

Analysis: The effect of the Length of a Single  
Rail Line on the Capacity of the Line

by

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Submitted in partial fulfilment of the requirements for the degree  
of

BACHELORS OF INDUSTRIAL ENGINEERING

in the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION  
TECHNOLOGY

UNIVERSITY OF PRETORIA

October 2012

## **ABSTRACT**

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Over the past 200 years, trains have vastly progressed the way in which people and goods have been moved from point A to point B. Proven to be one of the most effective modes of transport, railway network's capacity is often pushed to the limit. Global increase in demand for resources and South Africa's emerging economy has the consequence of the country's railway infrastructure needing to be pushed to the limit. This paper gives the reader insight into the infrastructure system behaviour with respect to capacity of a rail line. A study is done on the Sishen-Saldanha single heavy haul railway line; different scenarios will be tested with the help of simulation software, to determine what the effects of the length of a railway line are on the capacity of the line. This data will then be analysed and the results could be used for further research.

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## GLOSSARY

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Average Delay	The difference between the scheduled and actual arrival times for a train at a certain point on a rail line; over the period of 7days.
Capacity	Capacity has several definitions depending on the type of system; for this paper capacity is defined as the maximum number of trains that could run over a route during a specific time interval, given the operational conditions.
Constraint	A physical characteristic of a railway system that restrains proper working of the system and causes delays for scheduled train movements.
Heavy Haul	Reinforced railway line capable of withstanding heavy freight trains (ore, metallurgical products, etc.).
Homogenous Traffic	Trains consisting all of the same characteristics, such as mass, velocity, length etc.
Initial Delay	The difference in the scheduled and actual departure time for a train when departing from a specific point on a rail line.
Loop	An extra stretch of rail line built right next to another line to allow trains travelling in opposite directions to pass.
Reliability	The dependability on rail line system elements not to fail.
Saldanha	A town situated in the Western Cape province of South Africa, next to the Atlantic Ocean. The town has a port which is used to export iron ore to other foreign countries.
Simu	The simulation software package used for this paper, specifically designed to simulate railway networks.
Sishen	A town situated in the Northern Cape province of South Africa, that has its existence due to the mining activities in the area.
Timetable	A table showing the scheduled train departures and arrivals (including the movement in between) over a specific period of time.

# 1. INTRODUCTION AND BACKGROUND

## 1.1. South African Railway Systems

Railway and trains has been an essential part of our development and progress as humans for approximately 200 years. As locomotives and railway networks have been established for quite a long time, a lot of work has been done to improve this simple yet effective transportation mode.

In recent times South Africa has grown to be a big role player in the global market. Demand for resources has increased globally and so too did the efficient delivery thereof. Consequently the country's railway network needs to be pushed to the limit. This proves to be a difficult task seeing that most of the rail lines were laid a few years back, before public demand for resources and capacity constraints were precisely known. There is a need for proper analysis of the constraints and potentials of the country's railway systems. One can imagine the safety implications on the country's roads when taken into consideration that one train can take up to 50 trucks off the road.

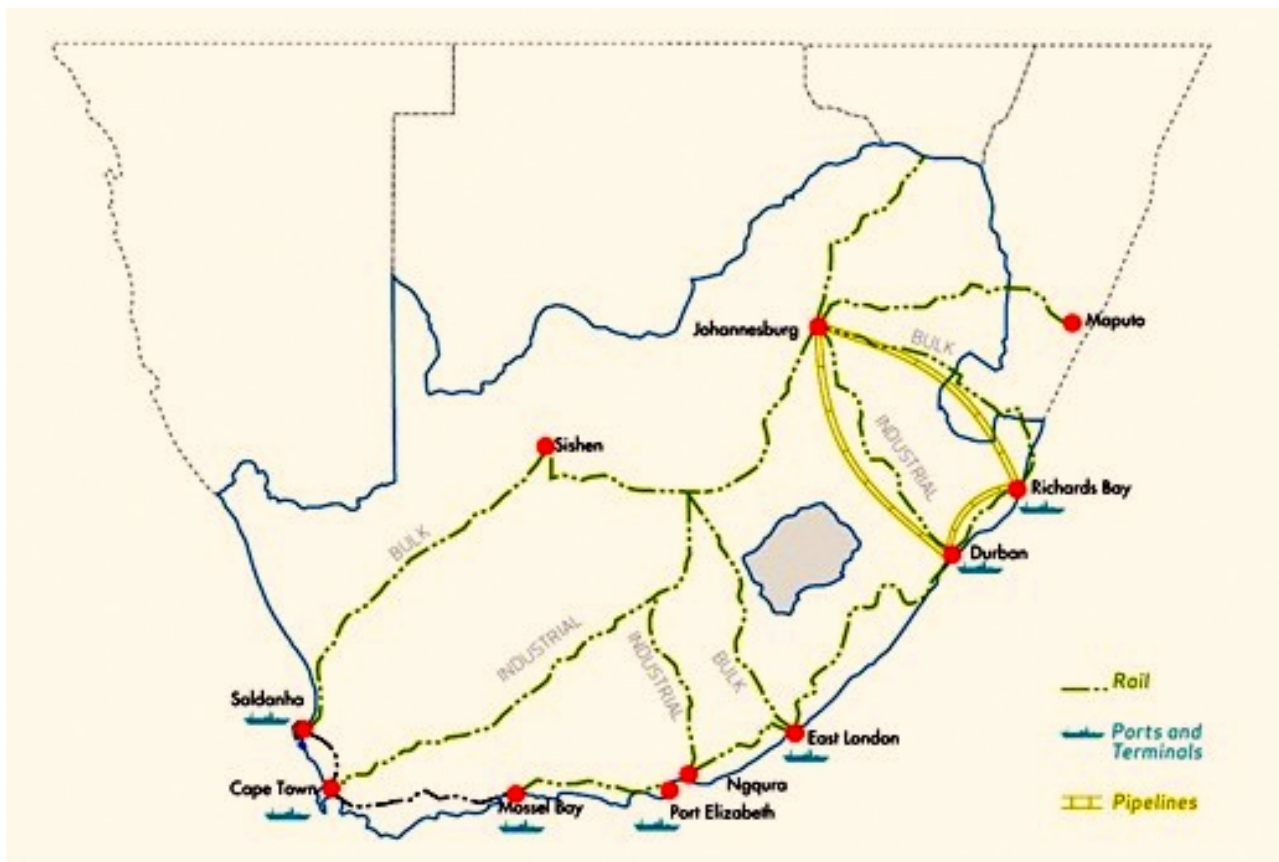


Figure 1: South Africa's Main Rail Network and Operational Reach. (Transnet Limited, 2007)

Capacity has long been a critical issue in the railway industry, and its definition has caused many a problem over the years. According to Abril, M et al. 2008, the goal of capacity analysis is *to determine the maximum number of trains that would be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions*. This capacity determination and control are some of the major tasks of any infrastructure management. Before considering investments on new railway tracks or heavy measurements on the infrastructure, it is essential to increase the existing capacity by optimizing the train timetable, or by adopting unplanned measurements in the operation, possibly with the support of computer systems. (Confessore, G. et al., 2009)

Literature (Abril et al, 2008) proves that many approaches and tools have been developed to address the problem of capacity; which are based on traffic patterns (Forsgren,2003), single-track analytical models (Petersen, 1974), or algebraic approaches (Egmond, 1999). Most of these methods were done on Europe's major double commuter rail lines – and are not very effective for South Africa's comprehensive single heavy haul rail lines.

## 1.2. Sishen-Saldanha Single Heavy Haul Rail line

The Sishen–Saldanha railway line is an 861 kilometres long heavy haul railway line that connects Sishen in the Northern Cape and the port at Saldanha Bay in the Western Cape. Also called the Oryx line, its main use is to transport iron ore from mines in the Sishen region to the port at Saldanha, the line does not carry any passenger traffic. The line was opened in 1976 (Boonzaaier, 2008) and is still in operation today. What's interesting about this rail line is that a world record was set here in 1989 when the longest and heaviest train ever assembled covered the distance. The train was 7,3km long, and the gross mass of the train totalled 71210 ton. (Route27SA, 2004)

Single track rail lines allow a flow of trains in opposing directions by carefully planning the location and use of sidings or sections of multiple tracks, also called loops (Harrod, 2009). Frank (1966) analyses these loops and defines two network types, T1 - which allows 1 train to wait clear of the main track, and T2 - which allows 2 trains to wait clear of the main track; (the second being a maintenance train for example) examples of which are shown in Figure 2. The loops in consideration for this project will only consist of the T1 type loops.

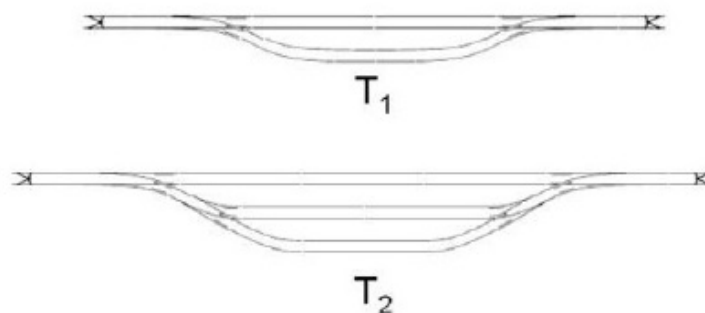


Figure 2: Track Layout of  $T_1$  and  $T_2$  Networks (Harrod, 2009)

A single set of tracks with 10 passing loops was constructed for the Sishen-Saldanha line; but according to a news article published on 9 April 2010 by Engineering News this has since been increased to 19 crossing loops to increase line capacity. This decision was made to meet the booming demand for iron ore, especially from the growing economies of Asia. (Dickson, 2007)

Dickson (2007) also states that it wasn't always so. In the mid 1980's, the demand for iron and steel dropped and the line was even considered for closure. Fortunately the demand resumed and the line is fully operative today. The line was originally built to carry 17.5 million tons a year of ore for export, but current upgrades that are soon to be finished has caused that number to jump up to 60 million tons a year. (Miningmx, 2011)

This Sishen-Saldanha Single Heavy Haul Rail Line will be used for this analysis, assuming homogenous traffic.

## **2. PROBLEM STATEMENT**

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A lot of research has been done on the capacity of railway networks in Europe, but the main problem is that most of Europe's railway networks consist of double commuter rail lines and are used for passenger trains only. This affects the overall capacity and management of the railway line immensely, as Abril et al. (2008) records variances in capacity of up to 300% between single and double rail lines for commuters.

No thorough research has been done to study various factors' impact on South Africa's comprehensive single rail line network, which is used mostly for the transport of freight.

## **3. PROJECT AIM**

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The aim of the project is to determine the effect of the length of a single rail line on the capacity of the line, assuming homogenous traffic. This will be done with the help of simulation software.

Project deliverables will include a clear understanding of the railway system behaviour under the specified operating conditions, as well as a simulation model and data that can be used further in research on South Africa's heavy haul single rail lines.



## 4. PROJECT SCOPE

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### 4.1. Scope of Study

According to Abril et al. (2008) there are 4 main areas/parameters of a railway network that affect the capacity thereof:

- The **number of trains**
- The **average speed** of the train
- The **stability** of the network
- The **heterogeneity** of the network

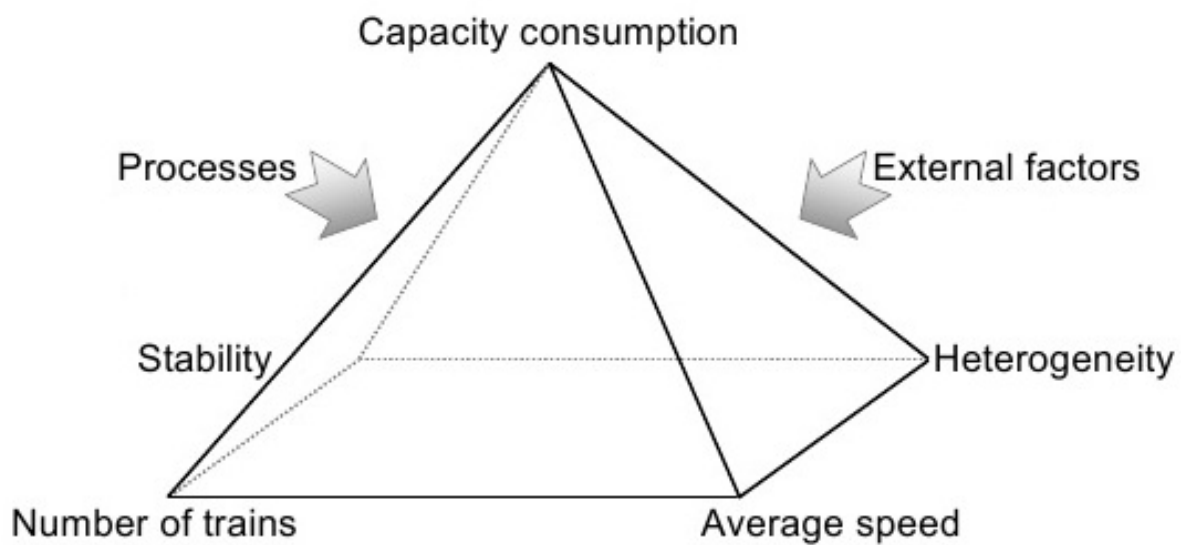


Figure 3: Main Capacity Factors - Capacity Pyramid (Landex 2007)

This Analysis will only deal with the '**number of trains**' factor of a rail line, incorporating it with the length of the rail line.

Project deliverables will include a clear understanding of the consequences of the length of a single heavy haul rail line on the capacity thereof.

Assumptions made for the study are stated in point nr 6.2.

### 4.2. Sishen-Saldanha Rail Line

The diagram on the next page illustrates the rail line in scope as well as the distances between certain essential nodes on the line.

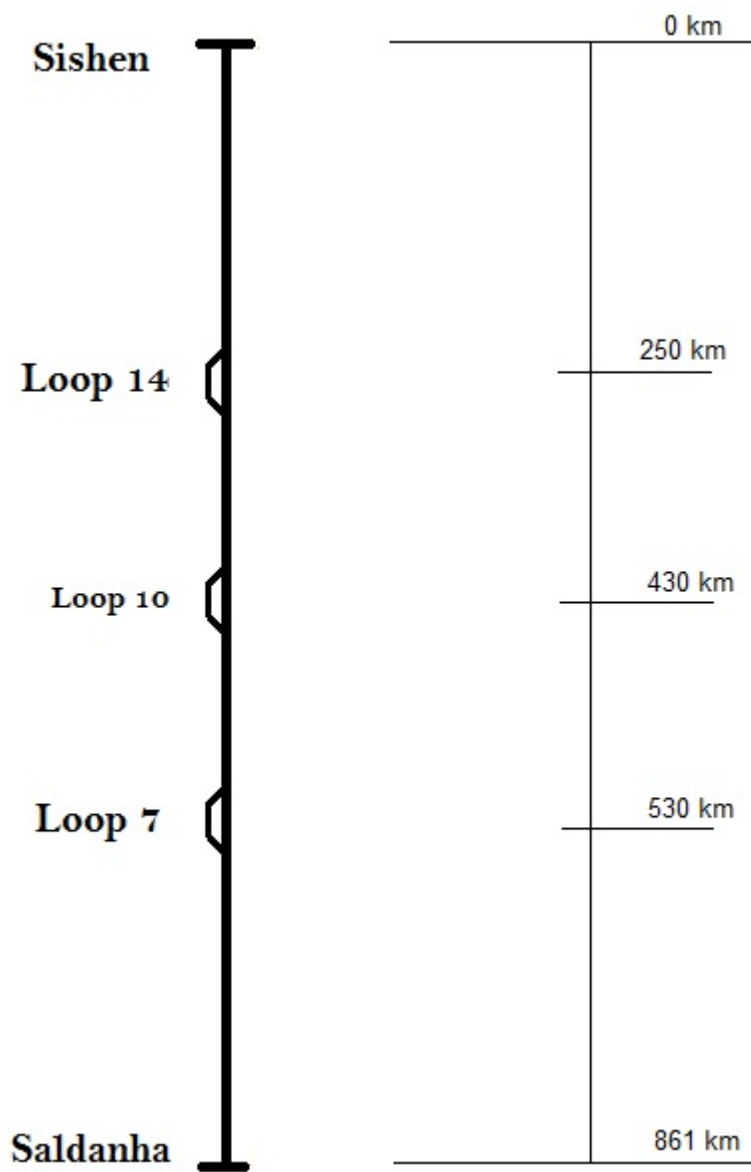


Figure 4: Sishen-Saldanha Single Rail Line, with 19 passing loops constructed

## 5. LITERATURE REVIEW

### 5.1. Capacity

Differences in requirements result in different views of capacity. This view of capacity can be according to market need, infrastructure planning, timetabling and operations. These are summarised in Fig. 3. (UIC Code 406)

Market (customer needs)	Infrastructure planning	Timetable planning	Operations
expected number of train paths (peak) expected mix of traffic and speed (peak) infrastructure quality need journey times as short as possible translation of all short and long-term market-induced demands to reach optimised load	expected number of train paths (average) expected mix of traffic and speed (average) expected conditions of infrastructure time supplements for expected disruptions maintenance strategies	requested number of train paths requested mix of traffic and speed existing conditions of infrastructure time supplements for expected disruptions time supplements for maintenance connecting services in stations requests out of regular interval timetables (system times, train stops, ...)	actual number of trains actual mix of traffic and speed actual conditions of infrastructure delays caused by operational disruptions delays caused by track works delays caused by missed connections additional capacity by time supplements not needed

Figure 5: Different views of capacity

Abril (2008) states that different types of capacity are usually used in the railway environment:

- **Theoretical capacity:** It is the number of trains that could run over a route, during a specific time interval, in a strictly perfect, mathematically generated environment, with the trains running permanently and ideally at minimum headway (i.e. temporal interval between two consecutive trains). It is an upper limit for line capacity. Frequently, it assumes that traffic is homogeneous, that all trains are identical, and that trains are evenly spaced throughout the day with no conflicting situations or disruptions. It ignores the effects of variations in traffic and operations that occur in reality. Theoretical Capacity is calculated using an empirical formula.

It is actually not possible to run/apply the number of trains that can be worked out theoretically, due to other constraints that needs to be considered. With the help of simulation software, this empirical formula could be calibrated to fit the heavy haul rail lines of South Africa.

• **Practical capacity:** It is the practical limit of “representative” traffic volume that can be moved on a line at a reasonable level of reliability. The “representative” traffic reflects the actual train mix, priorities, traffic bunching, etc. If the theoretical capacity represents the upper theoretical bound, the practical capacity represents a more realistic measure. Thus, practical capacity is calculated under more realistic assumptions, which are related to the level of expected operating quality and system reliability, as shown in Fig. 1. It is the capacity that can permanently be provided under normal operating conditions. It is usually around 60–75% of the theoretical capacity, which has already been concluded by Kraft (1982). Practical Capacity is the most significant measure of track capacity since it relates the ability of a specific combination of infrastructure, traffic, and operations to move the most volume within an expected service level.

This will be the definition and approach that will be followed in this project, with assumptions and scenario’s explained thoroughly in the model methodology. Abril (2008) names 2 more definitions for capacity, “used” and “available” capacity, but they are not applicable to this paper.

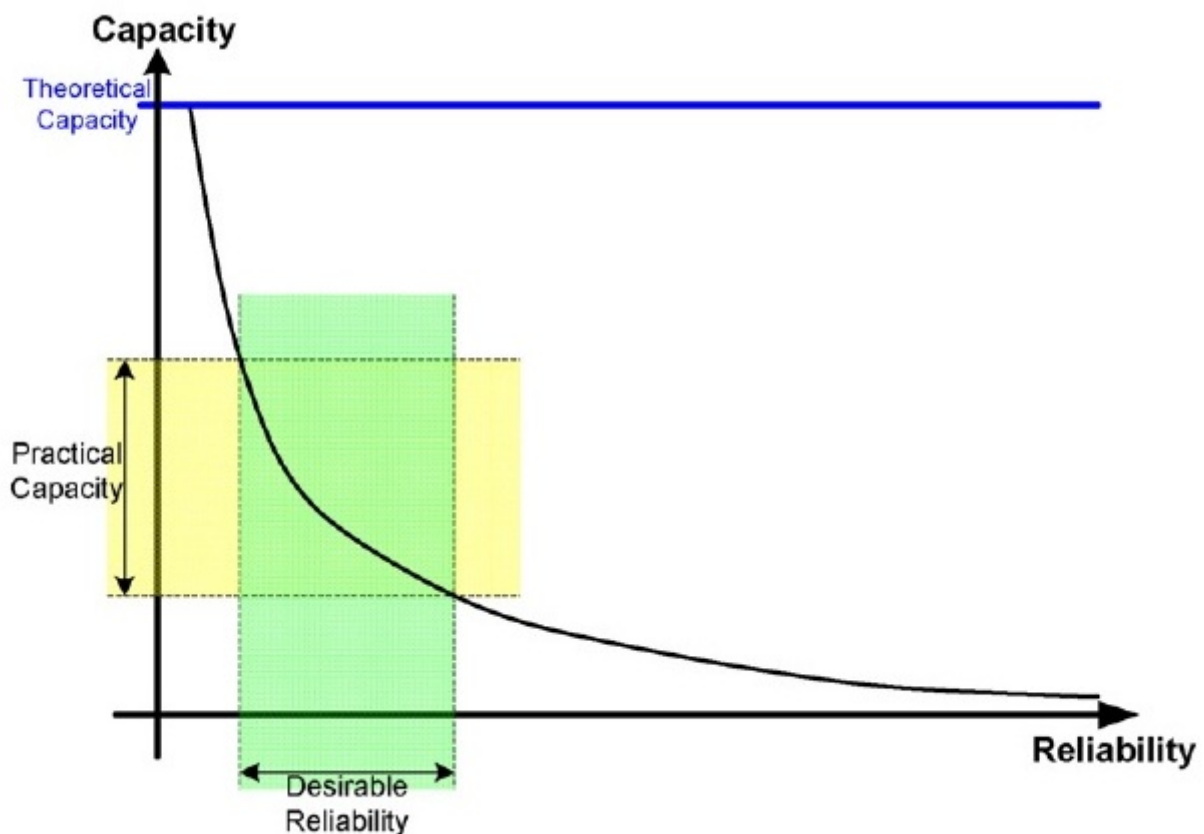


Figure 6: Practical capacity involves the desirable reliability level. (Abril, 2008)

## 5.2. Methods Used

Technical literature (Abril et al, 2008) divides the methods for estimating the capacity of a rail line into these main subsets:

- A “Capacity Calculation Method”, used by the UIC in Code 406.
- Analytical methods
- Optimization methods
- Simulation methods

### 5.2.1. Capacity Calculation Method (UIC Code 406)

This point describes the methodology for determining capacity consumption. Capacity consumption shall be measured by infrastructure occupation in a defined time position, to which is added time supplements for timetable stabilisation and, where necessary, maintenance requirements.

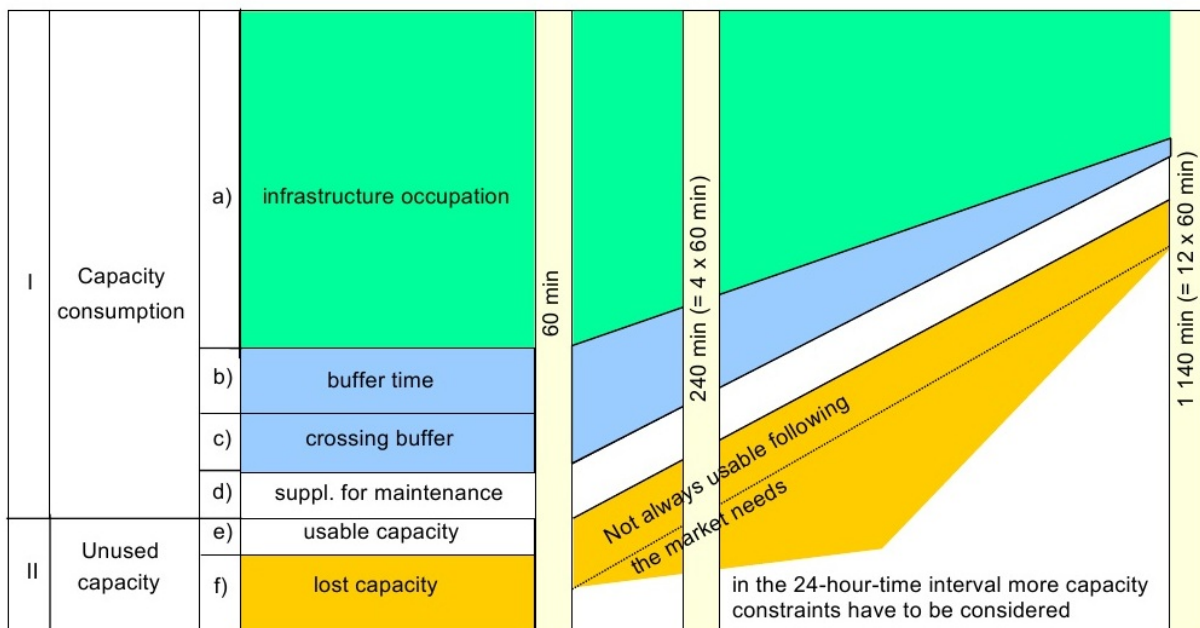


Figure 7: Determination of Capacity Consumption

The formula for determining capacity consumption shall be as follows:

$$k = A + B + C + D$$

k: total consumption time [min]

A: infrastructure occupation [min]

B: buffer time [min]

C: supplement for single-track lines [min]

D: supplements for maintenance [min]

$$K = k - 100 / U$$

K: capacity consumption [%]

U: chosen time window [min] (I + II)<sup>16</sup>

### 5.2.2. Analytical Methods

These are very simple models aimed at determining a preliminary solution. They are mostly used to model and calculate theoretical capacity, by means of mathematical formulae or algebraic expressions, and the practical capacity is then determined only as a percentage of the calculated theoretical capacity. (Abril, 2008)

### 5.2.3. Optimisational Methods

Optimisation methods are designed to provide a more strategic approach to solving the railway capacity problem and provide much better solutions than purely analytical formulae. These are based on obtaining optimal, 'maximum' timetables. These optimal timetables are usually obtained by using mathematical programming techniques (Mixed Integer Linear Programming Formulations and Enumerative algorithms). (Abril, 2008)

### 5.2.4. Simulation Methods

Abril (2008) defines: Simulation is the imitation of an operation of a real-world process or system over time. It is the representation of dynamic behaviour of a system by moving it from state to state in accordance with well-defined rules. Simulation methods provide a model, which is as close as possible to reality, to validate a given time-table. For train scheduling, simulation has often been used in combination with other methods, originating what could be defined as "hybrid models". Since the 1980s, Petersen (1974) are quoted for their work, which uses combined techniques, such as dynamic programming and branch-and-bound in a simulation context.

### 5.3. Simulation Software

There are numerous software packages available that are specially developed for railway networks. Abril et al. (2008) discusses these packages in detail, and they include software such as:

- DEMIURGE
- CMS
- RAILCAP
- VIRIATO
- CAPRES, etc.

The software that will be used for this project is “Simu” and was developed by the IBS Company situated in Germany, and who is now part of Hacon.

Simu also works in the same manner as the packages mentioned above. It allows users to add all the characteristics of a train and rail line as an input to the system; and then build a timetable to simulate. The characteristics include:

- Route length
- Route geometry (including altitude, rail line geometry)
- Stations on route
- Train length
- Train speed
- Departure times
- Stoppage times
- Delays
- Maintenance stoppages
- Constraints

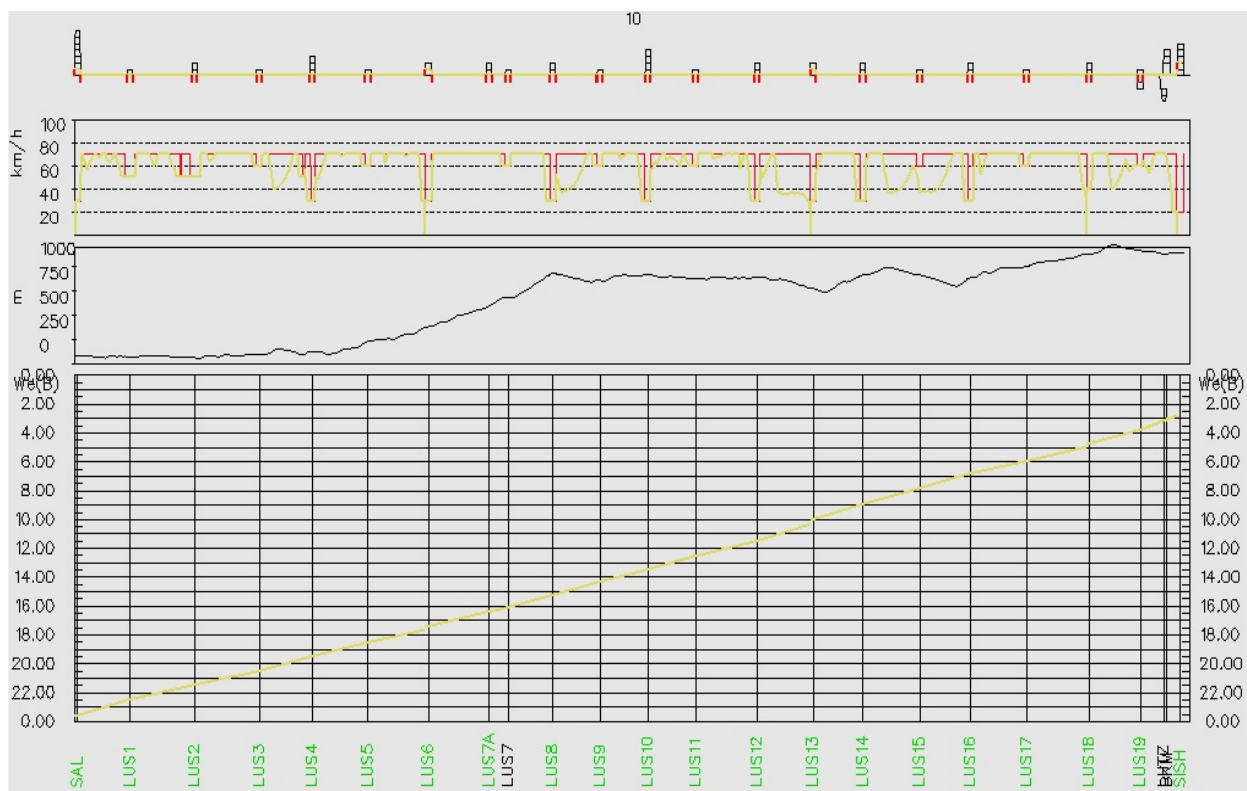
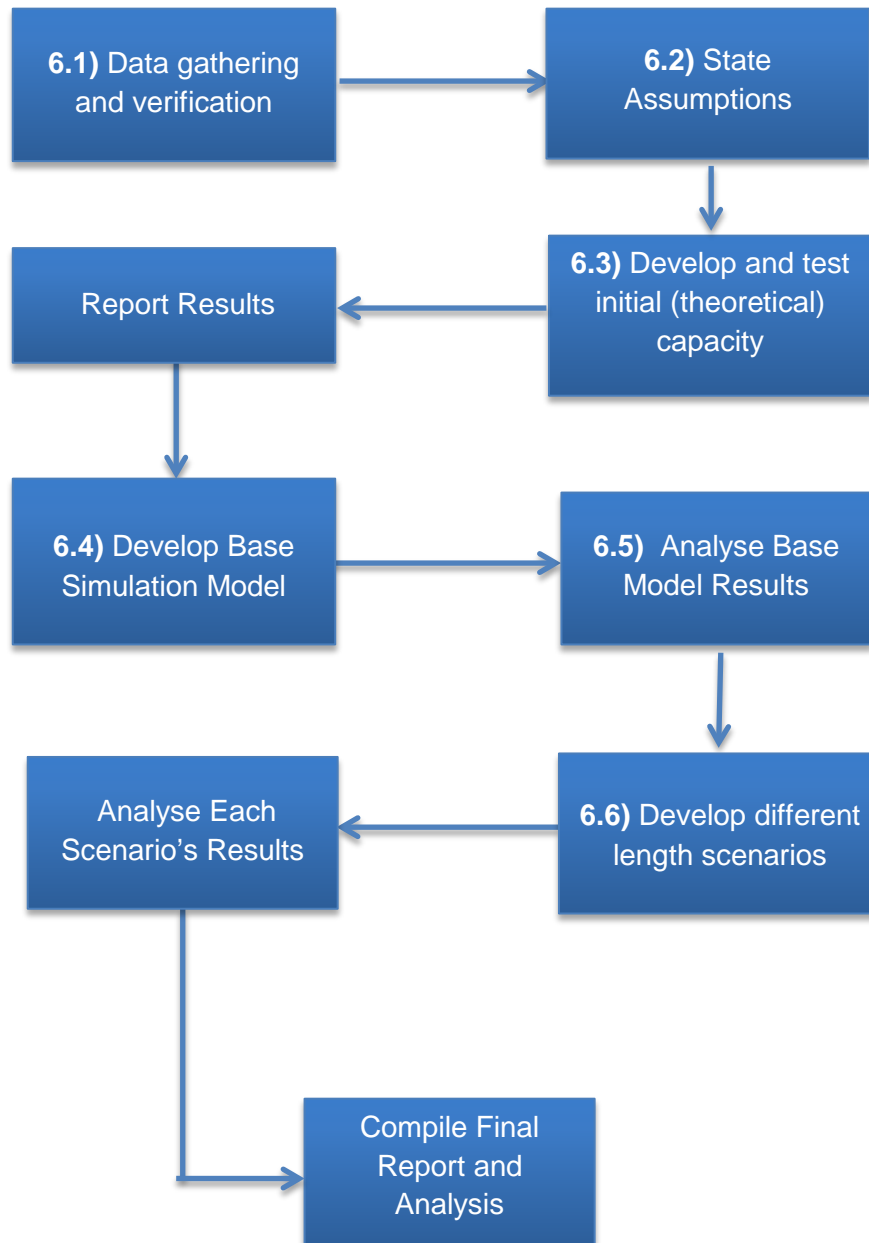


Figure 8: Typical view of the Simu software package

## 6. SIMULATION MODEL

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The following general simulation steps will be followed in the analysis:





## 6.1. Data Collection and Verification

The following data will be used in the simulation model:

- The time period for every simulation scenario is done for 7 full days (168 hours).
- The amount of simulation replications of each scenario is 20.

### Sishen – Saldanha Rail line:

- Total Length: 861km
- Maximum ascent: 1295m
- Number of passing loops: 19
- Standard distance between loops: 45km
- Only T1 type loops will be used for the simulation models
- Fully loaded trains travel from Sishen to Saldanha (Southbound) only, and empty trains from Saldanha to Sishen (Northbound). This is a representative assumption taken from reality, as all the trains gather iron ore from mines in the surrounding area around Sishen and transport the ore for export to the harbour at Saldanha.

### Train Characteristics:

- Top Speed of trains: 70km/h
- Total length of a train: 2400m
- Mass of trains:
  - Fully loaded train: 25920 tons
  - Empty train: 4860 tons

## 6.2. Assumptions

The assumptions for the simulation model that will be made are:

### 6.2.1. Software Assumptions

The Simu software package has certain logic that is already assumed in the software. This includes:

- A fully loaded train has priority (right of way) over an empty one.
  - The reason for this is to save power. It takes a fully loaded train an immense amount of energy to reach its maximum velocity. This is a general rule of act, to try and save as much power as possible.
- Empty trains wait in a loop whenever a crossing is needed.
- Acceleration and deceleration values are set

### 6.2.2. Homogenous traffic

The first assumption of the simulation model is that all trains used in the model will be homogenous. This means that all trains will be as stated in point 6.1.

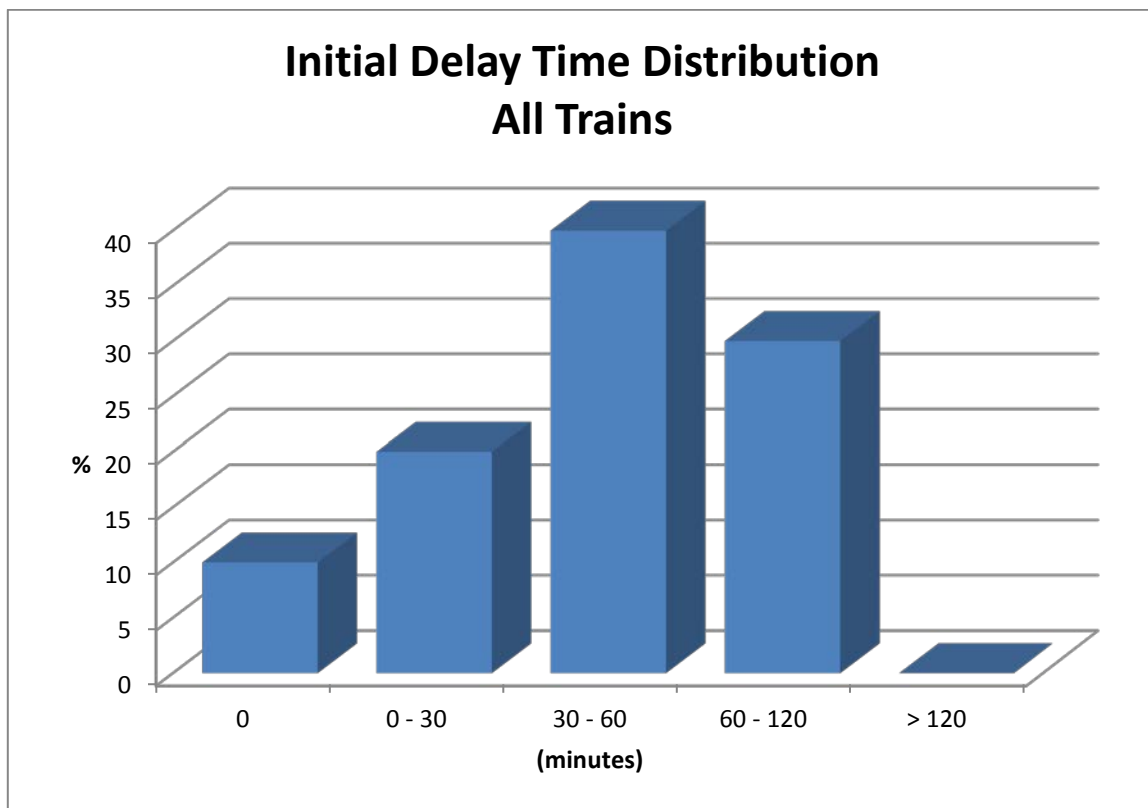
Loaded trains move in one direction (Sishen to Saldanha) and loaded trains in the opposite direction.

### 6.2.3. Reliability

The reliability/stability of the network will be of ideal conditions, with no breakages or maintenance stoppages.

### 6.2.4. Initial Delays

Initial delays are the time delay for a train when departing from a station. This is usually as a result of train operators being late, or trains departing late because of human error, etc. According to information received from Transnet, this value will be of the following distribution:



Time Value (min)	%
0	10
0 - 30	20
30 - 60	40
60 - 120	30
> 120	0

### 6.3. Development of Theoretical Capacity

As seen in point 5.1 of the literature study, theoretical capacity serves as an upper limit for capacity, and assumes all conditions as ideal. It is defined as the maximum number of trains that can fit onto the rail infrastructure without any conflicting situations, assuming ideal conditions.

#### Simulation Method (Simu)

This was done by:

- o Firstly, simulating a fully loaded train at ideal conditions to determine the running time between loops.
- o Simulate an empty train (with stops in loops – due to *right of way* regulation) to determine the running time between loops. Record the shortest possible running time between specific loops without any conflicting situations.
- o Populate a 7 day (168 hours) timetable according to this minimum running time value between loops that have been determined.

The maximum number of trains that can run on the current infrastructure in scope without conflicting situations within 168 hours was found to be 72; which will serve as the Theoretical Capacity. The shortest time between train departures were also found to be 2h 20min, which will serve as the standard interdeparture time for trains on this infrastructure.

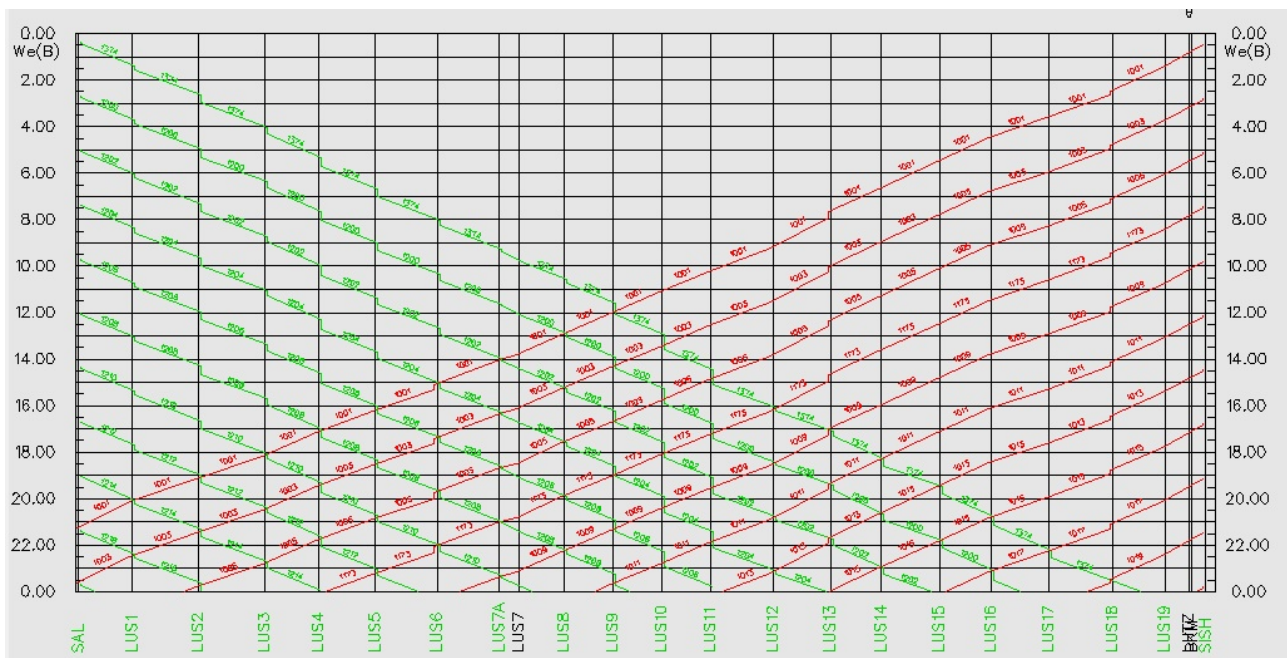


Figure 9: Timetable developed for determination of theoretical capacity

### 6.4. Develop and test Base Simulation Model

The initial delay value distribution was used as stated in 6.2 Assumptions, and the base simulation model consisted of a timetable for the whole length of the rail line (861km).

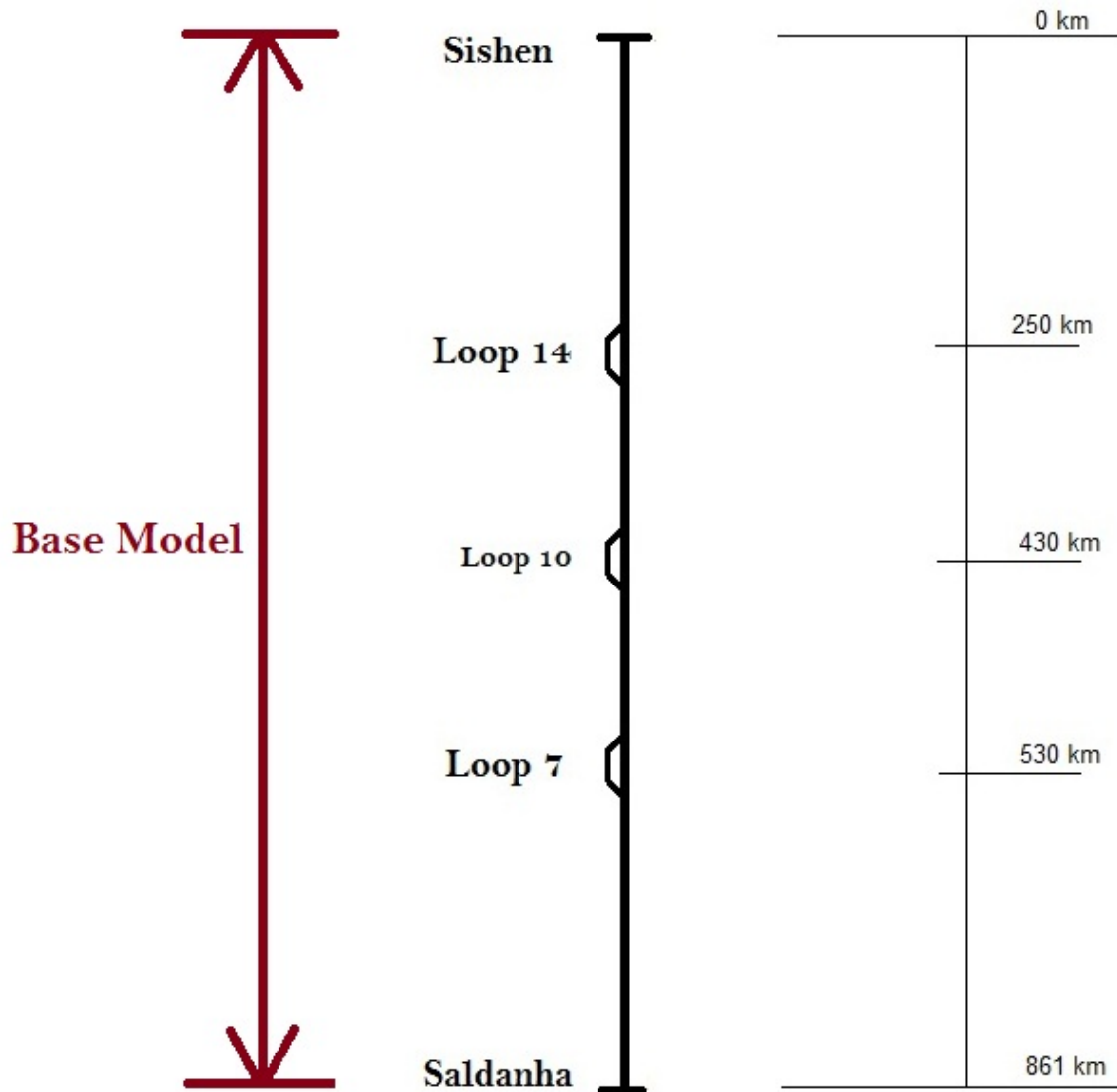


Figure 10: Base Model Simulation Rail Line Length

### 6.5. Base Model Results

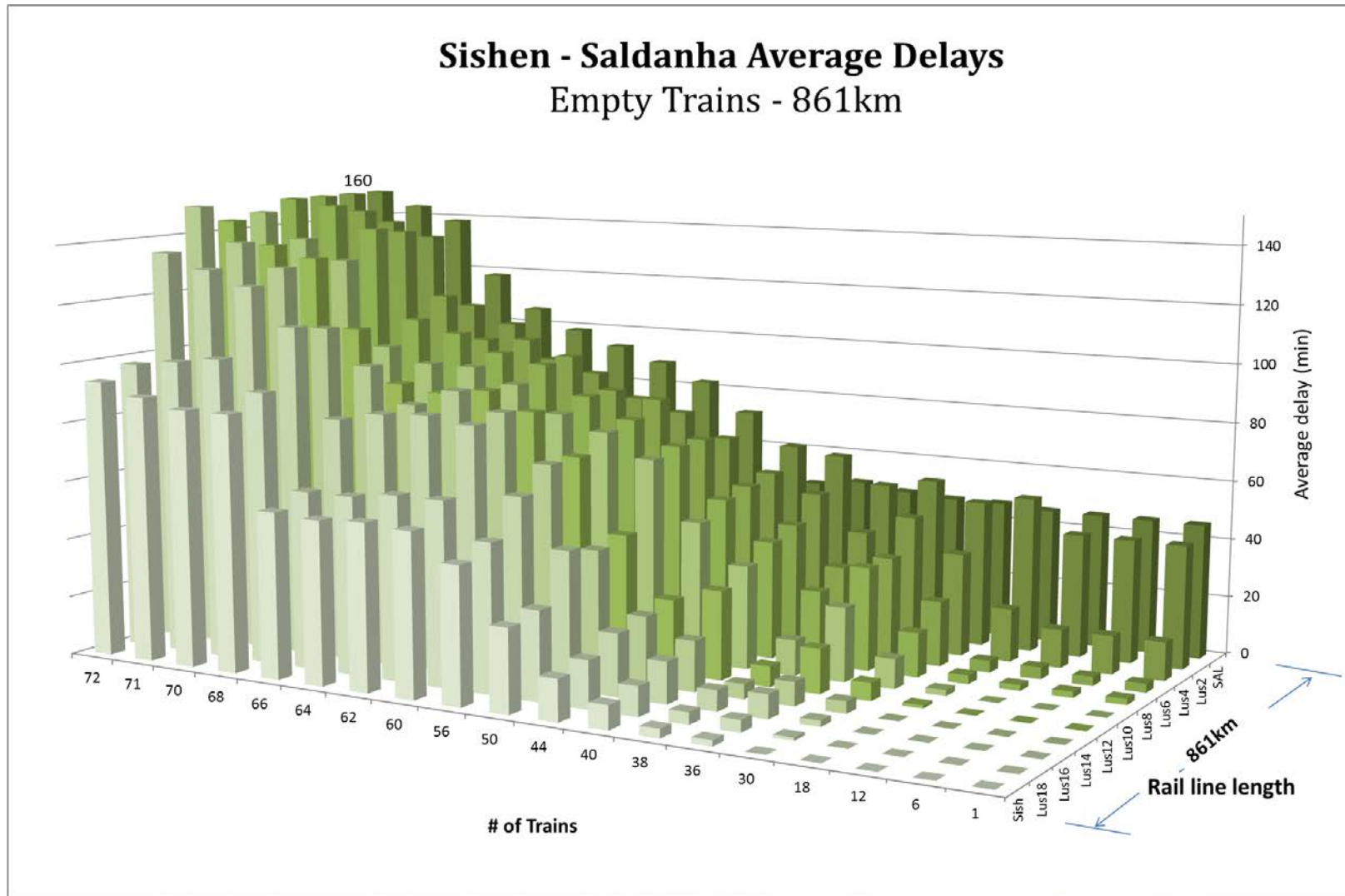


Figure 11: Base Model Results: Empty Trains

### Empty Trains – 861km

The graph shows the average delay time per train (in minutes) to reach a certain loop/station. As seen from the x-axis viewpoint, one can follow a train's delay times 'on-route' following the y-axis. For example: if we follow the most right-hand side on the x-axis of the graph, there is only 1 train in the system. We can see that there is absolutely no delay for this train in the system due to absence of congestion or disruptions – except that the last 4 columns of this single train shows a small delay; and this is due to the initial delay times being incorporated into the system. Empty trains travel from Saldanha to Sishen and this single train will 'make up' its lost time very rapidly within the first 4 loops – as seen in the graph.

If we follow along the x-axis we can see that the average delay values per train start increasing in an exponential manner as the number of trains in the system increases. This is due to congestion by the sheer number of trains in the system, as well as the initial delays being incorporated.

What is important to notice of this graph is:

- The trains' overall average delay time values at the point where the system nears the theoretical capacity value of 72
- The clear exponential shape of the graph
- The maximum delay value of 160minutes for this length of rail.

### Loaded Trains – 861km

The next graph on the following page shows the average delay values for the same scenario, but for the loaded trains in the system.

If we follow the same example of the single (initial) train on the graph, we see that its initial delay value after leaving from the Sishen station is close to 50minutes, but the train does not 'make up' the lost time through the following loops as rapidly as an empty train. There are 2 reasons for this:

1. An empty train has certain stoppages in loops already scheduled into its set of rules. Whenever an empty train reaches a loop where it is scheduled to stop, but there is no need for the train to stop and wait (as is the case for #1 train in the system) the train will eliminate wasted time. It will reach the next loop early and the system will record a decrease in the delay time.
2. A loaded train has no scheduled stoppages in the loops, so it cannot decrease the delay time value in the same manner as an empty train.

What is important to notice of this graph is:

- The much less rapid increase in the delay time with increase in # of trains in the system
- The high delay values at the end of the loaded trains' route (Saldanha). This is due to a very congested system and the result of the system nearing its capacity. The sum of the delay times for a loaded train becomes seemingly apparent near the end of its scheduled journey.
- The maximum delay value of 90 minutes.

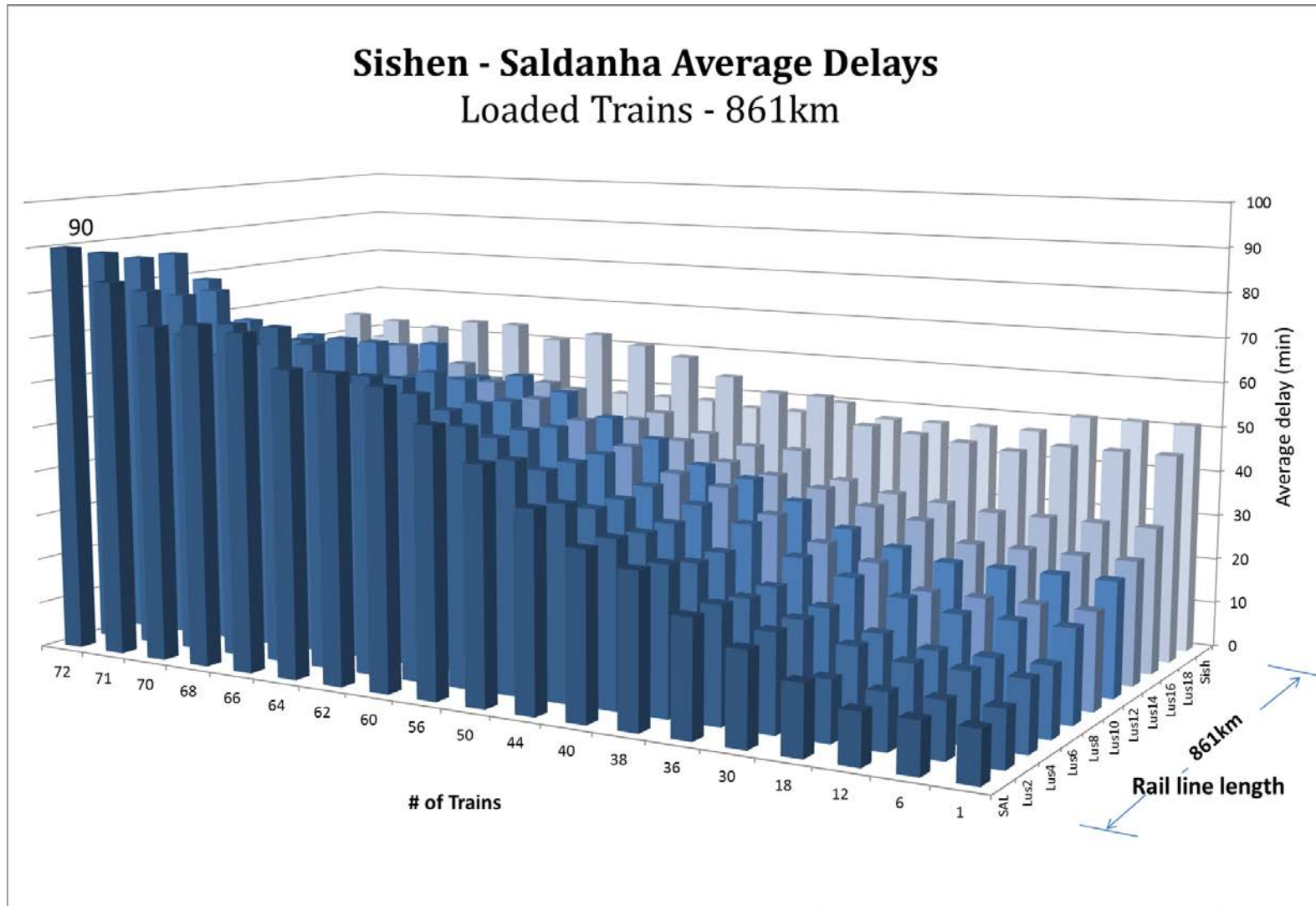


Figure 12: Base Model Results: Full Trains

### 6.6. Different Length Scenarios

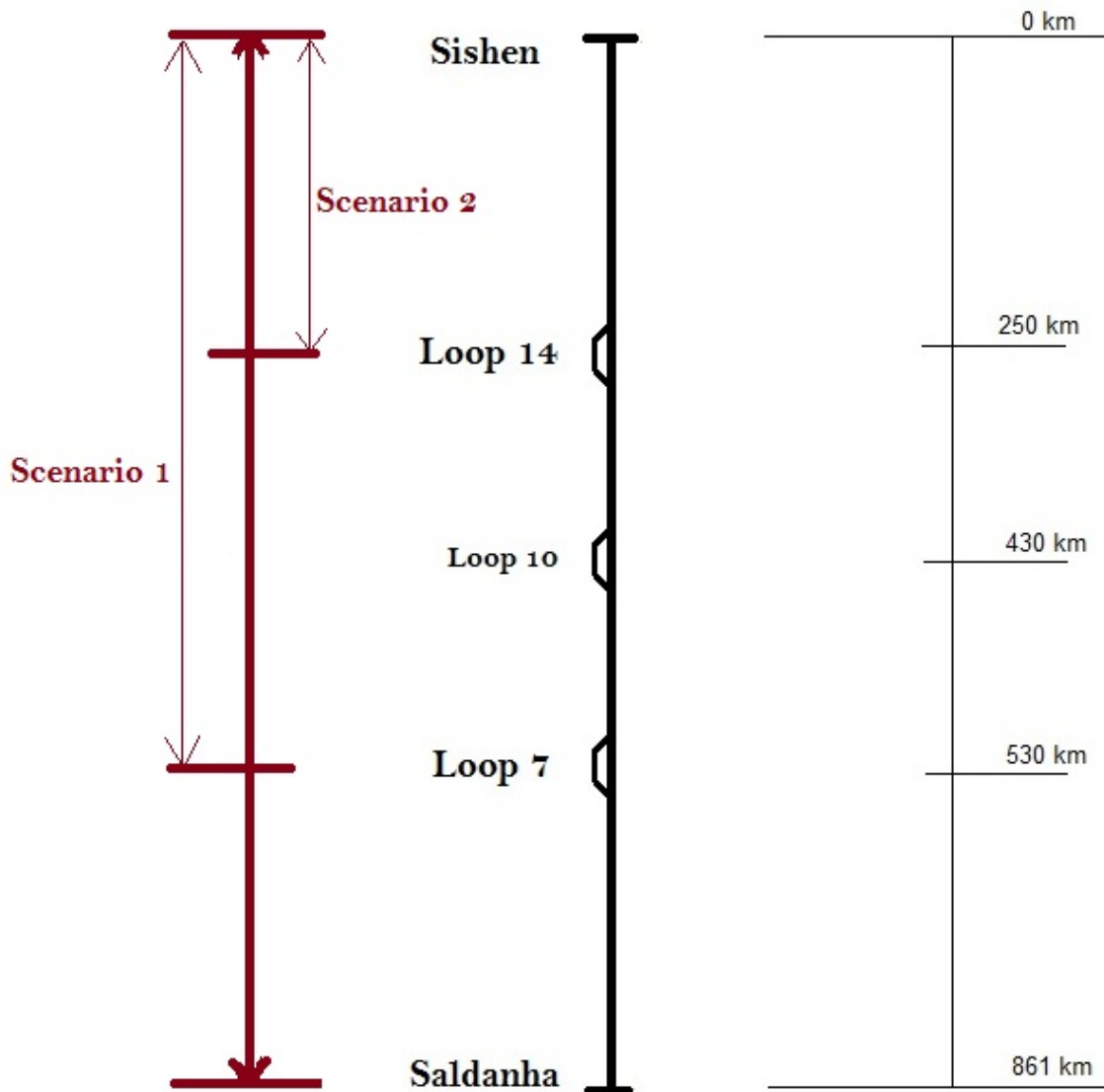


Figure 13: Different Length Scenarios

The next scenarios involve the altering of the rail line’s length and observing what variations it ensues to the system behaviour. The decision was made to alter the distance according to the passing loops on the rail line, in order to preserve uniformity in the results. The rail line was divided into thirds.

The first length scenario is based on 2-thirds of the 20 total nodes on the rail line, being shortened from Sishen station to Loop nr.7. The total distance measures 530km.

The second length scenario has the rail line shortened another third, from Sishen station to Loop nr.14. This total distance measures 250km.



6.6.1. Scenario 1: 530km

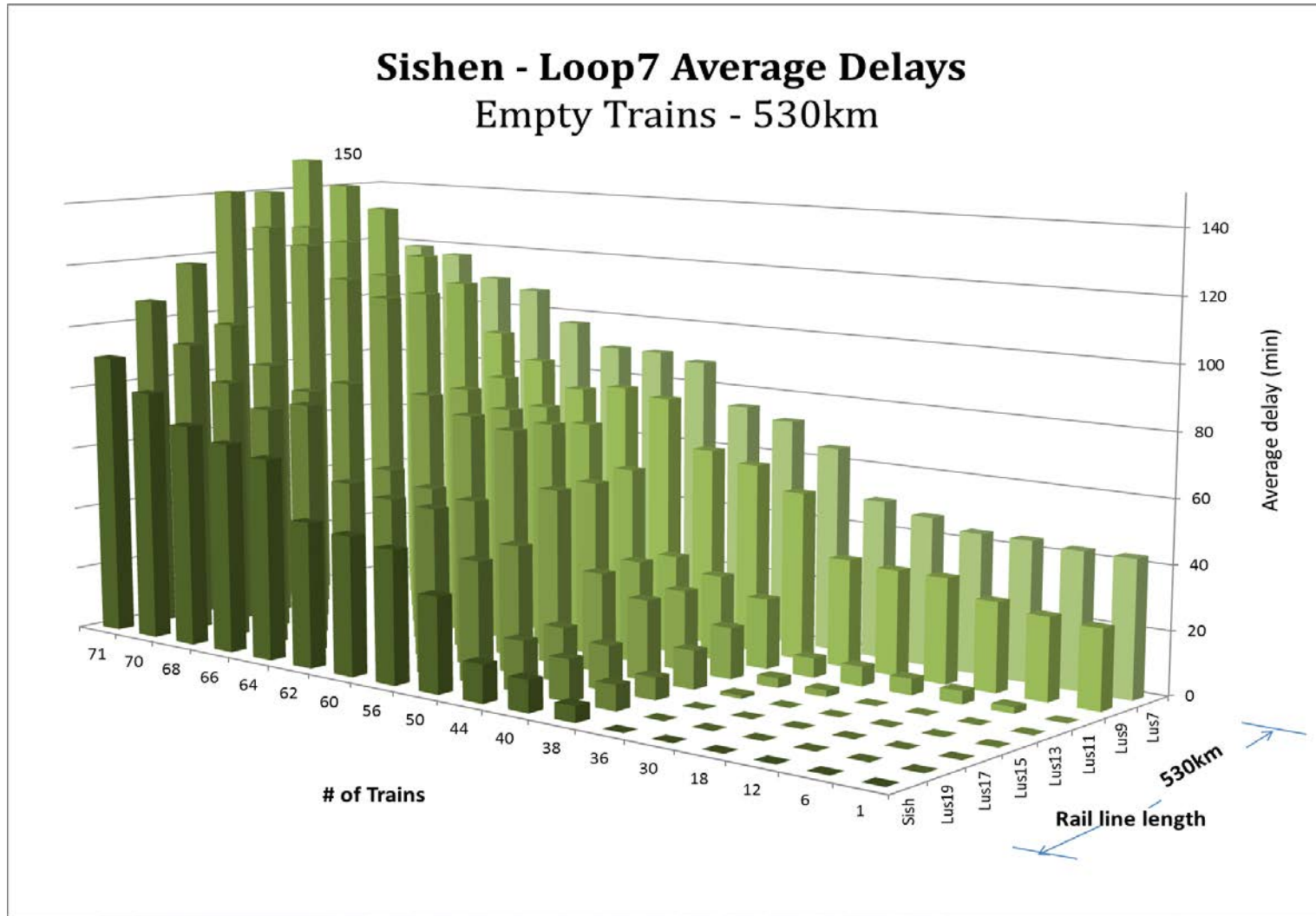


Figure 14: Length Scenario 1 (530km): Empty Trains

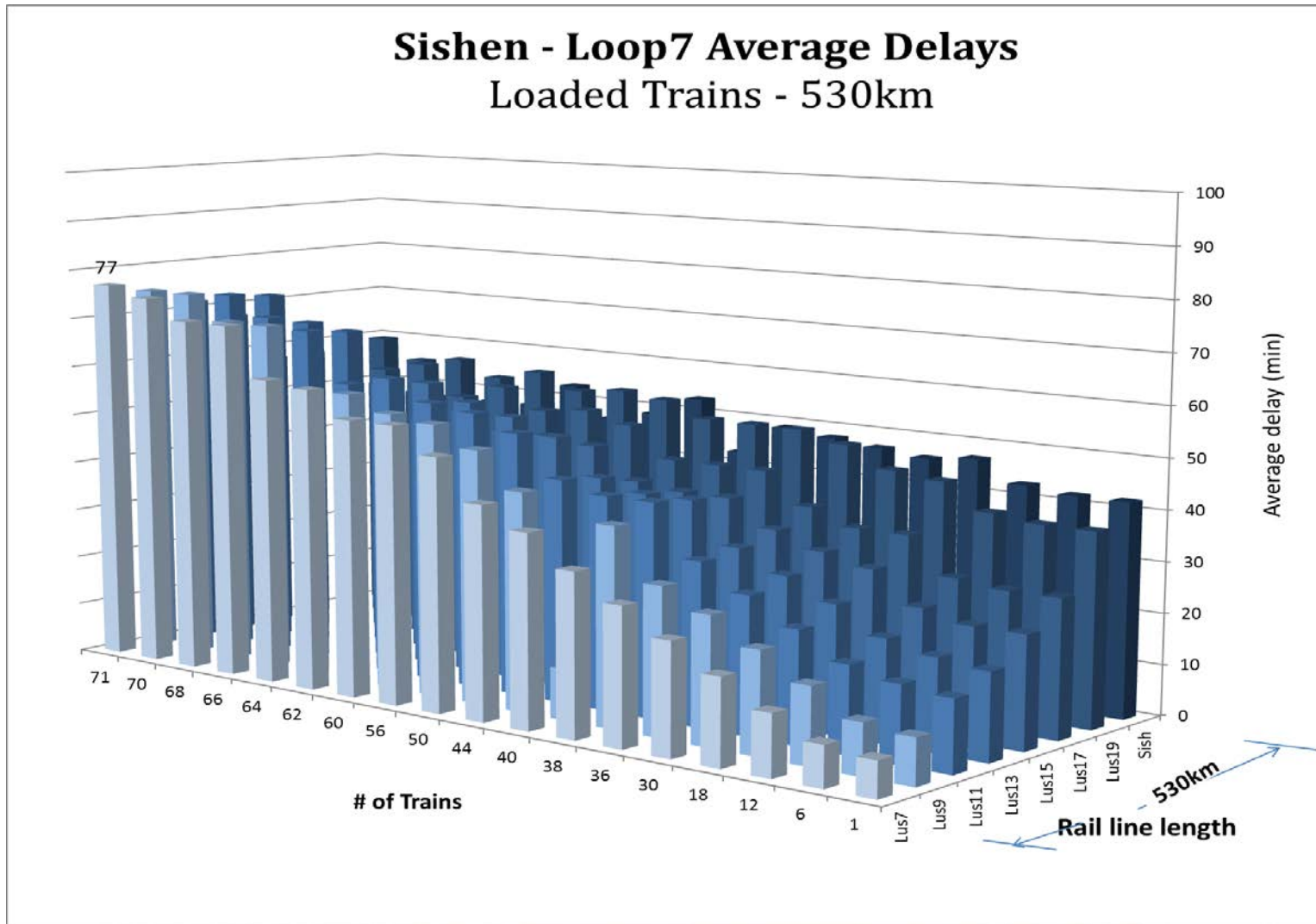


Figure 15: Length Scenario 1 (530km): Loaded Trains

### Empty Trains – 530km

Although the shape of the 2 graphs look the same as with the base model it is once again important to notice:

- The shape of the scenario's graph:
  - Notice the swift time made up by the trains, up to where #38 trains are in the system.
  - The overall delay values are also much less than in the base model, a smaller less rapid peak is reached from 70 to 72 trains.
- The maximum delay value of 150min.

### Loaded Trains – 530km

Once again, notice:

- The slow decrease in the delay times on-route for uncongested rail line. (# of trains < 12)
- Shape of the graph. There is a much more stable climb to the peak of the delay times' graph.
- The maximum delay value of 77min.
- The difference between the graph for empty trains and the graph for loaded trains. The empty trains' maximum delay value is twice as much as the loaded one. This is due to the 'right of way' regulation, where a full train has right of way on a single line; and an empty train always needs to stop to allow a loaded train to pass, resulting in the higher delay values.

## 6.6.2. Scenario 2: 250km

### Empty Trains – 250km

Important to notice:

- System behaviour. There is only a slight (if any) increase in delay times with increase in # of trains. The system appears very stable without any disruptions or any peaks in delay time value.
- The maximum delay value is 60min. This is more than half the value of the previous scenario. It is also only 15min more than the average starting initial delay.

### Loaded Trains – 250km

- System behaviour: The slow increase in delay times with the increase in # of trains.
- The maximum delay value of 72min.
- Maximum change of approximately 30minutes in delay times over the whole graph.

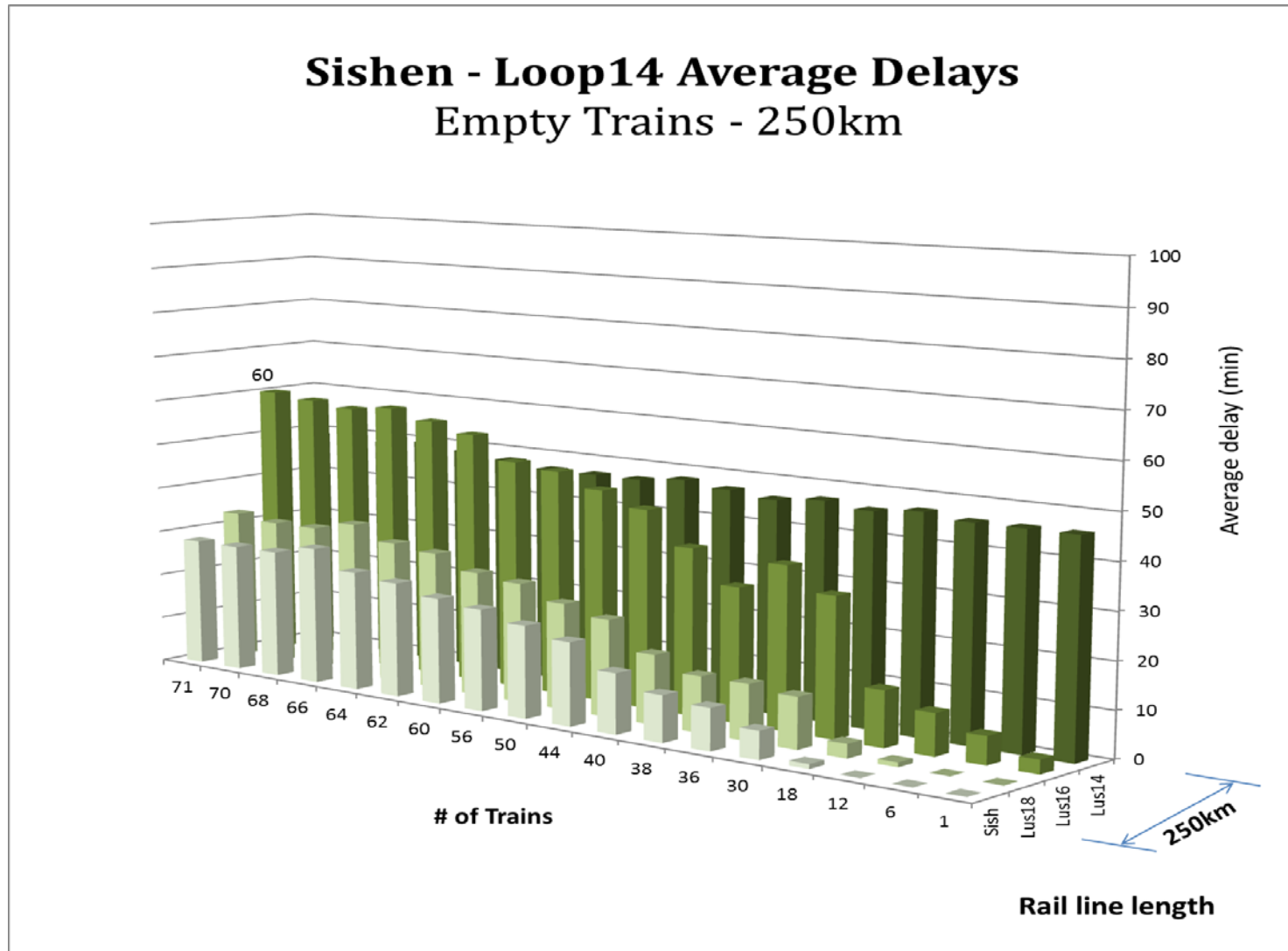


Figure 16: Length Scenario 2 (250km): Empty Trains

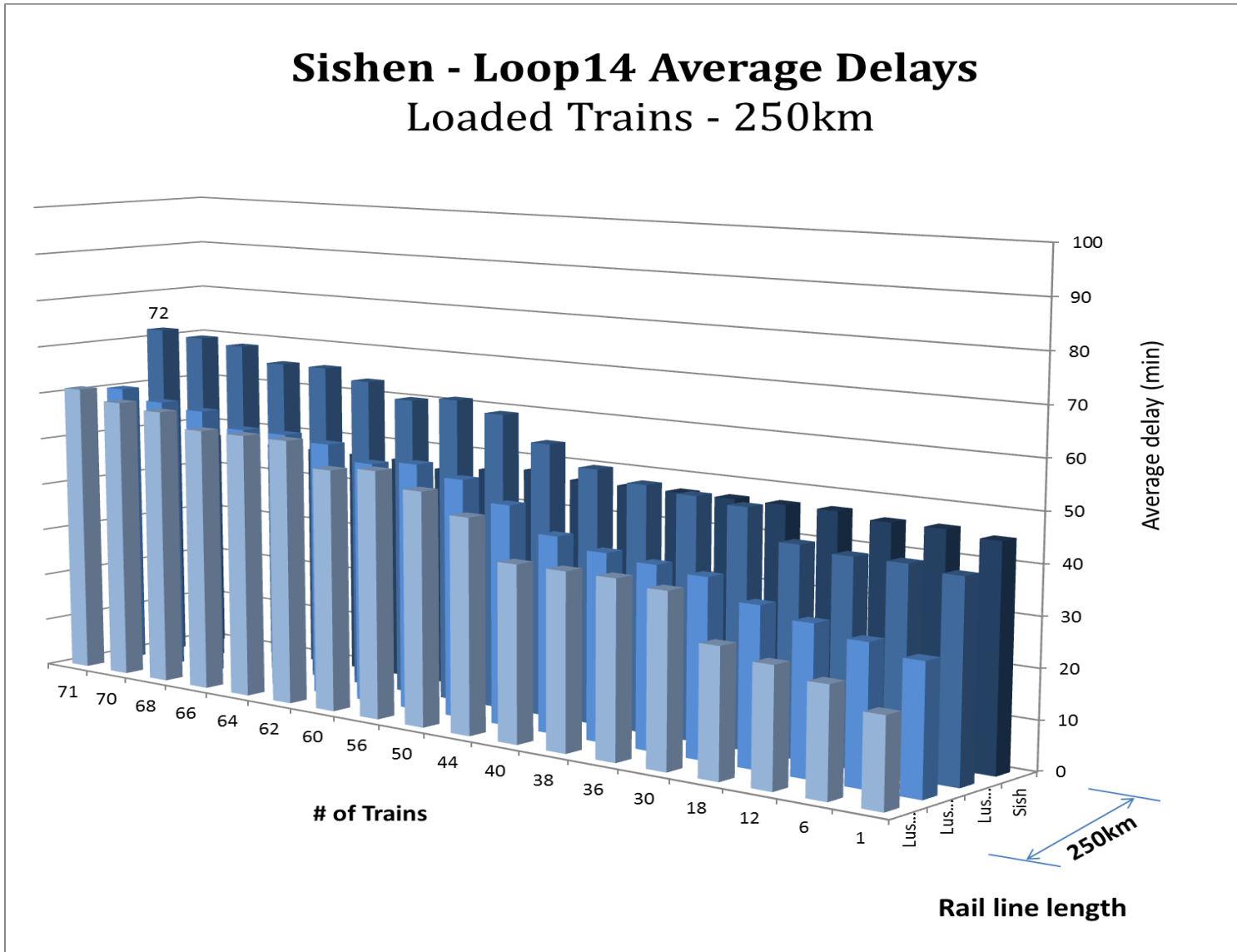


Figure 17: Length Scenario 2 (250km): Loaded Trains

## 7. CONCLUSION

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### 7.1. Theoretical Capacity

The maximum number of trains that could fit onto the ideal railway system without any conflicting situation (i.e. theoretical capacity) within the timeframe of 7 days or 168 hours was determined to be 72.

### 7.2. Base Model: 861km

The time to travel from Sishen to Saldanha

- for a loaded train is 20h 50min
- for an empty train is 25h 21min,

A maximum delay of 160minutes for the base simulation model seems reasonable; taking the above mentioned travelling times into consideration. But without any reliability, heterogeneity or maintenance constraints on the system this value is actually high. When all of the above mentioned rail line capacity factors are taken into consideration, the actual number of trains that could fit onto the whole length of rail line will be much less than 72.

The base simulation model will serve as a basis for future research to be done on the rail line.

### 7.3. Different Length Scenarios

Figure 18 depicts the results of all the scenario results graphically.

The simple fact of using the full length of the rail line affected the capacity consumption of the system within nearing the theoretical capacity limit the greatest of all the length scenarios – the highest peak of 102.3 minutes. All scenarios have similar system stability within low number of train ranges, (less than #36) but as this number of trains in the system increases, the delay value on the full length of the rail line increases the most significantly. This can be described as a ripple effect due to the fact that more trains can fit onto the rail line of 861km than any other length scenario – and the effect of one train arriving late at a station is emphasized throughout the system - thus the high delay values for the whole length of the rail line.

The delay values for the first length scenario of 530km are relatively high still, resulting in only a 9minute decrease in peak delay time although a third of the rail length is removed. Although the first scenario's delay values look more stable than the base model's values, the altering in rail line length still results in only a 9% reduction in peak delay time.

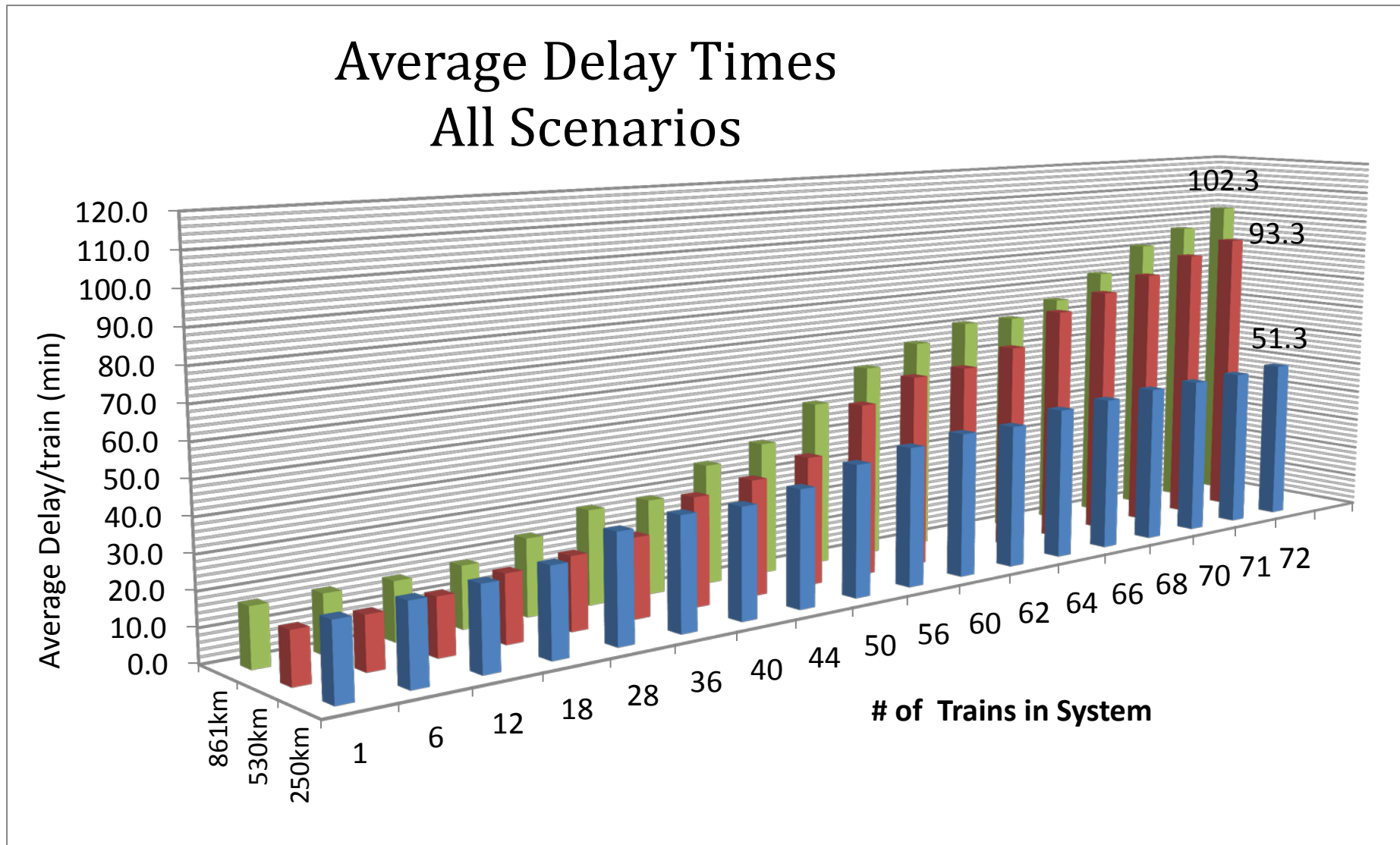


Figure 18: All Scenario Results

However, a 50% reduction in peak delay time values is observed for the second simulation scenario of 250km. No actual peak is reached within the theoretical capacity limit for this infrastructure and the system delay values appear to be very stable right throughout the increase of the # of trains in the system. The length of the rail line affected the capacity consumption of the system in a way that can be observed at train #72 of the system. The peak delay times for the different scenarios decrease exponentially with the nominal decrease in rail line length.

Against common logic – which reasons that the longer the rail line, the more trains must be able to “fit” onto the line – these results prove that one can increase capacity consumption for shorter single rail line lengths with a substantial factor. This is still dependant on numerous other factors (as mentioned) which needs to be taken into consideration before determining this increase in trains in the system.

These results and data will be made available for industry; to further study the impacts that external factors have on a rail network. All results can now be analysed accordingly and motivation behind system behaviour can be defined.

This information could prove essential for any railway-related company that is in the process of feasibility determination of future projections and impending planning.



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