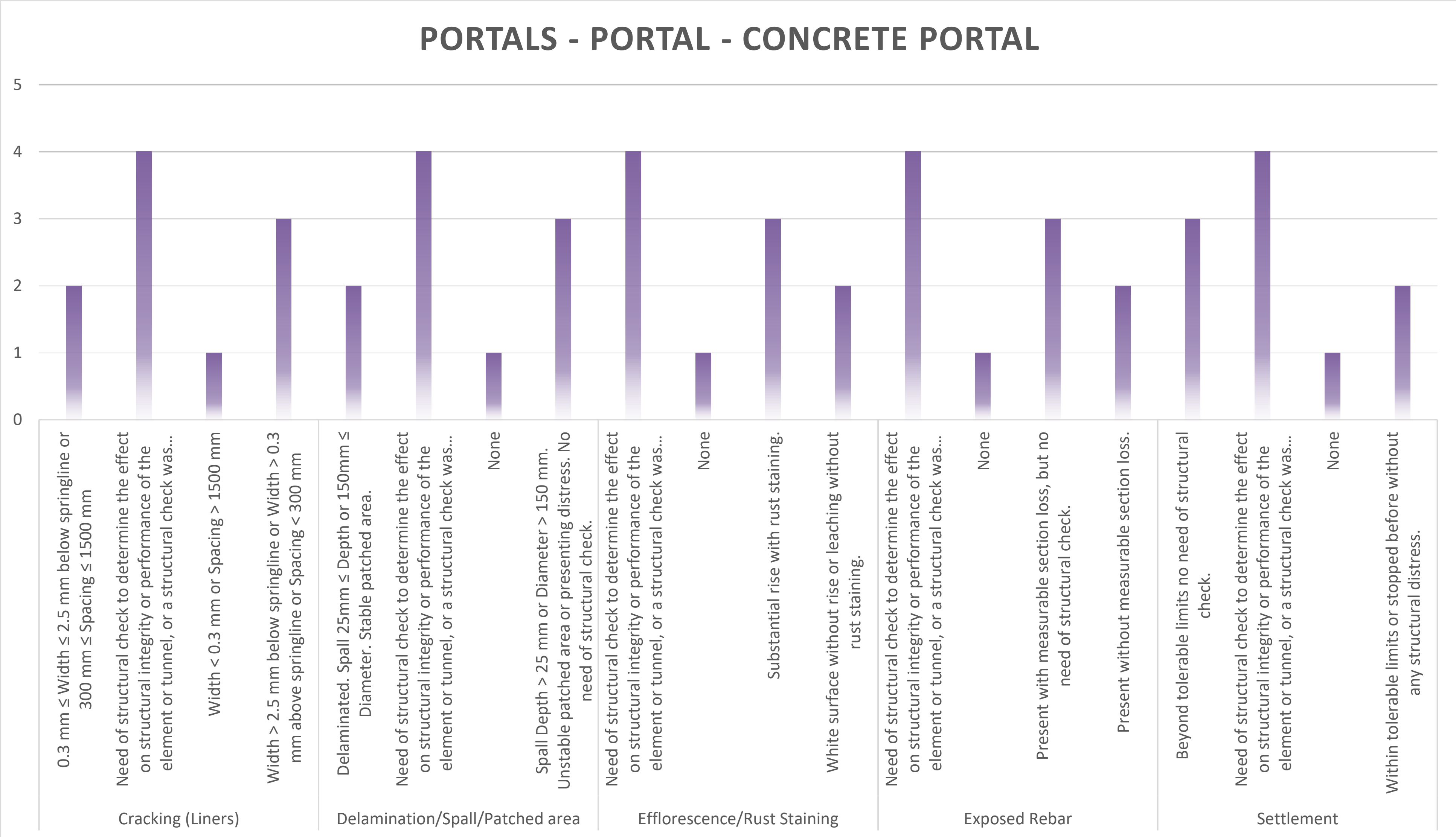

Figure D-5: Common Defects on Tunnel Concrete Portals

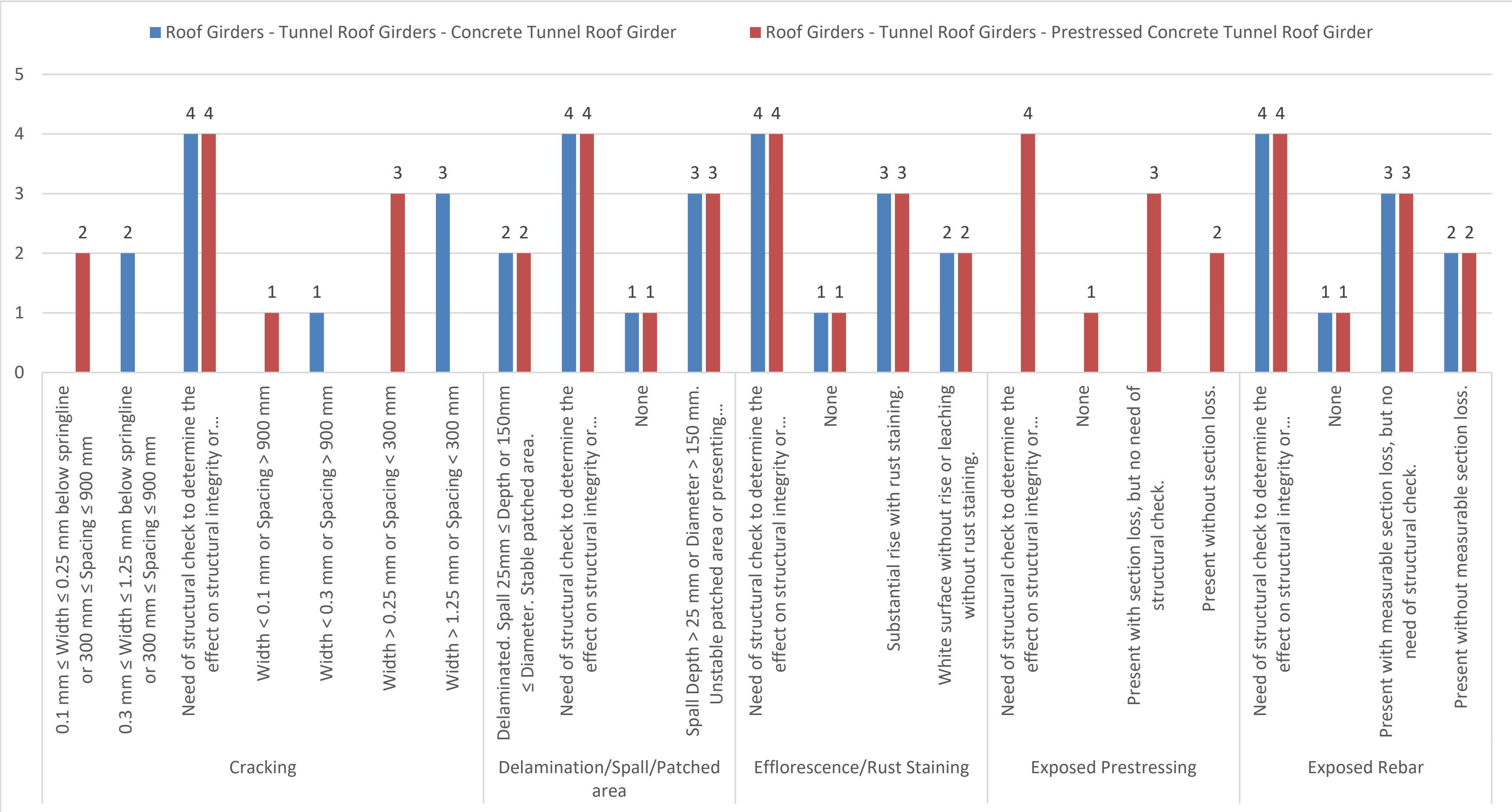

Figure D-6: Common Defects on Concrete (Prestressed) Tunnel Roof Girder

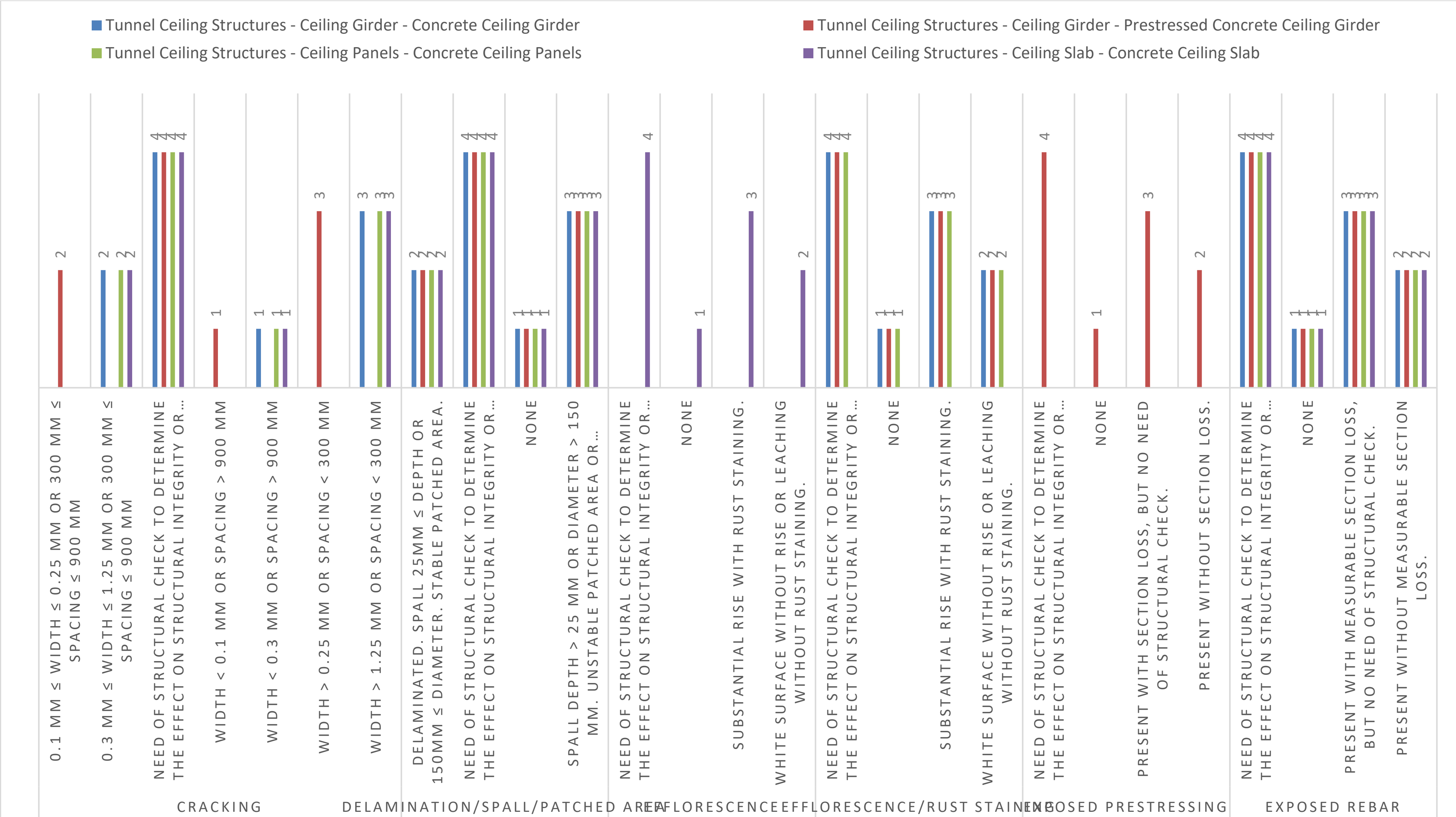

Figure D-7: Common Defects on Tunnel Ceiling Structures

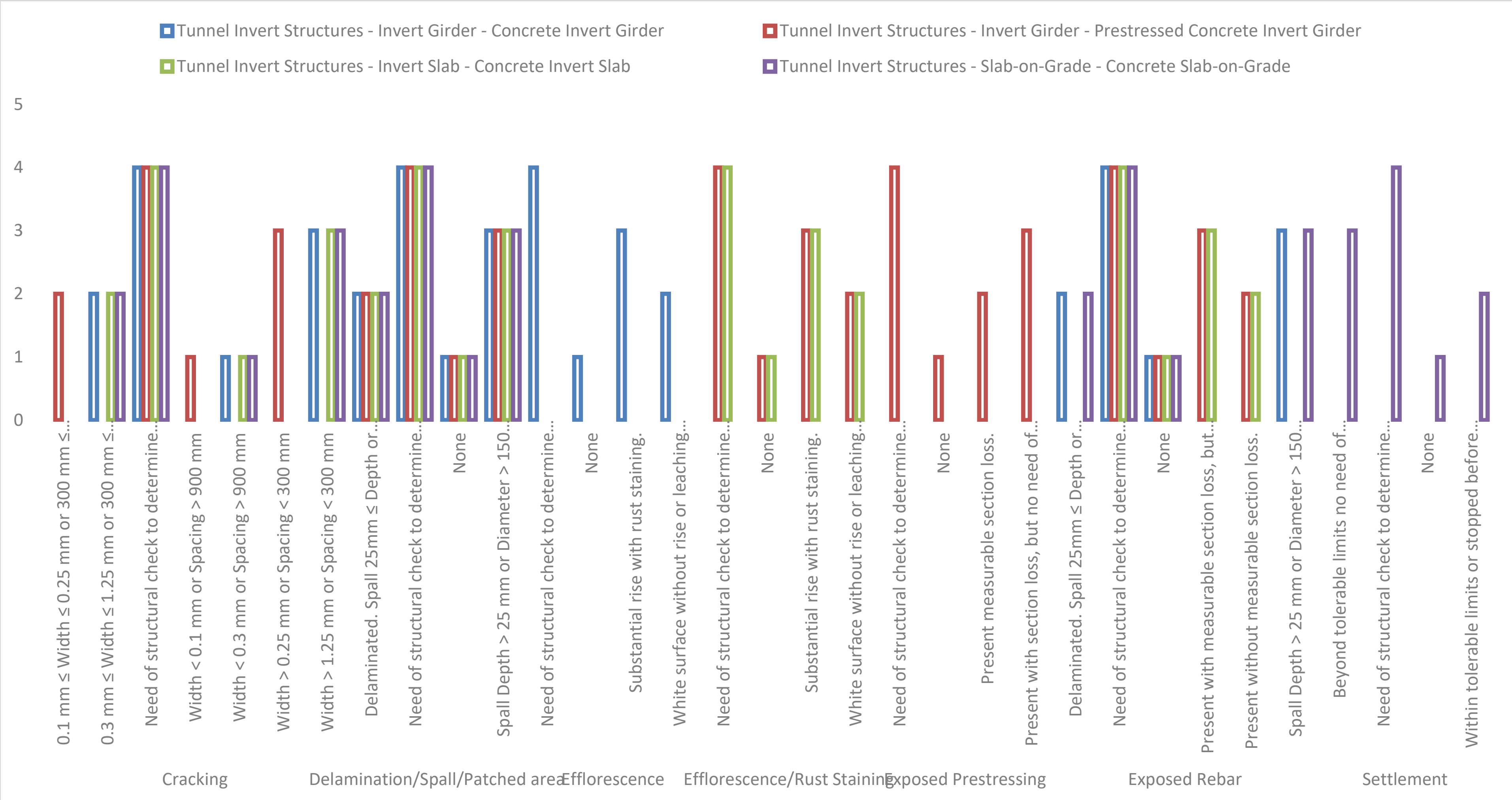

Figure D-8: Common Defects on Tunnel Invert Structures

Appendix E: Description of the Defects

Table E-1: Description of Defects

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
Cracking: Committee of Transport Officials (2016: 5-3) define the crack width ranges for structural concrete	0.1 mm ≤ Width ≤ 0.25 mm below springline or 300 mm ≤ Spacing ≤ 900 mm								2							
	0.1 mm ≤ Width ≤ 0.25 mm or 300 mm ≤ Spacing ≤ 900 mm										2				2	
	0.3 mm ≤ Width ≤ 1.25 mm below springline or 300 mm ≤ Spacing ≤ 900 mm							2								
	0.3 mm ≤ Width ≤ 1.25 mm or 300 mm ≤ Spacing ≤ 900 mm	2								2		2	2	2		2
	Need of structural check to determine the effect on structural integrity or performance of the element or	4						4	4	4	4	4	4	4	4	4

Crack Description	***Width***
Hairline	*<0.1mm*
Narrow	*0.1 – 0.3 mm*

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
Medium — *0.3 – 0.7 mm* *Wide* — *> 0.7 mm*	tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.															
The design of *reinforced concrete* structures considers their cracking under tensile stresses. Therefore, *some cracks do not present any threat to the structural integrity of the element affected or the whole structure*, and are not of concern. Owens (2009: 156) states that the effects of cracking can speed up environmental deterioration as cracks may accelerate ingress of harmful substances into the concrete. For crack widths	Width < 0.1 mm or Spacing > 900 mm								1		1				1	
	Width < 0.3 mm or Spacing > 900 mm	1						1		1		1	1	1		1
	Width > 0.25 mm or Spacing < 300 mm								3		3				3	
	Width > 1.25 mm or Spacing < 300 mm	3						3		3		3	3	3		3

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
≥0.15mm on prestressed concrete, an assessment of the exposure of the prestressing steel to ASR is required.																
Cracking (Liners) Fresh concrete cracks are due to settlement and bleeding, plastic shrinkage, slump loss, while creep, drying shrinkage, alkali-aggregate reaction, thermal contraction, corrosion of reinforcement provoke cracks in hardened concrete, etc.	0.3 mm ≤ Width ≤ 2.5 mm below springline or 300 mm ≤ Spacing ≤ 1500 mm		2	2	2	2	2									
	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.		4	4	4	4	4									
	Width < 0.3 mm or Spacing > 1500 mm		1	1	1	1	1									

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	Width > 2.5 mm below springline or Width > 0.3 mm above springline or Spacing < 300 mm		3	3	3	3	3									
Delamination: separation of a surface layer of concrete from the member mass, caused mainly by corrosion of reinforcement or fire. **Spall**: formed when delaminated concrete is removed. **Patched area**	Delaminated. Spall 25mm ≤ Depth or 150mm ≤ Diameter. Stable patched area.	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	Spall Depth > 25 mm or Diameter > 150 mm. Unstable patched area or presenting distress. No need of structural check.	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Distortion	Distortion has been structurally checked & has been mitigated.		2		2	2										
	Distortion has been structurally checked & not need of mitigation.		3		3	3										
	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural		4		4	4										

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	integrity & the performance of the element of tunnel.															
	None		1		1	1										
Efflorescence: identified when white deposits appear from leached out concrete. It is due to movement of salts in solution to the surface of the concrete where they form into crystals (mostly on the deck soffit). Efflorescence does not have an impact on the durability of concrete elements.	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.												4	4		
	None												1	1		
	Substantial rise with rust staining.												3	3		
	White surface without rise or leaching without rust staining.												2	2		

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
Efflorescence: / **Rust Staining**	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.	4	4	4	4	4	4	4	4	4	4	4			4	4
	None	1	1	1	1	1	1	1	1	1	1	1			1	1
	Substantial rise with rust staining.	3	3	3	3	3	3	3	3	3	3	3			3	3
	White surface without rise or leaching without rust staining.	2	2	2	2	2	2	2	2	2	2	2			2	2
Exposed Prestressing:	Need of structural check to determine the effect on structural integrity or performance of the element or								4		4				4	

Defect Name & Description	**Defect Evaluation**	**Concrete Column/Pile**	**Concrete Cross Passageway**	**Concrete Interior Walls**	**Cast-in-Place Concrete Tunnel Liner**	**Precast Concrete Tunnel Liner**	**Concrete Portal**	**Concrete Tunnel Roof Girder**	**Prestressed Concrete Tunnel Roof Girder**	**Concrete Ceiling Girder**	**Prestressed Concrete Ceiling Girder**	**Concrete Ceiling Panels**	**Concrete Ceiling Slab**	**Concrete Invert Girder**	**Prestressed Concrete Invert Girder**	**Concrete Invert Slab**
	tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.															
	None								1		1				1	
	Present measurable section loss.														2	
	Present with section loss, but no need of structural check.								3		3				3	
	Present without section loss.								2		2					
Exposed Rebar	Delaminated. Spall 25mm ≤ Depth or 150mm ≤ Diameter. Stable patched area.													2		
	Need of structural check to determine the effect on structural integrity or performance of the element or	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.															
	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Present with measurable section loss, but no need of structural check.	3	3	3	3	3	3	3	3	3	3	3	3		3	3
	Present without measurable section loss.	2	2	2	2	2	2	2	2	2	2	2	2		2	2
	Spall Depth > 25 mm or Diameter > 150 mm. Unstable patched area or presenting distress. No need of structural check.													3		
Leakage	Dry Surface		1		1	1										

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	Fully saturated surface with seepage.		3		3	3										
	Saturated surface indicating seepage or evidence of past seepage.		2		2	2										
	Seepage ranging from dripping to flowing.		4		4	4										
Settlement	Beyond tolerable limits no need of structural check.						3									
	Need of structural check to determine the effect on structural integrity or performance of the element or tunnel, or a structural check was implemented & the defects affect the structural integrity & the performance of the element of tunnel.						4									

Defect Name & Description	Defect Evaluation	Concrete Column/Pile	Concrete Cross Passageway	Concrete Interior Walls	Cast-in-Place Concrete Tunnel Liner	Precast Concrete Tunnel Liner	Concrete Portal	Concrete Tunnel Roof Girder	Prestressed Concrete Tunnel Roof Girder	Concrete Ceiling Girder	Prestressed Concrete Ceiling Girder	Concrete Ceiling Panels	Concrete Ceiling Slab	Concrete Invert Girder	Prestressed Concrete Invert Girder	Concrete Invert Slab
	None						1									
	Within tolerable limits or stopped before without any structural distress.						2									

Appendix F: List of Railway Tunnels in South Africa

Table F-1: Railway Tunnels in South Africa

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
A 01	107	Alicedale-Stonehaven: Tunnel No 1 107m	Eastern Cape	1879	Drill and Blast
A 02	77	Atherstone-Coldspring: Tunnel No 2 77m	Eastern Cape	1879	Drill and Blast
A 03	69	Aliwal North-Barkly East: "Fourth Reserve" Tunnel 69m	Eastern Cape	1911	Drill and Blast
A 05	370	Alicedale-Doringkom: Tunnel No 2 370m	Eastern Cape	1940	Drill and Blast
B 02	123	Brereton Ridge: Down Tunnel 123m	KwaZulu Natal	1917	Drill and Blast
B 03	174	Bomvas: Up Tunnel 174m	KwaZulu Natal	1917	Drill and Blast
B 05	174	Bomvas: Down Tunnel 174m	KwaZulu Natal	1933	Drill and Blast
B 06	119	Brereton Ridge Up 119m	KwaZulu Natal	1933	Drill and Blast
B 12	224	Bangor-Sherborne: Tunnel No 15 224m	Eastern Cape	1959	Drill and Blast
B 13	869	Balfour: Down Tunnel 869m	Mpumalanga	1960	Drill and Blast
B 23	869	Balfour: Up Tunnel 869m	Mpumalanga	1977	Drill and Blast
C 02	258	Coldspring-Westhill: Tunnel No 3 258m	Eastern Cape	1879	Drill and Blast
C 03	190	Ceres Tunnel 190m	Western Cape	1912	Drill and Blast
C 06	349	Cliffdale: Up Tunnel 349m	KwaZulu Natal	1933	Drill and Blast
C 07	976	Cathcart-Goshen: Tunnel No 11 976m	Eastern Cape	1944	Drill and Blast
C 08	679	Cathcart-Goshen: Tunnel No 10 679m	Eastern Cape	1945	Drill and Blast
C 12	183	Camp-Imvani: Tunnel No 12 183m	Eastern Cape	1946	Drill and Blast
C 13	111	Camp-Imvani: Tunnel No 13 111m	Eastern Cape	1947	Drill and Blast
C 16	1616	Carlton-Barradeel: Tunnel No 16 1616m	Northern Cape	1960	Drill and Blast
D 04	241	Dassenhoek Up Tunnel 241m	KwaZulu Natal	1919	Drill and Blast
D 05	292	Duff's Road: Seaward Tunnel 292m	KwaZulu Natal	1923	Drill and Blast

Record #	Tunnel Length_m	Tunnel Name	Province	Year Completed	Construction Method
D 07	241	Dassenhoek Down Tunnel 241m	KwaZulu Natal	1932	Drill and Blast
D 08	516	Dohne-Fort Cunynghame: Tunnel No 2 516m	Eastern Cape	1940	Drill and Blast
E 04	259	Eagles Crag-Boesmanspoort : Tunnel No 1 259m	Eastern Cape	1934	Drill and Blast
E 05	247	Escourt : Up Tunnel 247m	KwaZulu Natal	1952	Drill and Blast
E 06	247	Escourt : Down Tunnel 247m	KwaZulu Natal	1952	Drill and Blast
G 02	220	Groenheuwals-Saltaire : Tunnel No 5 220m	Eastern Cape	1952	Drill and Blast
G 04	801	Groenheuwals-Saltaire : Tunnel No 6 801m	Eastern Cape	1954	Drill and Blast
G 05	385	George-Boulders No 6 Tunnel 385m	Mpumalanga	1965	Drill and Blast
H 08	260	Haig 260m	KwaZulu Natal	1928	Drill and Blast
J 03	450	Jantingh Tunnel 450m	Northern Province	1966	Drill and Blast
K 04	198	Kenville - Seaward Tunnel 198m	KwaZulu Natal	1923	Drill and Blast
K 05	600	Klipfontein - Witmos: Tunnel No 11 600m	Eastern Cape	1955	Drill and Blast
K 07	310	Koppie Alleen : Down Tunnel 310m	Mpumalanga	1959	Drill and Blast
K 16	1462	Kraal: Down Tunnel 1462m	Mpumalanga	1960	Drill and Blast
K 31	310	Koppie Alleen : Up Tunnel 310m	Mpumalanga	1979	Drill and Blast
L 02	60	Le Roux Tunnel 60m	Western Cape	1903	Drill and Blast
L 03	167	Little Manzini Down Tunnel 167m	KwaZulu Natal	1917	Drill and Blast
L 04	243	Lidgeton : Up Tunnel 243m	KwaZulu Natal	1923	Drill and Blast
L 05	167	Little Manzini : Up Tunnel 167m	KwaZulu Natal	1933	Drill and Blast
L 06	243	Lidgeton : Down Tunnel 243m	KwaZulu Natal	1948	Drill and Blast
M 01	400	Manzini : Up Tunnel 400m	KwaZulu Natal	1917	Drill and Blast
M 02	69	Mamba Down Tunnel 69m	KwaZulu Natal	1918	Drill and Blast
M 03	424	Mount Edgecombe (Mushroom) Tunnel 424m	KwaZulu Natal	1922	Drill and Blast
M 05	400	Manzini : Down Tunnel 400m	KwaZulu Natal	1933	Drill and Blast
M 06	200	Mount Prospect Tunnel 200m	KwaZulu Natal	1938	Drill and Blast

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
M 13	304	Mkhuhlu-Ireagh : Tunnel 7 304m	Mpumalanga	1971	Drill and Blast
N 01	648	Nshongweni : Down Tunnel 648m	KwaZulu Natal	1917	Drill and Blast
N 06	648	Nshongweni : Up Tunnel 648m	KwaZulu Natal	1933	Drill and Blast
N 07	218	Newark Tunnel 218m	KwaZulu Natal	1934	Drill and Blast
N 09	1047	Nelland-Drennan : Tunnel No 12 1047m	Eastern Cape	1957	Drill and Blast
O 03	314	Ondervalle-Waterval Onder : Tunnel 3 314m	Mpumalanga	1964	Drill and Blast
P 06	728	Palmford : Down Tunnel 728m	Mpumalanga	1959	Drill and Blast
P 07	843	Pentrick : No 5 Up Tunnel 843m	KwaZulu Natal	1964	Drill and Blast
P 08	843	Pentrick : No 5 Down Tunnel 843m	KwaZulu Natal	1964	Drill and Blast
P 18	728	Palmford : Up Tunnel 728m	Mpumalanga	1978	Drill and Blast
R 06	724	Rosetta : Down Tunnel 724m	KwaZulu Natal	1953	Drill and Blast
S 03	95	Shallcross : Down Tunnel 95m	KwaZulu Natal	1918	Drill and Blast
S 09	95	Shallcross : Up Tunnel 95m	KwaZulu Natal	1932	Drill and Blast
S 10	321	Stutterheim-Dohne : Tunnel No 1 321m	Eastern Cape	1940	Drill and Blast
S 11	415	Surbiton-Gaika : Tunnel No 9 415m	Eastern Cape	1946	Drill and Blast
S 15	140	Stompdrift Tunnel 140m	Western Cape	1962	Drill and Blast
S 44	217	Steenbras 217m	Western Cape	1902	Drill and Blast
T 02	137	Topping-Power : Tunnel No 3 137m	Western Cape	1911	Drill and Blast
T 03	209	Topping-Power : Tunnel No 4 209m	Western Cape	1911	Drill and Blast
T 04	96	Topping-Power : Tunnel No 5 96m	Western Cape	1911	Drill and Blast
T 05	60	Topping-Power : Tunnel No 6 60m	Western Cape	1911	Drill and Blast
T 06	119	Topping Tunnel No 7 119m	Western Cape	1911	Drill and Blast
T 08	252	Tweedie : Up Tunnel 252m	KwaZulu Natal	1923	Drill and Blast
T 10	381	Thomas River-Surbiton : Tunnel No 6 381m	Eastern Cape	1941	Drill and Blast
T 11	393	Thomas River-Surbiton : Tunnel No 7 393m	Eastern Cape	1941	Drill and Blast

Record #	Tunnel Length_m	Tunnel Name	Province	Year Completed	Construction Method
T 12	538	Toise-Thomas River : Tunnel No 4 538m	Eastern Cape	1942	Drill and Blast
T 13	221	Thomas River-Surbiton : Tunnel No 5 221m	Eastern Cape	1942	Drill and Blast
T 15	252	Tweedie : Down Tunnel 252m	KwaZulu Natal	1945	Drill and Blast
T 16	395	Thorngrove-Klipfontein : Tunnel No 10 395m	Eastern Cape	1955	Drill and Blast
U 37	242	Umgeni : Inland Tunnel 242m	KwaZulu Natal	1961	Drill and Blast
V 12	35	Victoria Bay-Wilderness : Tunnel No 1 35m	Western Cape	1925	Drill and Blast
V 14	76	Victoria Bay-Wilderness : Tunnel No 3 76m	Western Cape	1925	Drill and Blast
V 17	539	Verulam : No 5 Inland 539m	KwaZulu Natal	1961	Drill and Blast
V 28	782	Van Reenen : No 7 782m	KwaZulu Natal	1958	Drill and Blast
V 29	361	Van Reenen : No 8 361m	KwaZulu Natal	1959	Drill and Blast
V 30	1021	Van Reenen : No 9 1021m	KwaZulu Natal	1959	Drill and Blast
W 03	67	Waterpoort Tunnel 67m	Northern Province	1913	Drill and Blast
A 11	644	Ashburton : No 3 Up Tunnel 644m	KwaZulu Natal	1964	Drill and Blast
A 12	644	Ashburton : No 3 Down Tunnel 644m	KwaZulu Natal	1964	Drill and Blast
A 13	1311	Ashburton : No 4 Up Tunnel 1311m	KwaZulu Natal	1964	Drill and Blast
A 14	1311	Ashburton : No 4 Down Tunnel 1311m	KwaZulu Natal	1964	Drill and Blast
B 07	403	Boscobello (BOCHABELLO TUNNEL) 403m	KwaZulu Natal	1937	Drill and Blast
C 04	349	Cliffdale: Down Tunnel 349m	KwaZulu Natal	1917	Drill and Blast
C 05	152	Clova Tunnel (Clove Loop) 152m	KwaZulu Natal	1925	Drill and Blast
C 15	406	Cypress Grove-Conway: Tunnel No 14 406m	Eastern Cape	1958	Drill and Blast
D 03	914	Delville Wood: Up Tunnel. 914m	KwaZulu Natal	1917	Drill and Blast
D 06	915	Delville Wood: Down Tunnel. 915m	KwaZulu Natal	1933	Drill and Blast
D 15	483	De Doorns No 1A (Up line) 483m	Western Cape	1976	Drill and Blast
D 16	483	De Doorns No 1B (Up line) 483m	Western Cape	1976	Drill and Blast
G 01	235	Garter Tunnel 235m	KwaZulu Natal	1918	Drill and Blast

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
G 13	473	Georges Valley Railway Tunnel (Tzaneen No 1) 473m	Northern Province	1975	Drill and Blast
H 02	831	Hilton Road Tunnel 831m	KwaZulu Natal	1916	Drill and Blast
H 11	843	Halesowen-Cradock : Tunnel No 13 843m	Eastern Cape	1958	Drill and Blast
I 01	556	Ingogo Tunnel 556m	KwaZulu Natal	1937	Drill and Blast
I 04	484	Ilangakazi-Intsamanzi Line 1 - Tunnel No 11 (ILANGAKAZI) 484m	KwaZulu Natal	1972	Drill and Blast
I 05	313	Ilangakazi-Intsamanzi Line 2 - Tunnel No 12 (INTSAMANZI) 313m	KwaZulu Natal	1973	Drill and Blast
I 06	282	Intsamanzi-Enqolotho Line 1 - Tunnel No 13 (INTSAMANZI) 282m	KwaZulu Natal	1973	Drill and Blast
I 16	313	Ilangakazi-Intsamanzi Line 1 - Tunnel No 12 (INTSAMANZI) 313m	KwaZulu Natal	1985	Drill and Blast
L 07	3235	Lowlands : Up Tunnel - (Hidcote - Lowlands Up) 3 235m	KwaZulu Natal	1956	Drill and Blast
L 08	4032	Lowlands : Down Tunnel - (Hidcote - Lowlands Down) 4 032m	KwaZulu Natal	1958	Drill and Blast
M 04	69	Mamba: Up Tunnel 69m	KwaZulu Natal	1928	Drill and Blast
M 11	686	Mount Edgecombe - No 4 Inland 686 m	KwaZulu Natal	1968	Drill and Blast
M 17	1004	Magoesbaskloof Tunnel (Tzaneen No. 2) 1 004m	Northern Province	1975	Drill and Blast
M 26	2160	Mqwabe-Zungwini Line 1: Tunnel No 1 (ZUNGWINI) 2 160m	KwaZulu Natal	1987	Drill and Blast
R 01	212	Rack Rail Tunnel 212m	Mpumalanga	1894	Drill and Blast
R 02	130	Roodepoort Tunnel 130m	KwaZulu Natal	1914	Drill and Blast
S 02	865	Stockton (New Dell) Tunnel 865m	KwaZulu Natal	1914	Drill and Blast
T 07	98	Town Hill Tunnel 98m	KwaZulu Natal	1916	Drill and Blast
U 14	240	Umgeni - Seaward 240m	KwaZulu Natal	1923	Drill and Blast
U 38	161	Umlaas Road: No 2 Up Tunnel 161m	KwaZulu Natal	1964	Cut and Cover
U 39	161	Umlaas Road: No 2 Down Tunnel 161m	KwaZulu Natal	1964	Cut and Cover
U 40	926	Umlaas Road: No 1 Up Tunnel 926m	KwaZulu Natal	1964	Drill and Blast
U 41	926	Umlaas Road: No 1 Down Tunnel 926m	KwaZulu Natal	1964	Drill and Blast
U 54	885	Umunywana-Isangoyana Line 2: Tunnel No 16 (ISANGOYANA) 885m	KwaZulu Natal	1972	Drill and Blast
V 31	388	Van Reenen: No 10 388m	KwaZulu Natal	1961	Drill and Blast

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
A 07	292	Aalwynpoort-Kommadagga: Tunnel No 7 292m	Eastern Cape	1953	Drill and Blast
A 08	816	Aalwynpoort-Kommadagga: Tunnel No 8 816m	Eastern Cape	1953	Drill and Blast
B 09	1164	Beacon Hill: Down Tunnel. (New Beacon Hill) 1 164m	KwaZulu Natal	1957	Drill and Blast
B 15	100	Bayview : Double Line Tunnel 100m	KwaZulu Natal	1968	Drill and Blast
D 40	302	Line 2: Tunnel No 1 (DOORNHOEK) 302m	KwaZulu Natal	1984	Drill and Blast
E 03	110	Eagle-Zangwa: Tunnel No 2 110m	Eastern Cape	1909	Drill and Blast
E 08	1708	Equasha-Ulolilwe Line 2: Tunnel No 7 (EQWASHA) 1 708m	KwaZulu Natal	1973	Drill and Blast
H 15	13301	Hex River Tunnel No 4 13301m	Western Cape	1988	Drill and Blast
I 02	262	Izolof-Eqwashe Line 1 Tunnel No 6 (LOTTERY) 262m	KwaZulu Natal	1971	Drill and Blast
I 03	704	Llangakazi-Intsamanzi Line 1-Tunnel No 10 (ILANGAKAZI) 704m	KwaZulu Natal	1972	Drill and Blast
I 07	282	Intsamanzi-Eqolothi Line 2 ; Tunnel No 13 (INTSAMANZI) 282m	KwaZulu Natal	1973	Drill and Blast
N 14	302	Nhlazatshe-Izolof Line No 1 : Tunnel No 3 (NHLAZATSHE) 302m	KwaZulu Natal	1971	Drill and Blast
N 15	183	Nhlazatshe-Izolof Line No 1 : Tunnel No 3 (LANGEWACHT) 183m	KwaZulu Natal	1971	Drill and Blast
N 17	302	Nhlazatshe-Izolof Line No 2 : Tunnel No 3 (NHLAZATSHE) 302m	KwaZulu Natal	1973	Drill and Blast
N 18	183	Nhlazatshe-Izolof Line 2 : Tunnel No 4 (LANGEWACHT) 183m	KwaZulu Natal	1973	Drill and Blast
N 19	487	Nhlazatshe-Izolof Line 2 : Tunnel No 5 (DUIKERFONTEIN) 487m	KwaZulu Natal	1973	Drill and Blast
U 57	2908	Ulundi-Ilangakazi Line 1 : Tunnel No 8 (ULUNDI) 2908m	KwaZulu Natal	1986	Drill and Blast
A 16	1090	Almeria No 2 (HEX RIVER RAIL TUNNEL No 2) 1090m	Western Cape	1987	Drill and Blast
A 18	1206	Almeria No 3 ; Almeria-Salbar, between De Doorns & Kleinstraat 1206m	Western Cape	1987	Drill and Blast
E 09	298	Enqolothi-Umunywana Line 1 : Tunnel No 14 (MFOLOZI) 298m	KwaZulu Natal	1972	Drill and Blast
E 10	1496	Enqolothi-Umunywana Line : Tunnel No 15 (MFOLOZI) 1496m	KwaZulu Natal	1972	Drill and Blast
M 23	643	Mswaneni-Sikame Line 2 : Tunnel No 2 (GOEDGELOOF) 643m	KwaZulu Natal	1988	Drill and Blast
M 24	565	Mswaneni-Sikame Line 1 : Tunnel No 3 (SIKAME) 565m	KwaZulu Natal	1988	Drill and Blast
M 26	2160	Mqwabe-Zungwini Line 1 : Tunnel No 1 (ZUNGWINI) 2160m	KwaZulu Natal	1987	Drill and Blast
O 10	3896	Overvaal Tunnel 3896m	Mpumalanga	1976	Drill and Blast

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
U 58	2442	Umunywana-Isangoyana Line 1 : Tunnel No 16 (ISANGOYANA) 2442m	KwaZulu Natal	1987	Drill and Blast
A 09	52	Alicedale-Doringkom : Tunnel No 3 52m	Eastern Cape	1957	Not known
B 08	1164	Beacon Hill : Up Tunnel (New Beacon Hill) 1164m	KwaZulu Natal	1957	Drill and Blast
B 16	1336	Bloubank-Nhlazatshe Line 1 : Tunnel No 2 (BLOUBANK) 1336m	KwaZulu Natal	1971	Drill and Blast
B 17	787	Bobbesjaansberg (Baboonpoint) 787m	Western Cape	1975	Not known
B 26	1336	Bloubank-Nhlazatshe Line 2 : Tunnel No 2 (BLOUBANK) 1336m	KwaZulu Natal	1985	Drill and Blast
C 17	6023	Cedera : Up Tunnel 6023m	KwaZulu Natal	1960	Drill and Blast
C 18	6023	Cedera : Down Tunnel 6023m	KwaZulu Natal	1960	Drill and Blast
C 19	572	Clove No 1 (VAN REENEN PASS No 1) 572m	KwaZulu Natal	1961	Drill and Blast
C 20	210	Clove No 2 (VAN REENEN PASS No 2) 210m	KwaZulu Natal	1961	Drill and Blast
C 21	200	Clove No 3 (VAN REENEN PASS No 3) 200m	KwaZulu Natal	1961	Cut and Cover
C 22	1175	Clove No 4 (VAN REENEN PASS No 4) 1175m	KwaZulu Natal	1961	Drill and Blast
C 23	447	Clove No 5 (VAN REENEN PASS No 5) 447m	KwaZulu Natal	1961	Drill and Blast
C 24	108	Clove No 6 (VAN REENEN PASS No 6) 108m	KwaZulu Natal	1961	Cut and Cover
D 01	53	Drummond Tunnel 53m	KwaZulu Natal	1880	Not known
D 10	296	Duff's Road : Inland Tunnel 296m	KwaZulu Natal	1960	Drill and Blast
D 12	302	Dassiehoogte-Lenjanedrif Line 1: Tunnel No 1 (DOORNHOEK) 302m	KwaZulu Natal	1970	Drill and Blast
D 13	246	Donkerpoort Tunnel 246m	Free State	1971	Drill and Blast
E 01	60	East Bank Tunnel 60m	Eastern Cape	1908	Not known
E 02	110	Eagle-Zangwa : Tunnel No 1 110m	Eastern Cape	1909	Not known
E 11	231	Elandshoek-Reception No 4 231m	Mpumalanga	1939	Not known
E 16	298	Enqolothi-Umunywana Line 1 : Tunnel No 14 (MFOLOZI) 298m	KwaZulu Natal	1986	Drill and Blast
E 17	1496	Enqolothi-Umunywana Line : Tunnel No 15 (MFOLOZI) 1496m	KwaZulu Natal	1986	Drill and Blast
E 18	2886	Eqwashe-Uloliwe Line 1 Tunnel No 7 (MPOLWENI) 2886m	KwaZulu Natal	1987	Drill and Blast
F 03	739	Fort Cunynghame - Toise : Tunnel No 3 739m	Eastern Cape	1941	Not known

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
G 03	1338	Groenheuwals-Saltaire : Tunnel No 4 1338m	Eastern Cape	1954	Not known
H 01	180	Hex River Pass No 1 180m	Western Cape	1877	Not known
H 09	189	Hex River Pass No 2 189m	Western Cape	1930	Not known
I 10	623	Ingogo No 2 Up (CLAVIS-LADYSMITH : No 2 UP) 623m	KwaZulu Natal	1983	Drill and Blast
I 11	623	Ingogo No 2 Down (CLAVIS-LADYSMITH : No 2 DOWN) 623m	KwaZulu Natal	1983	Drill and Blast
I 12	1030	Ingogo No 1 Up (CLAVIS-LADYSMITH : No 1 UP) 1030m	KwaZulu Natal	1983	Drill and Blast
I 13	1030	Ingogo No 1 Down (CLAVIS-LADYSMITH : No 1 DOWN) 1030m	KwaZulu Natal	1983	Drill and Blast
I 14	1861	Ingogo No 3 Up (CLAVIS-LADYSMITH : No 3 UP) 1861m	KwaZulu Natal	1984	Drill and Blast
I 15	1861	Ingogo No 3 Down (CLAVIS-LADYSMITH : No 3 DOWN) 1861m	KwaZulu Natal	1984	Drill and Blast
I 18	480	Ilangakazi-Intsamanzi Line 2 ; Tunnel No 11 (ILANGAKAZI) 480m	KwaZulu Natal	1986	Drill and Blast
K 01	34	Khat's Kop Tunnel 34m	KwaZulu Natal	1879	Not known
K 17	218	Kenville - Inland Tunnel 218m	KwaZulu Natal	1960	Drill and Blast
K 21	208	Kriekdraai Tunnel 208m	Free State	1970	Drill and Blast
K 32	1462	Kraal: Up Tunnel 1462m	Mpumalanga	1978	Drill and Blast
L 01	674	Laings Nek 674m	KwaZulu Natal	1890	Not known
M 08	666	Mount Edgecombe - No 4 Seaward 666 m	KwaZulu Natal	1961	Not known
M 14	559	Mswaneni-Sikame Line 1 : Tunnel No 2 (GOEDGELOOF) 559m	KwaZulu Natal	1973	Drill and Blast
M 15	600	Mswaneni-Sikame Line 1 : Tunnel No 3 (SIKAME) 600m	KwaZulu Natal	1973	Not known
N 16	487	Nhlazatshe-Izolof Line 1 : Tunnel No 5 (DUIKERFONTEIN) 487m	KwaZulu Natal	1971	Drill and Blast
N 21	1029	New Brereton : Up Tunnel 1029m	KwaZulu Natal	1974	Drill and Blast
N 22	1036	New Brereton : Down Tunnel 1036m	KwaZulu Natal	1974	Not known
O 01	99	Outeniqua 99m	Western Cape	1902	Not known
P 02	92	Power-George : Tunnel No 1 92m	Western Cape	1911	Not known
P 04	842	Pieters : Up Tunnel 842m	KwaZulu Natal	1957	Drill and Blast
P 05	842	Pieters : Down (Harts Hill) Tunnel 842m	KwaZulu Natal	1957	Drill and Blast

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
P 15	779	Paulpietersburg-Mahulumbe Line 2 : Tunnel No 1 (PAULPIETERSBURG) 779m	KwaZulu Natal	1974	Drill and Blast
R 09	292	Reception-Rivulets : Tunnel 5 292m	Mpumalanga	1965	Not known
S 12	451	Sheldon-Middleton : Tunnel No 9 451m	Eastern Cape	1952	Not known
S 29	529	Simuna No 1 Tunnel 529m	KwaZulu Natal	1983	Not known
S 30	68	Simuna No 2 68m	KwaZulu Natal	1983	Not known
S 34	1219	Salbar No 3 1219m	Western Cape	1986	Not known
T 01	204	Topping-Power : Tunnel No 2 204m	Western Cape	1911	Not known
T 14	392	Thomas River-Surbiton : Tunnel No 8 392m	Eastern Cape	1942	Not known
T 18	398	Table Harbour 398m	Western Cape	1967	Cut and Cover
U 13	180	Umbulwana - North : Double Track Tunnel 180m	KwaZulu Natal	1922	Not known
U 35	681	Umbulwana South - Up Tunnel 681m	KwaZulu Natal	1956	Drill and Blast
U 36	681	Umbulwana South - Down Tunnel 681m	KwaZulu Natal	1956	Drill and Blast
U 44	177	Umlazi No 2 - Up 177m	KwaZulu Natal	1966	Drill and Blast
U 45	177	Umlazi No 2 - Down 177m	KwaZulu Natal	1966	Not known
U 46	141	Umlazi No 3 - Up 141m	KwaZulu Natal	1966	Drill and Blast
U 47	141	Umlazi No 3 - Down 141m	KwaZulu Natal	1966	Drill and Blast
U 48	148	Umlazi No 1 - Up 148m	KwaZulu Natal	1967	Drill and Blast
U 49	148	Umlazi No 1 - Down 148m	KwaZulu Natal	1967	Drill and Blast
U 52	895	Ulundi-Ilangakazi Line 2 : Tunnel No 8 (ULUNDI) 895m	KwaZulu Natal	1971	Drill and Blast
U 53	527	Ulundi-Ilangakazi Line 2 : Tunnel No 9 (ULUNDI-ILANGAKAZI) 527m	KwaZulu Natal	1971	Drill and Blast
V 13	40	Victoria Bay-Wilderness : Tunnel No 2 40m	Western Cape	1925	Not known
V 33	567	Verulam : No 5 Seaward 567m	KwaZulu Natal	1968	Not known
V 38	424	Verulam Tunnel (Mushroom Tunnel) 424m	KwaZulu Natal	1922	Not known
W 02	381	Waterval Boven : Tunnel No 1 381m	Mpumalanga	1907	Not known

Record #	Tunnel Length_ m	Tunnel Name	Province	Year Completed	Construction Method
W 04	267	Walls End : Double Track Tunnel 267m	KwaZulu Natal	1939	Not known
W 08	459	Waterval Boven : Tunnel No 2 459m	Mpumalanga	1964	Not known

Appendix G: Railway Lines' Current Status

Table G-1: Status of Railway Lines

Railway Route	Date Closed	Note
Closed Lines		
Bridgend - Cape Collieries	1912	
Bamboo Junction - Bridgend	1917	
Lyttelton Junction - Roberts Heights	1913	
Sheba Halt - Sheba Mine	1926	
Valley Junction - Walmer	1928	Narrow Gauge. Walmer town branch of the Avontuur line. Replaced by bus service.
Monument - Sea Point	1929	This line ran from Cape Town City to Sea Point. Uplifted after closure.
Colesberg Junction - Colesberg	1931	Originally a terminus, this later became a spur off the Noupoort - Bloemfontein line.
Elandshoek - Mount Carmel	1931	Narrow Gauge.
Hamilton - Tempe	1932	
Point - Durban	1936	Original 1860 route (oldest line in South Africa)
Stanger - Kearsney	1941	Narrow Gauge. Kearsney - Stanger Light Railway
Okiep - Port Nolloth	1944?	Narrow Gauge. Namaqualand Railway
Knysna - Templeman	1949	Narrow Gauge. South Western Railway Co. Ltd
Opwekker - Tygerberg	1956	Milnerton Railway, opened 1904, last race train 1954. Heatherton - Milnerton - Ascot - Tygerberg (terminus) section uplifted shortly after closure.
Nancefield - Pimville	1974	(railway lines have been uplifted)
Wests - Cave Rock (Whaling Station)	197?	
Sarnia - New Germany	?	

Railway Route	Date Closed	Note
Delville Wood - Shongweni Dam	?	Service line for construction of dam.
Watburg - Windy Hill	?	
Touws River - Ladismith	1981	Closed due to line washaway caused by the 1981 flash flood.
Escourt - Weenen	1983	Narrow Gauge. Escourt - Weenen
Molteno - Jamestown	1984	(railway lines have been uplifted)
Fort Beaufort - Seymour	1984	
Komatipoort - Reserve	?	Part of the Selati Line through the Kruger National Park
Umlaas Road - Mid Illovo	1985	Narrow Gauge.
Umzinto - Highflats	1985	Narrow Gauge. Part of the Umzinto - Donnybrook narrow gauge railway
Ixop - Highflats	1985	Narrow Gauge. Part of the Umzinto - Donnybrook narrow gauge railway
Union Bridge - Madonela	1985	Narrow Gauge. Part of the Umzinto - Donnybrook narrow gauge railway
Ixopo - Donnybrook	1986	Narrow Gauge. Part of the Umzinto - Donnybrook narrow gauge railway
Port Shepstone - Harding	1986	Narrow Gauge. Re-opened in 1988, see Alfred County Railway
Kelso - Umzinto	1987	Cape Gauge, closure after abandonment of the Umzinto - Donnybrook narrow gauge railway
Gingindlovu - Eshowe North	1987	Closed after line washaway
Boughton - Hilton	1987	Part of old alignment of the Natal Main Line
Umlaas Road - Thornville	1988	Part of old alignment of the Natal Main Line
Bowkers Park - Tarkastad	1988	(railway lines have been uplifted)
Imvani - Qamata	1988	(railway lines have been uplifted)
De Doorns - Kleinstraat	1989	Old Hex River Pass line. Replaced by Hex River Tunnel
Matroosberg - Kleinstraat	1989	Loop line for the old Hex River Pass. Replaced by Hex River Tunnel. (railway lines have been uplifted)
Groveput - Copperton	1991	Closure of mine.
Schoombee - Hofmeyr	1992	
Grahamstown - Port Alfred	1993	Port Alfred Railway Line
Armoed - Calitzdorp	1993	

Railway Route	Date Closed	Note
Cookhouse - Somerset East	1993	
Barkly Bridge - Alexandria	1993	
Louterwater - Avontuur	1993	Narrow Gauge. Section of the Avontuur line
Hercules - Magaliesburg	1996	Passed through Hartbeespoort
Pinetown - Cato Ridge	1997	
Modderpoort - Ladybrand	199?	
Marseilles - Ficksburg	Open	
Volksrust - Bethal	?	
Witpilaar - Vrednburg	?	A spur off the Hopefield - Saldanha line. (railway lines have been uplifted)
Pieters - Harts Hill	?	Service line to quarry
Estantia - Klipstapel	?	
Paarl - Franschhoek	?	
Merrivale - Howick	?	
Hilton - Cedara	?	Part of old alignment of the Natal Main Line
Theunissen - Winburg	199?	Branch opened 1898. Branch was originally planned to be extended to Senekal
Orkney - Vierfontein	?	Uplifted after washaway. Re-laid, open December 2012
Springfontein - Koffiefontein	2001	
Dover - Vredefort	2001	
Wolvehoek - Heilbron	2001	
Arlington - Heilbron	200?	
Chelsea - New Brighton	2001	Narrow Gauge. Private branch of the Avontuur line, to PPC cement factory. Caused by closure of all limestone mines along Avontuur line.
Aliwal North - Barkly East	2001	
Sterkstroom - Maclear	2001	
Rosmead - Stormberg	2001	

Railway Route	Date Closed	Note
Hutchinson - Calvinia	2001	
Kootjieskolk - Sakrivier	2001	Branch line off the Hutchinson - Calvinia line.
Cor Delfos - Voortrekkerhoogte	2001	
Nylstroom - Vaalwater	2002	
Naboomspruit - Zebediela	2003	
Pienaars River - Marble Hall	2003	
Pentrich - Mkondeni	2004	Service line. Part of old alignment of the Natal Main Line.
Alfred County Railway	2004	Narrow Gauge. Started 1988, Port Shepstone - Harding
Cor Delfos - Mooiplaas	2004?	Service line to PPC Dolomite quarry at Erasmia near Pretoria, passed through Laudium
Sannaspos - Zastron	2006	
George - Knysna	2006	Original Outeniqua Choo Tjoe route. Closed due to line washaway.
India Junction - Alberton	2007	
Grootvlei - Redan	?	
Alicedale - Grahamstown	2008	Port Alfred Railway Line
Thornville - Richmond	2008?	
Assegaaibos - Louterwater	2009	Narrow Gauge. Section of the Avontuur line
Gamtoos - Patensie	2009	Narrow Gauge. Section of the Avontuur line
Kaydale - Nigel	2010	
Re-opened		
Klipplaat - Graaf-Reinet	2001	Closed in 2001, re-opened 2015.
Graaff-Reinet - Rosmead	1993	Closed in 1993, re-opened in 2015.
Wolseley - Prince Alfred Hamlet (branch line)	2002	Closed in 2002, re-opened in 2015.
Unsure Status		
Firham - Vrede		

Railway Route	Date Closed	Note
Kaapmuiden - Barberton		
Nelspruit - Plaston		
Buhrmannskop - Lothair		
Makwassie - Vermaas		
Vermaas - Pudimoe		
Klerksdorp - Ottosdal		
Franklin - Matatiele		
Franklin - Kokstad		
Ennersdale - Bergville		
Schroeders - Bruyns Hill		
Dalton - Glenside		
Chailley - Mount Alida		
Greytown - Kranskop		
Dreunberg - Zastron		
Addo - Kirkwood		

Appendix H: Railway Routes - Tunnel Cross Sections

Table H-1: Rail Routes – Tunnel Cross Section

Province	**Cross Section (m^2)**												
Railway Routes	26	Horseshoe 26	30	60	67.96	70	Arch on walls 60	Box Culvert 30	Double Rail	Double Track 60	Horseshoe shape	Not known	**Grand Total**
Eastern Cape			*34*									*1*	***35***
Alicedale - Port Alfred			3										**3**
Aliwal North - Barkly East			1										**1**
Amabele - Umtata			2										**2**
Blaney - Queenstown			13										**13**
Cookhouse - Noupoort			6										**6**
Port Rex - Terminus on the Chiselhurst			1										**1**
Swartkops - Cookhouse			8									1	**9**
Free State			2										**2**
Donkerpoort - Prior			1										**1**
Kriedraai - Meets			1										**1**
KwaZulu Natal			*127*	*1*			*1*	*2*	*1*	*2*		*4*	***138***
Access Line - Limestone Quarry			1										**1**
Booth Junction - Cato Ridge			11										**11**
Cedara - Mooi River			4										**4**
Coal Line			2										**2**
Colenso - Ladysmith			4	1									**5**

Province	Cross Section (m^2)												
Railway Routes	26	Horseshoe 26	30	60	67.96	70	Arch on walls 60	Box Culvert 30	Double Rail	Double Track 60	Horseshoe shape	Not known	**Grand Total**
Danskraal - Van Reenen			4										**4**
Durban - Verulam			1										**1**
Haig station - Mtubatuba			1										**1**
Ladysmith - Van Reenen			5					2					**7**
Ladysmith - Volksrust												1	**1**
Main North Coast Lines			2										**2**
Merebank - Crossmore									1				**1**
Mooi River - Estcourt			6										**6**
Mount Edgecombe - Verulam			1										**1**
Natal Main Line			11										**11**
near Estcourt at Ennersdale			2										**2**
near Laing's Nek Pass			2										**2**
Near Phoenix and Ottawa			1										**1**
New Line to Umlazi Township			6										**6**
Not known			41				1			2		3	**47**
Ottawa - Verulam			1										**1**
Pietermaritzburg - Cedara			4										**4**
Raillink - Limestone Quarry			1										**1**
Rossburgh - Cato Ridge			1										**1**

Province	Cross Section (m^2)												
Railway Routes	26	Horseshoe 26	30	60	67.96	70	Arch on walls 60	Box Culvert 30	Double Rail	Double Track 60	Horseshoe shape	Not known	**Grand Total**
Stanger - Mandini			1										**1**
Umgeni - Duff's Road			1										**1**
Umlaas Road - Pietermaritzburg			11										**11**
Volksrust - Newcastle			1										**1**
Vryheid - Empangeni			1										**1**
Mpumalanga			*11*								*1*	*5*	***17***
avoiding the Kruger National Park			1										**1**
Komatipoort on the Mozambique border			1										**1**
Machadodorp - Ressano Garcia			1									3	**4**
Not known			1									2	**3**
Standerton - Volksrust			1										**1**
Union Junction - Volksrust			6										**6**
Waterval Boven - Elands Valley											1		**1**
Northern Cape			*1*										***1***
Cookhouse - Noupoort			1										**1**
Northern Province			*4*										***4***
Groenbult - Beitbridge			1										**1**
Not known			2										**2**
Warmbaths - Nylstroom			1										**1**
Western Cape	*1*	*1*	*14*		*1*	*1*						*7*	***25***

Province	**Cross Section (m^2)**												
Railway Routes	26	Horseshoe 26	30	60	67.96	70	Arch on walls 60	Box Culvert 30	Double Rail	Double Track 60	Horseshoe shape	Not known	**Grand Total**
Almeria - Salbar		1	1										**2**
Eerste Rivier - Bredasdorp			1										**1**
George - Knysna			2									1	**3**
Klipplaat - Oudtshoorn			1										**1**
Mossel Bay - George												1	**1**
on line Table Bay New Harbour					1								**1**
Osplaats - Matroosberg												2	**2**
Oudtshoorn - George			5									2	**7**
Salbar - Kleinstraat						1							**1**
Sishen - Saldanha												1	**1**
through the Hex River Valley and pass			2										**2**
up the Hex River Valley	1												**1**
Vlakeplaas - Stompdrift			1										**1**
Wolseley - Prince Alfred Hamlet			1										**1**
Grand Total	**1**	**1**	**193**	**1**	**1**	**1**	**1**	**2**	**1**	**2**	**1**	**17**	**222**

Appendix I: Algorithms of Management System Integration

I-1. Append Data to the Database

```
Attribute VB_Name = "TunnelDatabaseUpdate"
Option Compare Database

Public Sub TunnelUpdate()
'Define object variables

Dim Frm1 As Form
Dim Ctrl1 As Control
Dim Ctrl2 As Control
Dim MxId As String

Set Frm1 = Forms![INVENTORY PRELIMINARY]
Set Ctrl1 = Frm1.[TUNNEL NUMBER]
Set Ctrl2 = Frm1.[TUNNEL NAME]

Dim TlNer As Integer
TlNer = Ctrl1.Value

Dim TlNme As String
TlNme = Ctrl2.Value
TlNme = " ' " & TlNme
TlNme = TlNme & " ' "

'Define the record to append
MxId = "INSERT INTO [TUNNELS]"
MxId = MxId & " ( [Tunnel #], [Tunnel Name] ) VALUES ("
MxId = MxId & TlNer
MxId = MxId & ", "
MxId = MxId & TlNme
MxId = MxId & ")"

'Add Tunnel# & Tunnel Name to the Database
DoCmd.RunSQL MxId

'Release variables
Set Frm1 = Nothing
Set Ctrl1 = Nothing
Set Ctrl2 = Nothing

End Sub
```

I-2. Update Inspection Form

```
Private Sub Command106_Click()
'Build Tunnel Inspection Form from SQL

TunInsForm = "SELECT TUNNELS.TL_ID, TUNNELS.[Record #], TUNNELS.[Tunnel #], TUNNELS.[Tunnel Length_m], TUNNELS.[Tunnel Name],"
TunInsForm = TunInsForm & " LOCATION_TL.Province, LOCATION_TL.[Geological System], [ADDITIONAL INFO].[Railway Route],"
TunInsForm = TunInsForm & " [ADDITIONAL INFO].[Year Completed], [ADDITIONAL INFO].[Cross-Section m2],"
TunInsForm = TunInsForm & " [ADDITIONAL INFO].[Construction Method] INTO [TUNNEL INSPECTION FORM 1]"
TunInsForm = TunInsForm & " FROM (TUNNELS LEFT JOIN LOCATION_TL ON TUNNELS.[TL_ID] = LOCATION_TL.[TL-LOC_ID])"
TunInsForm = TunInsForm & " LEFT JOIN [ADDITIONAL INFO] ON LOCATION_TL.[LOC_ID] = [ADDITIONAL INFO].[LOC-INFO-ID]"

DoCmd.RunSQL TunInsForm
DoCmd.Rename "TUNNEL INSPECTION FORM", acTable, "TUNNEL INSPECTION FORM 1"
End Sub
```

I-3. Tunnel Inspection Evaluation

```
Private Sub Command95_Click()
'Define the variable to store SQL statement

Dim InspectionScore As String

'Build InspectionScore string from the SQL statement

InspectionScore = "SELECT [TUNNEL INSPECTION FORM].TL_ID, [TUNNEL INSPECTION FORM].[Record #], [TUNNEL INSPECTION FORM].[Tunnel #],"
InspectionScore = InspectionScore & " [TUNNEL INSPECTION FORM].[Tunnel Name], [TUNNEL INSPECTION FORM].Province,"
InspectionScore = InspectionScore & " [INSPECTION DETAILS].[ID-TUNNEL-ID],"
InspectionScore = InspectionScore & " [INSPECTION DETAILS].[Inspection Date], [INSPECTION DETAILS].[Inspection Type],"
InspectionScore = InspectionScore & " [TUNNEL ELEMENTS].[ID-TI-TE], [TUNNEL ELEMENTS].[Elt Name],"
InspectionScore = InspectionScore & " [TUNNEL ELEMENTS].[Value Measured], [TUNNEL ELEMENTS].Unit, [ELEMENT DEFECTS].[ID-TEL-ELD],"
InspectionScore = InspectionScore & " [ELEMENT DEFECTS].[Defect (Cdtion of Elt)], [ELEMENT DEFECTS].[Extent (Size)],"
InspectionScore = InspectionScore & " [ELEMENT DEFECTS].[Significance (Importance)], [ELEMENT DEFECTS].[Intervention (Urgency)],"
InspectionScore = InspectionScore & " [ELEMENT DEFECTS].[Element Score], [ELEMENT DEFECTS].[Relative Score] INTO [TUNNEL INSPECTION EVALUATION]"
InspectionScore = InspectionScore & " FROM (([TUNNEL INSPECTION FORM] LEFT JOIN [INSPECTION DETAILS]"
```

```
InspectionScore = InspectionScore & " ON [TUNNEL INSPECTION FORM].[TL_ID] = [INSPECTION DETAILS].[ID-TUNNEL-ID])"
InspectionScore = InspectionScore & " LEFT JOIN [TUNNEL ELEMENTS] ON [INSPECTION DETAILS].[ID-ID] = [TUNNEL ELEMENTS].[ID-TI-TE])"
InspectionScore = InspectionScore & " LEFT JOIN [ELEMENT DEFECTS] ON [TUNNEL ELEMENTS].[ID-TEL] = [ELEMENT DEFECTS].[ID-TEL-ELD]"
InspectionScore = InspectionScore & " WHERE ((([INSPECTION DETAILS].[Inspection Date]) Is Not Null))"

'Now execute the SQL statement
DoCmd.RunSQL InspectionScore

End Sub
```

I-4. Tunnel Inspection Plan

```
Attribute VB_Name = "InspectionPlan1"
Option Compare Database

Public Sub InspectionPlan2()
'Declare the forms and controls involved
Dim Frm1 As Form
Dim Frm2 As Form
Dim Ctr1 As Control
Dim Ctr2 As Control
Dim Ctr3 As Control
Dim Ctr4 As Control
Dim AcDe As Date
Dim TlAge As Integer

'Assign Objects to object variables created
Set Frm1 = Forms![TUNNEL INSPECTION PLAN]
Set Frm2 = Forms![INSPECTION DETAILS]
Set Ctr1 = Frm1![Year Completed]
Set Ctr2 = Frm2![Inspection Date]
Set Ctr3 = Frm2![Inspection Type]
Set Ctr4 = Frm2![Planned Inspection]

'Define Tunnel Age
AcDe = Date
TlAge = Year(AcDe) - Ctr1

'Set the value for Planned Inspection
If Ctr2 = "Preliminary Inspection" Then
   Ctr4 = Ctr2 + 730
Else
   If TlAge < 50 Then
      Ctr4 = Ctr2 + 1460
   Else
```

```
        If 50 <= TlAge <= 100 Then
            Ctr4 = Ctr2 + 1095
        Else
            Ctr4 = Ctr2 + 730
        End If
    End If
End If

Set Frm1 = Nothing
Set Frm2 = Nothing
Set Ctr1 = Nothing
Set Ctr2 = Nothing
Set Ctr3 = Nothing
Set Ctr4 = Nothing

DoCmd.Close acForm, "TUNNEL INSPECTION PLAN", acSaveYes
DoCmd.Close acForm, "INSPECTION DETAILS", acSaveYes

End Sub
```