A FEASIBILITY STUDY INTO THE USE OF STRING TRANSPORT SYSTEMS FOR PASSENGER RAIL IN NEW SOUTH WALES

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ABSTRACT

String Transport Systems (STS) are an efficient rail technology currently under development in Russia by String Technologies Unitsky. This technology utilises high tension steel cables within a concrete filler on an elevated structure, in place of conventional steel rails. The feasibility of implementing a new rail technology in New South Wales (NSW); specifically STS in this case, has been explored throughout this dissertation.

To determine the feasibility of STS application, a technical analysis and design has been carried out in this dissertation, particularly in relation to; application site selection, demand estimation, design, and costing. Based on this research, the best use for this novel technology was found to be a route from Sydney's Kingsford-Smith Airport to Bondi Beach which has been designed and developed. The structural and geotechnical elements of this route were designed using Australian Standards, and compared with data available from String Technologies Unitsky. This information allowed preliminary costing figures to be calculated.

This design found that the route was capable of carrying 12,300 passengers per day between the Kingsford-Smith Airport and Bondi Beach, with provisions to increase this number to 80,000 in the future. The travel time was 25 minutes on this 20.42 km route, which is less than current public transport options, as well as personal transit. Structurally, the typical supports and foundations of a STS network were compliant with Australian Standards, ensuring a satisfactory design. The string-rail, the novel component within this technology, also sufficed design loading and when life cycle costing was considered, STS offered savings of 75% when considering its counterparts.

From the analysis of the transport elements, and structural and geotechnical design of the structure, STS has been proved feasible for small scale implementation in highly urbanised NSW areas. Based on this conclusion, further research towards implementation should now be possible.

ACKNOWLEDGEMENTS

The technology discussed in this dissertation, String Transport Systems, is the patented technology of Doctor Anatoly Yunitskiy. Where the technology has been discussed, and where Yunitskiy's conclusions have been referred to, due referencing has been used. It is acknowledged that this technology belongs to him, and this dissertation is aimed at providing a feasibility into this futuristic technologies applications in New South Wales.

Doctor Upali Vandebona of the University of New South Wales has acted as the supervisor for this dissertation. His tireless guidance and mentorship have assisted in the production of this dissertation which would not have been possible without his support and years of experience.

I also wish to thank my family and friend for their love, support and assistance throughout my studies at the University of New South Wales as well as completion of this dissertation.

CERTIFICATE OF ORIGINALITY

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the dissertation. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the dissertation. I also declare that the intellectual content of this dissertation is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

Signed

Aaron James Hargraves

1st November 2013

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LIST OF ACRONYMS

ACN	Australian Company Number
AS	Australian Standard
AUD	Australian Dollar
CBD	Central Business District
CHS	Circular Hollow Section
CPI	Consumer Price Index
DC	Direct Current
FOS	Factor of Safety
GOA	Grade of Automation
HV	High Voltage
LRT	Light Rail Trains
NPV	Net Present Value
NSW	New South Wales
Q&A	Question and Answer
RAAF	Royal Australian Air Force
STS	String Transport Systems
STU	String Technologies Unitsky
TSY	Transport Systems Yunitskiy
UB	Universal Beam
UDL	Uniformly Distributed Load
UNSW	University of New South Wales
UST	Unitsky String Transport
USD	United States Dollar
YST	Yunitskiy String Transport

PART 1: INTRODUCTION

1 INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The New South Wales' passenger rail network is expansive, extending to the majority of New South Wales, spanning many thousands of kilometres. There are currently light rail and heavy rail services in use, with most of Sydney's suburbs having rail transit options.

Sydney's urban rail network is suffering from excessive patronage putting a large demand on the network. This has resulted in the network reaching capacity in many locations, and with high levels of urbanisation, network extensions are both costly and technically difficult.

Areas such as Sydney's Eastern suburbs do not have a rail network and have been required utilising lengthy bus journeys to reach the city. This and other current methods of dealing with these rail network problems have been inferior, with the problems reaching breaking points before the Government has acted on the problem in many cases. Light rail extensions have been suggested to get around urbanising issues, as well as costly tunnelling works, however they are either slow or costly options.

With these meagre attempts at addressing the problems facing the current Sydney rail network, an appropriate solution is yet to be found. Until such a technology is found, and is implemented, these 'Band-Aid' approach solutions will have to suffice.

String Transport Systems, a developing Russian technology, uses high tension steel cables within a concrete filler on an elevated structure, in place of conventional steel rails. A typical cross section is presented in Figure 22 and from design and testing it appears to be able to operate and satisfy the requirements and needs specified above.

The feasibility of implementing an alternate technology, String Transport Systems in this case, is therefore the topic of this investigation.

1.2 OBJECTIVES

To conclude on this feasibility of implementing an alternate rail technology for use in passenger rail in New South Wales, the following objectives have been set for completion in this dissertation:

- conduct research into the technology, String Transport Systems, and the associated performance measures;
- determine the need for an alternate technology, and the best application for it;
- develop a route or a network for the technology including the estimated demand on the network;
- ensure the structural integrity of the rail technology under operation to Australian Standards;
- determine the financial feasibility of introducing the technology to the New South Wales Passenger Rail Network; and
- determine the feasibility of implementing this technology based on all of the above information.

With these objectives achieved, a realistic conclusion will be able to be made on the implementation of an alternate transport system.

2 LITERATURE REVIEW

String Transport Systems are a unique approach to passenger transportation that combine the concepts of high tensioned steel cables with railway. This technology has been under development in Russia by Dr. Anatoly Yunitskiy since 1977 and is still in development with no active railway of its kind currently built in the world. All that exists is a 1.5 km test model built in 2001 as well as several scaled models of 1:2, 1:5, 1:10 size (Yunitskiy, 2010). A variety of patents and inventions are linked to String Transport Systems. In August of 2010 Yunitskiy published a detailed technical paper on the applications of String Transport Systems technology for use in iron ore transport within Australia (String Transport Systems Limitied, 2010). This will form a platform on the technical design aspects in this dissertation. Multiple suggestions have also been made for possible routes in Tasmania, Adelaide, Gold Coast, Sydney, and interstate predominantly published by Yunitskiy's Transnet company (Yunitskiy, 2013d). These applications as well as the countless papers based on Russian networks will form the basis of the review of the literature associated with the feasibility of the use of String Transport Systems for passenger rail in New South Wales. Where gaps exist, relevant resources will be used in an attempt to fill the gaps for a holistic feasibility study.

2.1 KEY VENDORS

String Technologies Unitsky (STU) is the overarching company responsible for String Transport Systems directed by Dr. Anatoly Yunitskiy. The technology platform, STU has grown from a variety of research developments, representing all of Yunitskiy's innovative technologies and infrastructure including String Technologies Unitsky (STU), String Transport Systems (STS), Unitsky String Transport (UST), Transport Systems Yunitskiy (TSY), Yunitskiy String Transport (YST), all directed by Anatoly Yunitskiy (Yunitksiy, 2013a).

The Company String Technologies Unitsky operates in Russia and is responsible for all technology and developments. This includes development in the rail, automotive and aviation industry. Three subsidiaries are operated in Australia. String Technologies Unitsky Pty Ltd

(ACN 144 498 251) is the freight based application of the technology whilst String Transport Systems Pty Ltd (ACN142 651 812) is the passenger based application. The company Transnet, also owned by Dr. Anatoly Yunitskiy, operated in both Russia and Australia. This company has a slightly different focus than String Technologies Unitsky Pty Ltd and String Transport Systems Pty Ltd, with a focus on a global transportation network. Yunitskiy is quoted as "Internet — global information network, which helps the transition of humanity to a new level in the 20th century. Transnet — global transportation network that will provide a transition to humanity to the next quality level of development in the 21st century." (Transnet, 2012a). The goal of this company is to provide an international network, with sub networks within each continent littered with infrastructure including hotels along the network. Figure 1 below outlines the company hierarchy.

Let it be noted that due to translation of reports from Russian to English and the adaption of the Russian name to English, that several different naming conventions exist within publications and web material. From here on in, the overarching company will be referred to as String Technologies Unitsky and the director, Anatoly Yunitskiy.

Due to the large number of companies set up by Yunitskiy, with such large varieties of applications, the commercial viability of the technology is very prevalent. Each company carries out a variety of different tests and research projects helping to promote the technology towards implementation.

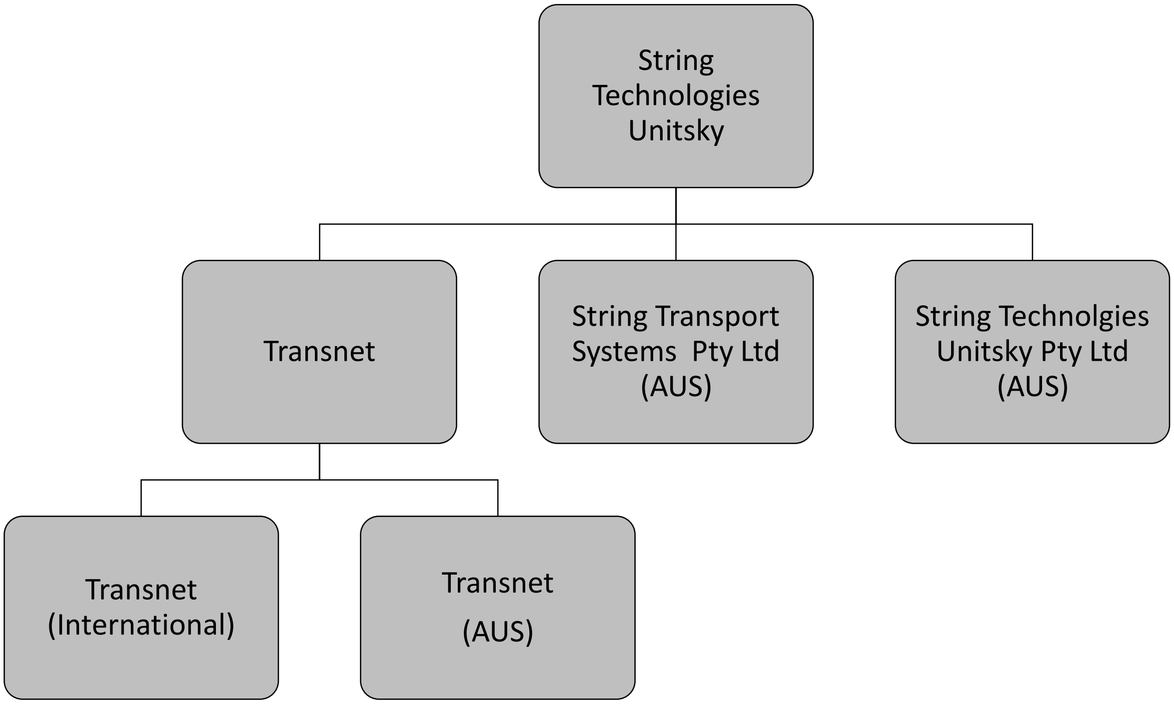


Figure 1: String Technologies Unitsky Company Hierarchy

2.2 Key Innovations

The company String Transport Unitsky has registered more than 50 Russian and Eurasian patents over the past 20 years (Transnet, 2012b). The technology including the patents had an estimated value of 1-14 Billion USD in 2010 (Yunitskiy, 2010). This is a considerable amount of money for a technology, which is yet to be implemented into an operational railway. Yunitskiy himself has invested 100 million USD into this technology, clearly demonstrating his belief in the technology. His hopes for the company are perhaps a little ambitious with a quote from his website, “And you can overcome all and for all in this niche market, the capacity of which is not less than a trillion dollars [USD] in each of these areas. Strategic investor, we're looking for, be able to capture at least 50% of the market. This has already succeeded in history. For example, Boeing.” (Yunitksiy, 2013b).

Transnet's paper, Unitsky String Technologies - Overground Transport System (Transnet, 2012b) also lists various other awards won by Yunitskiy and his technology. They are listed below:

- three Certificates of National Competition winners of "Russian Brand" National Program to promote the best Russian goods, services and technology (2001);
- more than 100 scientific articles and reports;
- two United Nations grants (1998 and 2002);
- two gold medals by Russian Exhibition Centre (1998 and 2002);
- three Certificates of National Competition winners of "Russian Brand" National Program to promote the best Russian goods, services and technology (2001); and
- two diplomas to the winners of the national award of public transport industry in Russia "Golden Chariot" in the "Project of the Year of the transport industry" (2009 and 2011).

Others have also suggested that this is cutting edge and innovative technology. When presented to the President of Russia, Dmitry Medvedev in 2009 he was quoted as saying "150 years ago, when it was told about a locomotive, experts in the field of horse traffic were smiling too, like some kind of nonsense talk. But then it became a whole industry which, by the way, is leaded by you". (Yunitskiy, 2009) This indication from the Russian President shows that this technology, although not currently implemented, is innovative, and some may find it unfeasible, but it could be a future form of Transport, led by String Technologies Unitsky.

Some of the key technology developments (and patents) worth noting are the method of the curve development of this technology. Eurasian Patent Number 06,112 'Transport System Unitsky and the method of construction of the transport system' (Yunitskiy, 2004) has a unique approach to the construction of curve development of the curves utilized in the network. Muhametdinov, later noted for his validation of String Transport System high-speed calculations, presented a diagram below in Figure 2, on the patented curve structure of String Transport Systems (Muhametdinov, 2012).

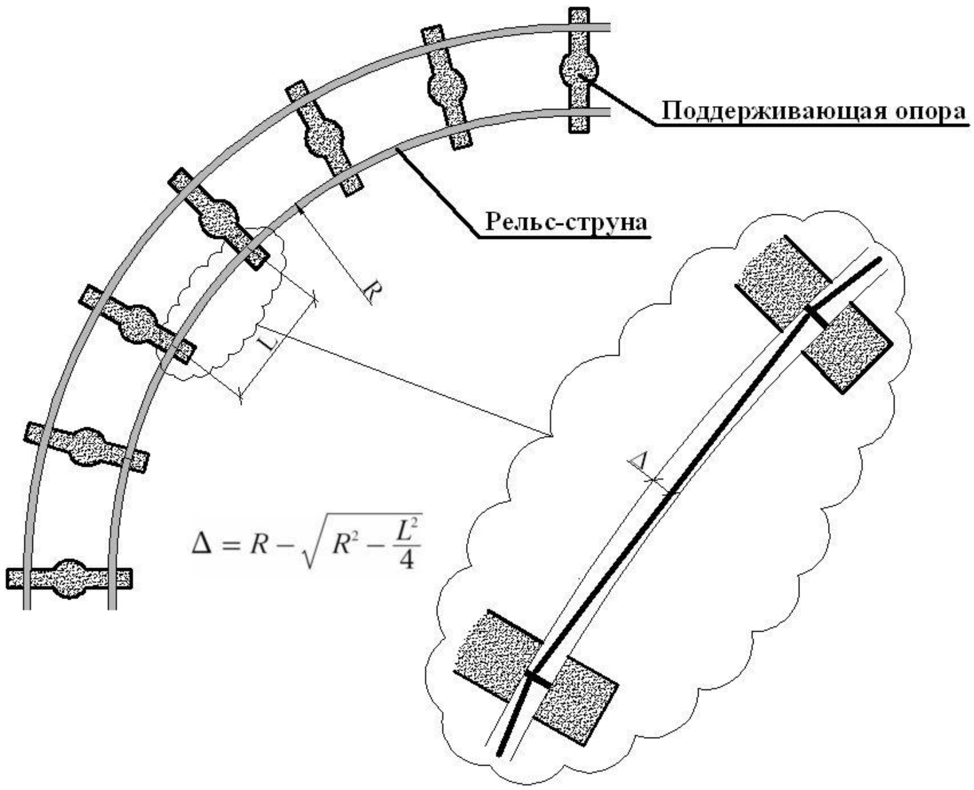


Figure 2: String Transport System Curve Development

This curve development, having already been patented is clearly a very effective method at keeping string tension high, but allowing curves to be used on the rail network. This method of construction is what will be used later in Chapter 5.2.2 when designing a String Transport System route.

2.3 STRING TRANSPORT SYSTEM USAGE

2.3.1 String-Rail

Yunitskiy has published numerous reports on the specifications of his technology. Whilst a large amount of this information is confidential, hence the value in his companies, these publications do provide the specifications of the both the networks and the rolling stock. This will form the basis of the below details on the specifications of String Transport Systems.

With rail speeds exceeding 300 km/hr. on the string networks, it is a rigid yet robust design. In String Transport Systems Pty. Ltd. paper on technical capabilities for bulk commodity haulage, the use of 'upward bowed rails' is suggested producing a maximum upward acceleration of 0.3 ms^{-2}. (String Transport Systems Limitied, 2010). It is reminded that this is for bulk commodity haulage and ride comfort is not considered in this fully automated system. It is noted that it is currently industry best practice for a maximum of 0.1g (0.1ms^{-2}) for passenger comfort (Parsons Brinckerhoff Quade & Douglas, inc. , 1999).

A detailed analysis and independent calculations of String Transport Systems is carried out in Chapter 5 of this dissertation predominantly drawing from information provided in the previously mentioned report on iron ore transport in Australia (String Transport Systems Limitied, 2010). Due to the detailed nature and applicability of this data, where gaps in Yunitskiy's data exist, current railway and structural design practice have been used to determine results and vice versa.

2.3.2 Uses in Rural Rail

Inter-urban railway within New South Wales is currently run by CountryLink. There are four main services; the North Coast Train Services, North Western Train Services, Western Train Services and the Southern Train Services. Figure 3 below shows the network in New South Wales, also showing the uses of coaches to extend the network even further into areas not currently accessible by rail.

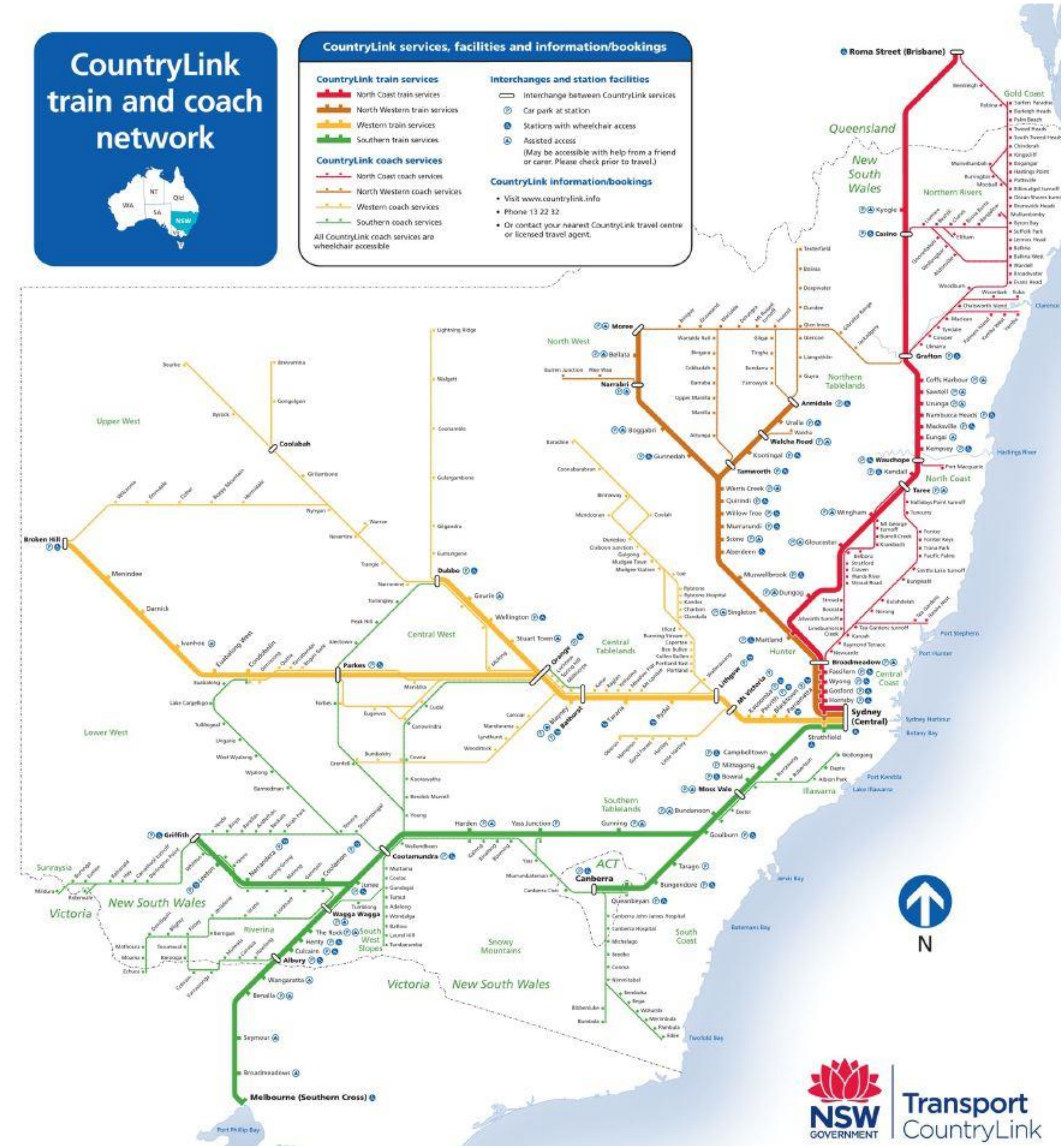


Figure 3: CountryLink Transport Network (CountryLink, 2012)

At this time point in time as demonstrated by Figure 3, the rural rail network is extensive and a 'reroute' of the network is not required. The issue with the network however is the rolling stock's deteriorating nature and urgent need of replacement. The Sydney Morning Herald published an article in 2012 highlighting that 30 years after CountryLink's XPT trains had been introduced, they had travelled over 3 million kilometres more than they were designed to (Saulwick, 2012). The suggestion presented was to retire the rolling stock in place of new and faster ‘premium trains’ such as ‘tilt trains’, trains capable of travelling at higher speeds due to their ability to ‘tilt’ and negotiate curves at higher speeds. This rolling stock is more expensive however it is believed that the costs recovered from higher patronage and the increased speed would be sufficient to cover purchasing costs. In this article, the opposition’s Transport Spokeswoman, Penny Sharp was quoted as saying “…given that this report says the trains are going to be unworkable by around 2018...” (Saulwick, 2012), suggesting there is currently 5 years to deal with this matter at hand.

A key area researched by Yunitskiy on String Transport Systems, is the high speeds which the rolling stock can operate at. Yunitskiy published a paper in 2006 giving answers to the many questions people had about his technology. In this paper he states that the technology is capable, on paper, of speeds up to 400 km/hr (String Transport Unitksy, 2006). Research was undertaken to validate this operating speed through independent calculations and testing and was validated for operation at 300+ km/hr. (Muhametdinov, 2012). With String Transport Systems Pty Ltd already registered in Australia, the company would be able to commence work in a short time frame with the rollingstock already proved for high-speed rail operations.

As the current network is already well developed, the String Transport System rolling stock would have to be retrofit for operation on the current network. However, costs are lower and train speed is higher so recovery of the cost of redesigning rolling stock has the potential to be rapid. New South Wales would then be moving towards a potential technology of the future, again, as mentioned by Russian President Dmitry Medvedev (Yunitskiy, 2009).

This application of String Transport Systems differs from what Yunitskiy had originally dreamed for his technology, with the hallmark of his work, the string-rail. Only utilising his rolling sock in a retrofit manner is not an appropriate way to consider the implementation of String Transport Systems when many other alternatives do exist.

2.3.3 Intercity High-Speed Rail

The Melbourne-Sydney-Brisbane High-Speed Rail Network has been looked at for some time now. In 2011 AECOM headlined a consortium of consultants on the ‘Phase 1 High Speed Rail Study’ for the Department of Infrastructure and Transport to provide an insight into when the design would likely be feasible and where to progress design to. The report suggests that by 2036, the project would have a Positive Net Present Value (NPV) and should be considered (AECOM Australia Pty Ltd, 2011).

This application has significant potential for String Transport Systems as construction costs are lower and hence the design is feasible earlier based on NPV. The trip from Albury to Sydney currently takes 6 hours and 38 minutes (Tourisminternet, 2013). At a distance of 553 km, this trip would take under 2 hours on the high-speed string network as well as a similar time for the proposed high-speed rail. The difference; Yunitskiy noted in his paper, Unitsky String Technologies - Overground Transport System, was that the land acquisition for elevated string technology is only 2.5% that of conventional rail, 1.6% of automotive transport and 40% that of monorail. (Transnet, 2012b). With the phase 2 report released in April 2013 and the land acquisition data available, the saving in land acquisition costs could then be estimated. The study indicated that land acquisition costs are 3.4 % of the total cost which is estimated at $114 Billion in 2012. This is almost 4 billion dollars in land acquisition (AECOM Australia Pty Ltd, 2013). With String Transport Systems requiring only 2.5% the land acquisition of conventional railway, the savings are over 3.5 billion AUD.

This example clearly shows a feasibly application for String Transports Systems use in passenger rail in New South Wales.

2.3.4 Uses in Urban Environment

Sydney’s transport network, specifically the rail network, is severely overcrowded. Capacity has already been met in many locations and drastic measures are already underway to fix the problem. Two current projects under study/design are the light rail project to Randwick, and the recently approved 1 million AUD study on tram lines connecting Parramatta with Castle Hill and Macquarie Park.

These technologies are under investigation due to the highly urbanized areas within Sydney. Suggestions were even made to tunnel a section of the CBD and South East Light Rail Project due to the inability to find an appropriate or wide enough corridor. With the option for fixed or elevated string transport structures this technology is more than suitable. The previously mentioned paper on freight based application of String Transport Systems outlines that supports for the structure are as little as 200 mm diameter pipes (String Transport Systems Limitied, 2010) whilst something like the Sydney monorail has support beams which are over 600mm in width. This clearly shows how String Transport Systems are the superior design option for this use, when minimising the physical footprint is an issue.

A key consideration that needs to be assessed is whether the rolling stock is able to change tracks to allow for a more complex network than just a shuttle operation. Yunitskiy has suggested methods for this and the research looks promising with similar technology to conventional rail employed. This will be analysed as part of the network design in Chapter 5.2.6

With such a small physical footprint characterising String Transport Systems, uses in urban rail is another possible application for their use in passenger rail in New South Wales.

2.3.5 Freight vs. Passenger Implications

String Transport Systems Pty Ltd have published numerous reports on the application of string technology for freight haulage in Australia which will help form the basis of this comparison. Yunitskiy's report on bulk commodity haulage, once again, will be one of the key papers used in the development of this dissertation (String Transport Systems Limitied, 2010). This technology won the 2011 'Transport Project of the year at the International Transport Awards Ceremony' (Rail Express, 2011), clearly demonstrating the quality of this paper. Other award winning papers and projects will also be included in analysis, all of which can be found on String Technologies Unitsky's website (Yunitskiy, 2013d).

2.4 STRING TRANSPORT SYSTEMS, WITHIN ALTERNATIVE TRANSPORT SYSTEMS

2.4.1 Comparison

Rail transit can be broken into a variety of categories. These categories distinguish the different methods of rail transit and their uses. The main categories include, but are not limited to; light rail, high-speed rail, personal rapid transit, conventional rail and alternative/sustainable transport solutions.

String Transport Systems have been in development for a number of years and the design has progressed from a concept, through to a proven full-scale test with freight and passenger implications. Due to the environmental and sustainable benefits associated with this technology, it fits into the overarching group of alternative/sustainable transport solutions.

String transport has applications in almost all these areas but is best represented under the heading of alternative/sustainable transport solutions. Chapter 2.4.2 through 2.4.6 provide a brief explanation into these methods of rail transport and their relation with String Transport Systems.

2.4.2 Light rail

Light rail transit is used for medium capacity passenger transport usually in highly built up urban environments. It includes trams, monorail and light metro that can run on metro systems, elevated track, as well as heavy rail track. A good definition provided in 1977 by the United States Transportation Research Board is “a mode of urban transportation utilizing predominantly reserved but not necessarily grade-separated rights-of-way. Electrically propelled rail vehicles operate singly or in trains. LRT provides a wide range of passenger capabilities and performance characteristics at moderate costs” (Transportation Research Board, 1977).

Track used for light rail in Australia is usually 1435mm standard gauge (Ginn, 1998) (excluding monorail). In comparison to String Transport Systems, this is similar to the microSTU concept with a 1500mm gauge width. MiniSTU has a 2000mm gauge width however the gauge width is similar to the rolling stock width with the aerodynamic shape of the body putting the wheels at the very outset of the rolling stock. (String Transport Unitksy, 2006). This can be seen in Figure 4 below, taken from another of Yunitskiy's papers – Benefits of Unitsky String Transport (Yunitskiy, 2013c).

Figure 4: Rolling Stock Width and Gauge Size (Transnet, 2012a)

When comparing the width of trams in operation in Australia, the rolling stock width is over a meter wider than the gauge at 2.65 m. (VicSig.net, 2013). The monorail that was used in Sydney's CBD until June 2013, is also a similar width to STU with a specified width of 2.06m (Churchman, 1995). Capacities for the three are very similar proving that STU has light rail applications, however light rail is not its only application.

2.4.3 High-Speed Rail

High-speed rail is a method of mass transit very well developed in the European and Asian regions. It includes rolling stock capable of travelling at speeds in excess of 500 km/hr.

MacroSTU has a gauge width of 2500m with a rolling stock width of approximately 3000mm (String Transport Unitksy, 2006). Typical high-speed rolling stock has a width of 3380mm (Japan California High Speed Rail Consortium, 2012). The speeds String Transport Systems are capable of approaching 400 km/hr, as mentioned in Chapter 2.3.2. These high-speed capabilities with similar rolling stock dimensions demonstrate the suitability for String Transport Systems being used for high-speed rail.

2.4.4 Personal Rapid Transit

Personal rapid transit involves high-speed transit in small or individual ‘pods’. This includes technologies such as Bishops Transport Solutions, cable cars, T ways and ‘pods’, such as the pods in use at Heathrow Airport connecting the terminals with the long term car park.

Bishops Transport Solutions are a concept developed in the 1980’s based on the concept of personal rail vehicles operating on a fully automated GoA4 network. This concept is quite similar to MicroSTU technology discussed in Yunitskiy’s Q&A paper (String Transport Unitksy, 2006).

Cable Cars are essentially elevated hanging String transport structures. Cable Cars are more commonly known for their applications in mountainous environments with large slopes to be contended with. Yunitskiy again has demonstrated that his STU technology is capable of similar applications with a Transnet report of his, outlining the capabilities of the rolling stock up to a 15% track gradient. (Transnet, 2012a). Perhaps not the same slope as a cable car is capable of, but none the less, not too dissimilar.

T-ways are bus specific lanes which are used to increase speeds to decrease travel times. This principle can be applied to String Transport Systems as they operate on their own network, not slowed by other rail vehicles.

MicroSTU as discussed in Yunitskiy’s Question and Answer paper are very similar to this pod concept. (String Transport Unitksy, 2006). This pod concept is only one application of String Transport Systems but it does demonstrate its versatility.

2.4.5 Conventional Rail

Conventional rail is the freight and passenger applications of railway clearly seen around the world as the most common form of rail transport. With String Transport Systems capable of running mounted to the ground, it acts in almost the exact same manner as conventional rail at a fraction of the cost with many added benefits.

2.4.6 Alternative/Sustainable Transport Systems

Alternative/sustainable transport systems are essentially in form of transport built for the purpose of lessening its impact on the environment. In Yunitskiy's paper Transnet: an overground transportation system, he suggests reductions in emissions compared to conventional rail of over 300% (Transnet, 2012b). With such a reduction in emissions, String Technologies clearly fit into this area. Anatoly Yunitskiy has won several awards for his developments in this area including a Diploma for Sustainable development of the Eurasian continent at the International Forum on Sustainable Development (International Forum on Sustainable Development, 2008), as well as being recognized as an 'Ambassador for Peace' by the Universal Peace Federation for his work 'exemplifying the ideal of living for the sake of others'. (Federation, 2012).

2.4.7 Evolution of Rail Transport

Rail transport technologies have developed over time. Conventional rail was obviously first and was predominantly linking cities/towns for passenger and freight transport. The first recorded utilization of railway was in 600 B.C. with 'Rutway' used for transport of goods. (Lewis, 2000). As cities began to grow, so did the need for a compact network. This saw the introduction of light rail. This was first introduced in Wales in 1807 with a horse drawn Tram (Rogers, 1995).

With dozens of cities long distances apart in some countries, the implementation of high-speed rail was then developed to link these hubs. The 'bullet train' was the first high-speed rail vehicle and it began operations in 1964. Technology was then developing in leaps and bounds and along came the implementation of personal rapid transit for an often automated transport network of small pods. This technology was introduced in the mid 1970's and is currently in early stages, with scattered examples around the world. In more recent years with the effects of over population and global warming, alternative/sustainable transport systems have begun to develop. Since the turn of the century Alternative Transport Systems have come on the scene and from the research above, and look like they will dominate the market in the future.

2.5 TECHNICAL SPECIFICATIONS

Dr. Anatoly Yunitskiy has conducted a considerable amount of research into the technical specifications of this technology. His website (Yunitskiy, 2013d) has many technical papers that detail his method of calculating parameters and the subsequent designs. This Chapter aims to explore key considerations in regard to the 'string' as this is the unique element of the technology, not seen in other railway. Technical specifications of the supports and foundation will be based on standard design practise and detailed in Chapter 6.

2.5.1 Idealised Structure

The idealised structure for freight applications is presented by Yunitskiy and detailed below in Figure 5. It is noted that the distance between supports is 15 metres in this case but the distance between supports can be increased to up to 50 metres.

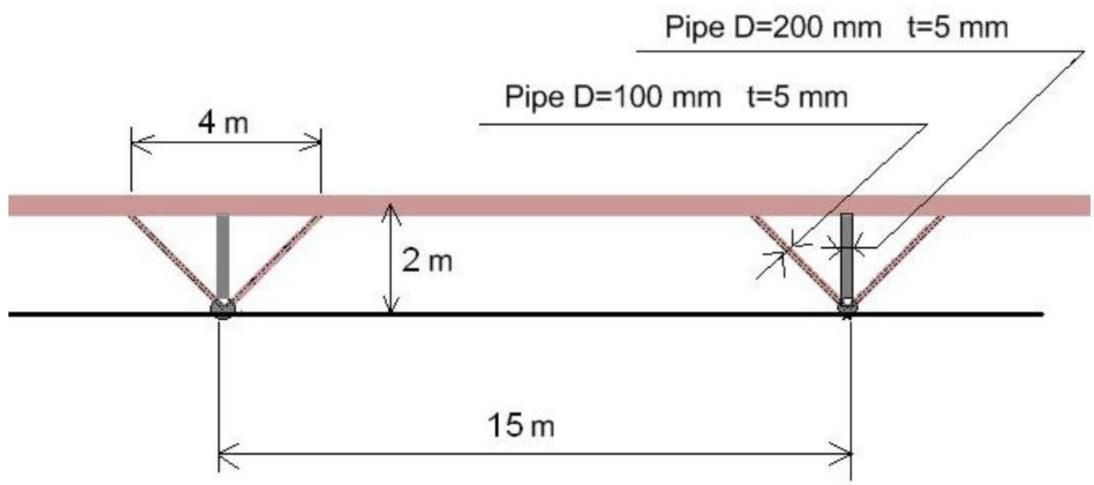


Figure 5: Idealised Track Structure (String Transport Systems Limitied, 2010)

2.5.2 Bending Moment

The bending moment is parameter which needs to be considered in design of the string due to deflections that this causes. As bending moment increases the structure deflects more, increasing the chance of the string-rail fracturing, or of derailment. Figure 6 below shows the induced bending moment on the structure from a train moving at 100 km/hr. The bending moment is presented in Newton-metres. This information will be critical in the design and development of a typical support in Chapter 6.3. No dynamic analysis or testing has been carried out, so this will form the pseudo values for this purpose.

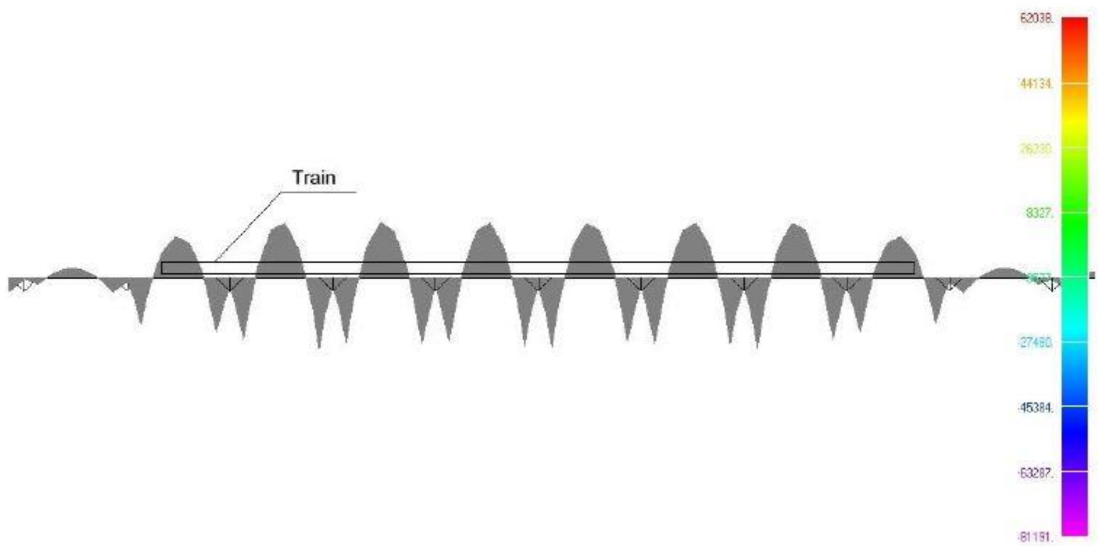


Figure 6: Bending Moment Caused by Train Moving at 100 km/hr. (String Transport Systems Limitied, 2010)

2.5.3 Displacement

Displacement needs to be considered when safe operation and user comfort are being considered. Large displacements at the centre of the spans resulted in the train travelling over what appears to be a serious of "bumps" at the supports. This can cause large vertical accelerations, injuring passengers, or even derailing the train. Figure 7 below shows the displacement of the rail in millimetres when a train travelling at 100 km/hr, travels over it with displacement presented in metres.

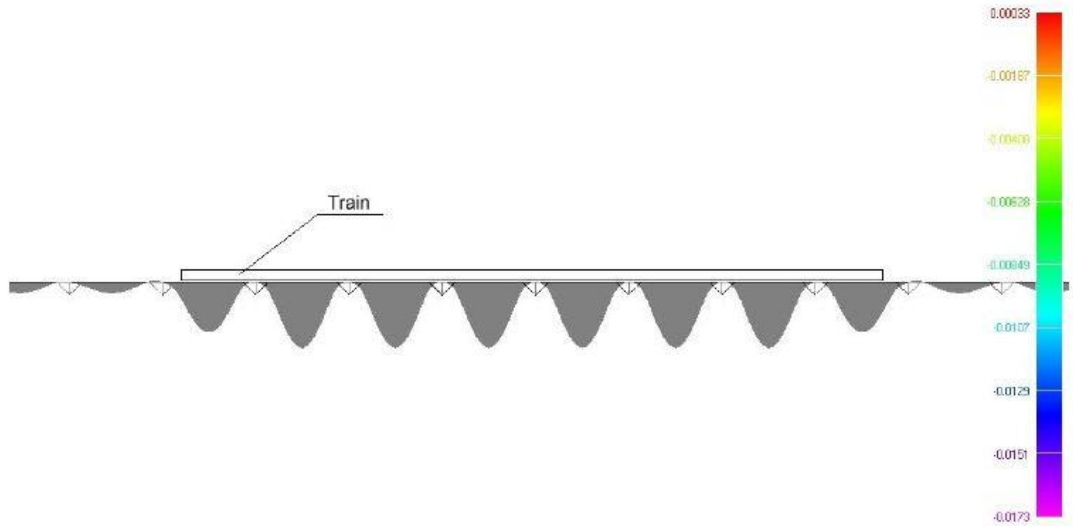


Figure 7: Displacement of Rail Caused by Train Moving at 100 km/hr. (String Transport Systems Limitied, 2010)

From the dynamic testing carried out here, it is clear what sort of deflections can be expected from a typical String Transport System train moving at 100 km/hr. It will later be shown in Chapter 6.4.3, that the deflection observed is quite similar to that presented here, and hence will be satisfactory for design.

2.5.4 Stress

Stress is ultimately what will caused the steel to yield. Detailed analysis has been carried out by Yunitskiy to not only ensure that the structure does not yield each time a train travels of the top of it, but to ensure the durability of the steel structure, so an adequate number of cycles can occur before replacement is required. Stress on the bottom of the rail is show in Figure 8 and stress on the top of the rail is show in Figure 9.

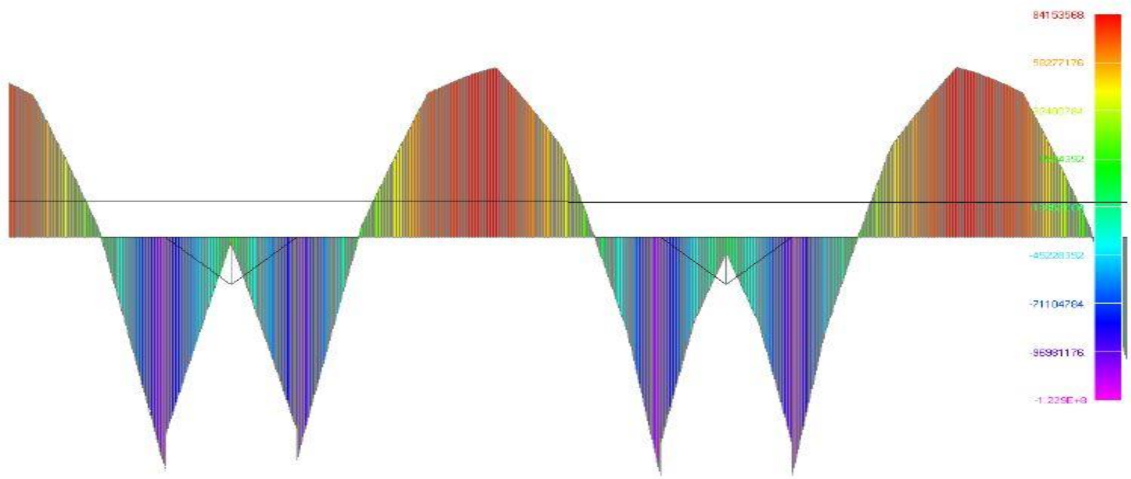


Figure 8: Stress on the Bottom of the Rail as a Result of a Train Travelling at 100 km/hr. (String Transport Systems Limitied, 2010)

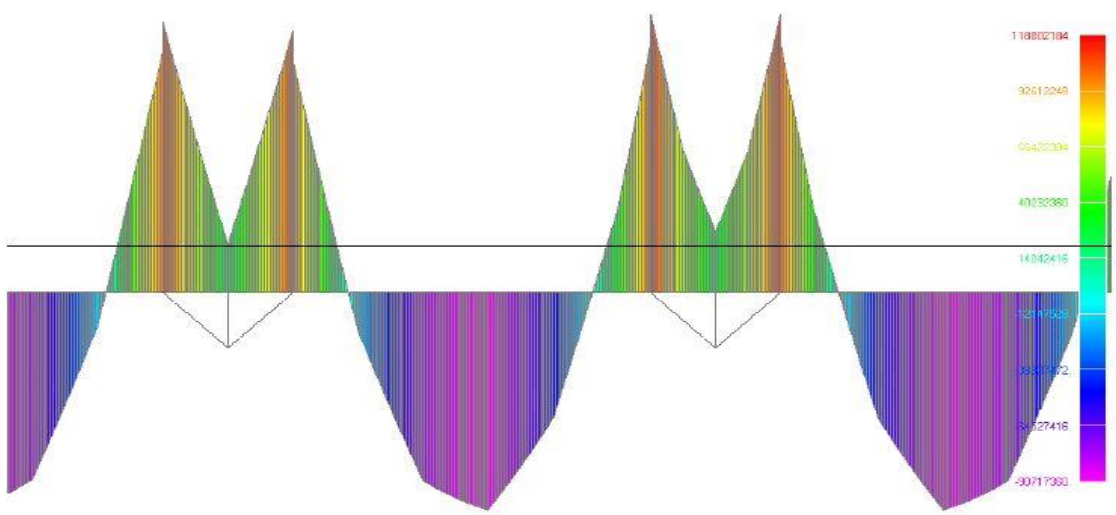


Figure 9: Stress on the Top of the Rail as a Result of a Train Travelling at 100 km/hr. (String Transport Systems Limitied, 2010)

These stress values have been used by Yunitskiy to help determine the number of cycles a string rail can be exposed to before failure. This information will be used later on in the dissertation, as again, no dynamic analysis or testing has been undertaken.

2.6 INTEGRATION

Integration with the current New South Wales network is necessary for successful implementation of String Transport Systems for passenger rail. Due to this, information provided in this literature review will be used to form a basis for the String Transport System application decision, to ensure the best usage of this technology is selected for Passenger Rail in New South Wales.

2.7 CONCLUSION

It is conclusive from the literature reviewed that the state of New South Wales is in need of a technology to enhance its current network. The rural rail network is suffering from an ailing fleet of rolling stock in need of replacement and some of New South Wales' major cities such as Sydney are clogged with infrastructure, with networks approaching capacity. Feasibility studies are underway to install a high speed interstate route, however the state is in need of an alternative to provide mass transit within the city.

The technology, although not in implementation anywhere in the world, has been developed and from thorough research of many of Yunitskiy's research papers, is demonstrated to be able to be implemented effectively in New South Wales. This dissertation will ultimately represent this.

3 METHODOLOGY

The desired outcome of this dissertation was to assess the feasibility use of String Transport Systems for passenger rail in New South Wales.

A detailed analysis of current literature on both the technology being considered, as well as the New South Wales passenger rail network has been conducted and is outlined in Chapter 2. This outlines current String Transport System best practices as well as the applications and for it within passenger rail in New South Wales. This literature review also explores the current states of New South Wales passenger rail network and the implication this has on String Transport Systems.

A String Transport System route was then produced to demonstrate the travel time capabilities of the technology. Detailed curve and alignment design was undertaken, producing maximum curve speed data, and ultimately, a route travel time. This data, coupled with demand estimation was then used to produce a timetable and subsequently, a trajectory diagram. Information in regard to rolling stock (rolling stock refers to locomotives, carriages, wagons, and other vehicles used on a railway (Oxford Dictionaries, 2013)) and its subsequent interaction with the rail has not been found for this investigation, however the rolling stock is assumed to behave in a similar manner to that of conventional rolling stock (String Transport Unitksy, 2006).

The demand estimation was based on Australian Bureau of Statistic population data, combined with current public transport information in the area of interest. This allowed an approximate value for the demand to be found and was deemed to be satisfactory for a feasibility level of design. Detailed demand estimation would be required before a final route could be installed. Demand estimation is an inherently error prone process however, as shown by many of Sydney's tollways, hence the assumption to use approximation methods, holds.

From the route produced, a typical support structure was designed structurally and geotechnically to Australian Standards. The most unfavourable loading conditions were applied to this structure, which was designed in the worst soil conditions that would be expected along the route in order to assess the impact, in worst case soil conditions. Key strength and serviceability values were calculated to determine the factor of safety that the structure was designed to when designed to Australian Standards. Where dynamic information was required, Yunitskiy specified information was used, as no dynamic analysis or testing was undertaken.

The cost of construction of the route was carried out based on all of the above information. The costing aimed to produce a value per kilometre, which could be compared to typical values per kilometre of other forms of rail transit. Involved in this costing were; labour, materials, traffic works, site management, design, commissioning, land acquisition, rolling stock, stations and a depot as well as a contingency value due to the inherently high level approach taken to a feasibility level design. Other rail projects around New South Wales, and in some cases, Australia were averaged to produce their costs for a comparison. When considering lower operational costs of String Transport Systems, the saving produced by this technology was outstanding.

All of the information presented above was then used together to conclude on the holistic feasibility of implementing this technology in New South Wales for use in passenger rail.

This dissertation has been structured in three parts. The first part is the introduction, used to present the background of the study, including the studies objectives, as well as a literature review and a methodology. The second part is the design, including determining the best application for the technology within the New South Wales passenger rail network, design of the route and structure, as well as costing. The final part is part 3, containing the recommendation as well as the references and appendices complementing the information provided in part 2. The dissertation is structured in this way for ease of understanding and to present a flowing document. The dissertation was not necessarily written in this order.

PART 2: DESIGN AND COSTING

4 SELECTION OF APPLICATION SCENARIOS FOR ANALYSIS

Within the literature review above in Chapter 2, the current state of the New South Wales passenger network has been analysed. This information will be used here to determine the most appropriate area of implementation for String Transport Systems within New South Wales.

4.1 RURAL RAIL SCENARIOS

The rural rail network does not currently require an extension. The network reaches over 365 destinations with well over 2000 km of track (Transport NSW TrainLink, 2013). The issue with this network however is the state of the current rolling stock.

The current rolling stock used in New South Wales' rural passenger rail network has travelled more than 3 million km further than it was originally designed for (Saulwick, 2012).

There are three scenarios here where String Transport Systems can be applied to the rural passenger rail network. The first involves removing all track currently in use, and replacing it with a String Transport System network. This is rejected as option due to the large costs associated with this, as well as the impact on the continued network running whilst this was occurring.

The second scenario, would be using String Transport System for any network extensions that were to occur in the future. This would require passengers to either change rolling stock at these locations to a String Transport System module, or would require retrofit of current rolling stock to be able to run on a string transport system track. This again is not a viable option.

The third scenario would be to replace the current aged fleet with String Transport System rolling stock. This would involve retrofitting the specified rolling stock to be able to run on the standard gauge (1435mm) track. The String Transport System rolling stock also boasts low emissions and low costs for operation however it were used in this way, it would be required to run on the outdated 1500V DC power supply that the current fleet run on. This again, is not appropriate.

At present it appears that there is limited potential for applications of String Transport Systems for rural passenger rail in New South Wales.

4.2 HIGH-SPEED RAIL SCENARIOS

Australia is yet to implement a high-speed rail network; however there have been feasibility studies carried out to determine when the network would be feasible both financially and in terms of patronage. At this stage it is deemed feasible to commence operation in 2035 (AECOM Australia Pty Ltd, 2013) when the project would first yield a positive net present value.

String Transport Systems are characterised by their reduced small physical footprint and hence very small land acquisition costs. This results in a smaller cost of construction, and due to the minimalistic structure, the material costs are also reduced.

Whilst the exact costing of a String Transport Systems high-speed rail network has not been carried out in the dissertation, it is assumed that the cost would make immediate construction financially feasible in terms of the projects net present value. The reduced cost would result in smaller fares for passengers, increasing estimated demand for the network, doubling the effect.

This however is seen as a non-feasible option for implementing a String Transport System. The technology is yet to have an operational network anywhere in the world, and hence is not proven. For such high-speed implications, the network would require a significant level of safety due to the disastrous consequences should a train derail for any reason. Without the technology being proven and precedented, implementing the technology in this application would be difficult to be accepted by federal or state governments due to the high level of risk they would have to bare.

A high-speed String Transport System rail network is currently infeasible due to safety concerns and a lack of prior networks established internationally. High-speed String

Transport Systems are therefore not a feasible area for the implementation with in New South Wales.

4.3 URBAN RAIL SCENARIOS

When considering urban rail, Sydney's urban rail network will be considered. This network is currently at capacity in many locations and due to high levels of urbanisation, many locations are not currently reachable by rail. A current network extension in to Sydney's Hills District, North West Rail Link, requires 15 km of tunnel to reach its desired destinations (Transport for New South Wales, 2013a). Sydney's Eastern suburbs are also without a rail network due to high levels of urbanization, with plans to introduce a light rail network to help this public transport congestion in the area.

String Transport Systems are characterised by elevated structures and when considering the high levels of urbanisation are perfectly suited for such applications. Structures are spaced between 10 and 25 metres in the design to follow, so the physical footprint will be small enough to not effect heavily urbanised areas.

The current urban network is very established although there are limited opportunities for further expansion in urban areas. String Transport Systems provide an alternative to allow for expansion into these areas, however due to compatibility between String Transport Systems and the current network, String Transport Systems would be required to be a stand-alone network with transport interchanges to effectively integrate it into the Sydney public transport scheme.

4.4 RECOMMENDATION

When considering the above information it is clear that the most compatible and appropriate use for String Transport Systems would be in the form of a stand-alone route or network in a highly urbanised area where conventional rail is unable to be built, or was not a cost effective option. This recommendation will form the basis for completion of Chapter 4 to 7.

5 ROUTE DESIGN PROCESS

For String Transport Systems to be effectively included as part of New South Wales' passenger rail network and greater public transport scheme, the technology must be capable of integration. This chapter aims to develop a route and the required interchanges, to effectively implement String Transport Systems into the New South Wales' passenger rail network. The focus of this chapter is on the design of the route layout consistent with accepted urban transport planning objectives.

5.1 PLATFORM/INTERCHANGE

The design, installation and operational logistics of the station structures are out of scope of this dissertation and will not be included. In Chapter 7 to follow, the cost of typical station will be required for a total route cost. In this case, a typical light rail/monorail station cost will be included, and due to similar patronage this will be deemed acceptable. In terms of a terminus/stabling yard, Yunitskiy's design will be used. In all cases here, Yunitskiy specification of rolling stock will be used.

5.1.1 Platform Length

The most suited rolling stock for the mentioned application is rolling stock similar to the STU specified Unibus U-361 (String Transport Unitksy, 2006). This is shown below in Figure 10.

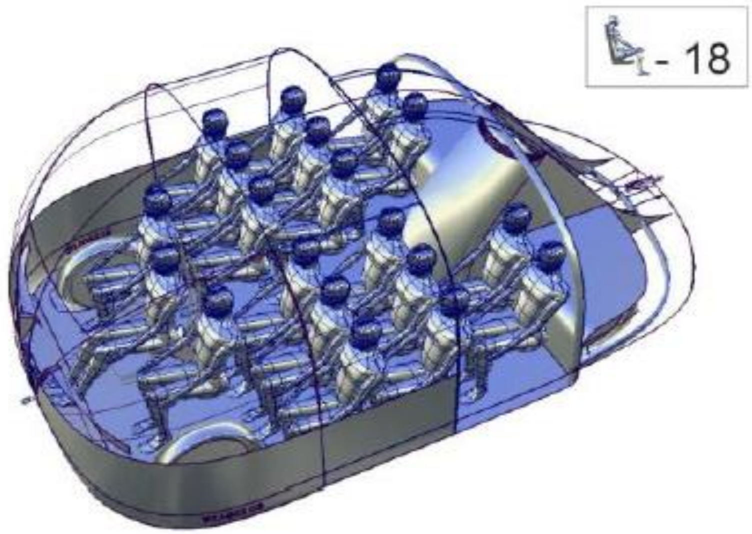


Figure 10: Unibus U-361 (String Transport Unitksy, 2006)

Figure 10 shows a typical carriage with 18 seats and 5 carriages per train design. The carriages are approximately 8 metres in length with singular doors per vehicle. This gives a train length of 42.5 metres (allowing 0.5 metres between carriages) with 8.5 metre spacing between doors. Should the train be extended to 10 carriages, to cope with increased demand in the future, the length would then become 95 metres. With a typical monorail vehicle being up to 97.5 metres in length, with door spacing of approximately 6 metres (Bombardier Transportation, 2010), the previous assumption that a typical monorail station would suffice, holds.

5.1.2 Station Locations

There will be up to 100 passengers leaving, and 100 passengers entering the train at a time. This value will rise to 200 should the number of carriages be increased in the future. With such large patronage values, with as little as 6 minutes headways (refer Chapter 5.2.5), the location of stations will need to be at current key transport interchanges to cope with the large volumes of passengers. This forms the reasoning behind the station locations along the route presented in Chapter 5.2.1.

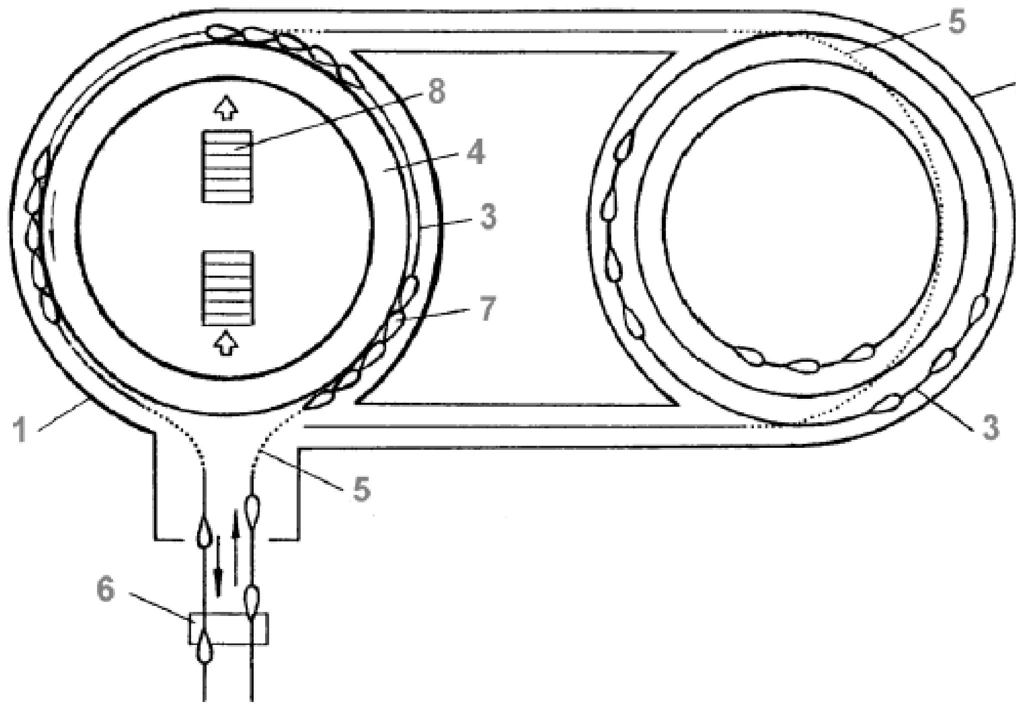
5.1.3 Design of Terminus

Yunitsky's suggested terminus design is shown below in Figure 11. This includes a depot/stabling area to the right of the figure, and a turning facility on the left hand side of the figure. This is what is included in the design at the start and end of the out and back route presented in Figure 12. Due to the short route, stabling at only one end would suffice, and the requirement for the stabling area would not be necessary at the other end. It is this reason why when costing the structure in Chapter 7, that only one and a half of these buildings are included, due to half of the terminus building at one end, not being required.

The specified diameters of the ring in the terminus building is 60 metres (String Transport Unitksy, 2006). This allows for a total of 190 metres of train to be servicing the platform at one time, which is made up of 4 rolling stock when a 5 carriage set is considered and 2 rolling stock once future demand is increased and 10 carriage sets are required.

In terms of stabling, a 3-ring structure is considered. The outer ring is 60 metres in diameter and the two inner rings are 50 metres and 40 metres respectively. This gives 190 metres, 160 metres and 125 metres of stabling room. This is room for 9 trains to be stabled in total. Given the maximum number of trains to fit on the route being 9 (refer Chapter 5.2.4) this will accommodate all trains. When the carriage sets are increased however, a stabling area will likely be required to be added to the other terminal building at the far end of the route to accommodate all trains.

The central ring is where passengers can use escalators to return to ground level, as well as maintenance staff to gain access to the rolling stock in the stabling area.



1-terminal building; 2-depot building; 3- ring track; 4-ring-shaped platform; 5-turnout; 6-terminal entrance; 7-vehicle; 8-passenger entrance/exit to the terminal.

Figure 11: Interchange Design (String Transport Unitksy, 2006)

5.2 SELECTION OF ROUTE LAYOUT

There are a variety of route and network layouts that can exist in railway design. The recommendation given in Chapter 4.4, is for a stand-alone, independent route/network with an out and back configuration. This configuration will be what is designed in the following chapter.

Novel networks such as this are often used to connect new infrastructure such as theme parks or airports to city networks. An example of this was when Sea World on the Gold Coast opened their monorail in 1986, Australia's very first one (Sea World, 2013). With the location of Sydney's new airport currently favouring the RAAF base in Richmond (Sydney Airport, 2012), and the location of Sydney's new waterpark being in Prospect, String Transport Systems is a viable option to connect either of the two and the city.

String Transport Systems are of course well known for their ability to be used in most terrain due to the elevated structure of the strings and the minimal physical footprint required by the foundations. Sydney's eastern suburbs are highly urbanised and do not currently have a tram or train line. For example, someone wishing to travel from Kingsford-smith airport to Bondi beach by public transport, they must take 2 trains and a bus or 2 buses, with a journey time of around an hour (NSW Government, 2013). This is a considerable amount of time for a 20 km journey. String Transport Systems ability to traverse highly urbanised areas make this the perfect solution for high-speed rail transport in Sydney's Eastern suburbs.

The NSW government as of December 2012 have approved construction subject to planning approval of a light rail service between the Sydney CBD and Randwick/Kingsford (Transport For New South Wales, 2012). This aims to decongest and solve some of the eastern suburbs passenger rail woes, however will only reach Randwick and Kingsford, a small portion of the Eastern Suburbs. Considering this, the most appropriate use for a route would be an out and back route servicing the eastern suburbs between Sydney's Kingsford-Smith Airport and Bondi Beach.

This suggested route for consideration is shown in Figure 12 below.

5.2.1 Location of Stations

The design of the network in this case is an 'out and back' route rather than a network, with a terminus at each end as detailed in Chapter 5.1.3. The route connects the suburbs of Bondi, Bondi Junction, Randwick, Coogee, Maroubra Beach, Maroubra Junction, and Eastgardens with the Sydney Airport.

As discussed in Chapter 5.1.2, large patronage and small headways would result in large numbers of passengers at each station. This is what formed the basis of the station locations, with one in each of the previously mentioned suburbs. These stations are located at current Sydney Bus terminuses or major bus stops. Each of these is also located at a demand centre, such as the Eastgardens station being located at Westfield Eastgardens.

From the route below in Figure 12 the route has longer flowing curves in most areas allowing for high-speed transport and simpler acceleration/deceleration patterns. With minimal stops compared to a bus route, the route travel time between terminuses will be far less than that of normal buses. Connecting Sydney airport and Bondi junction is the 400 bus route (effective September 2013). This route takes 45 minutes in minimal traffic (NSW Government, 2013), with an approximate time to reach Bondi Beach being one hour. Chapter 5.2.3.3 below shows the calculations of the route and its associated key performance measures.

Note that for further calculations and figures, stations will be numbered as follows.

Airport Terminus (1)

East Gardens (2)

Maroubra Junction (3)

Maroubra Beach (4)

Coogee Beach (5)

Randwick (6)

Bondi Junction (7)

Bondi Beach (8)

North Bondi Terminus (9)

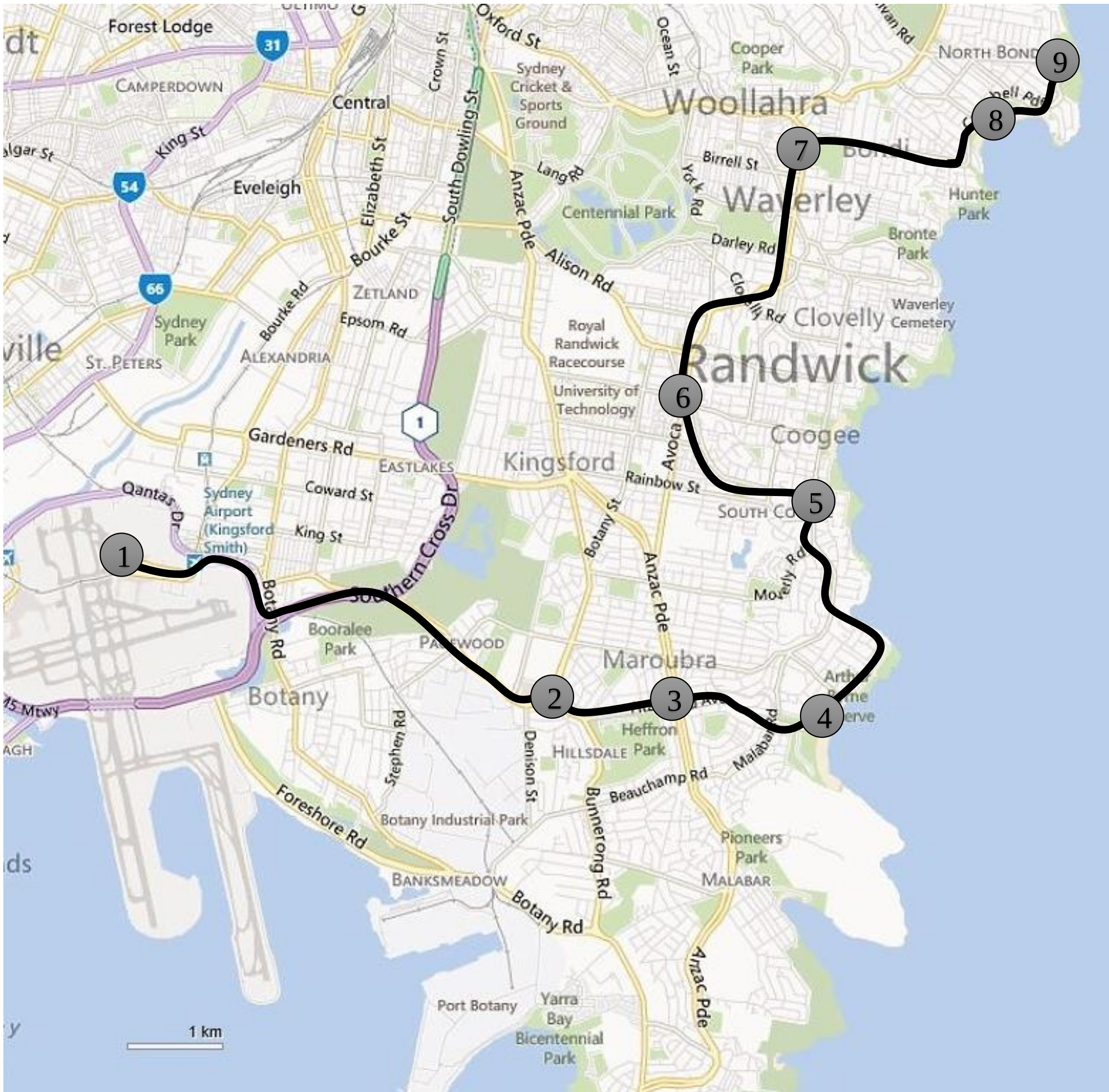


Figure 12: Proposed Route Between Kingsford-Smith Airport and Bondi Beach

5.2.2 Alignment

The horizontal alignment of the route presented in Figure 12 consists of 22 curves ranging in radii from 250 metres to 2.2 kilometres, as well as 10 straight sections. The chainage of each of these curves and straight section has been included in Table 25 in Appendix A. The high usage of curves although difficult to construct, has been used for the aesthetical applications, to mimic the rolling curves of the Sydney coastline. The route does however aim to travel down the centreline, specifically the median strip, of major roads due to the negligible land acquisitions that this will require. This has dictated a large portion of the alignment.

Vertical alignment has not been considered at the feasibility stage as String Transport Systems utilise elevated structures and hence can minimise the effects of sharp rises in elevation with gradual increases by altering support heights.

Chapter 5.2.3 below looks at the performance measures of the route.

5.2.3 Network Calculations

5.2.3.1 Maximum Velocity

For calculation of the maximum allowable velocity for a given curve radius, the following equation was rearranged. This is the formula that is produced when trigonometric functions are combined, when the track is canted such that the trains weight and centrifugal force act straight down through the rail, rather than horizontally due to adverse effects on the rail.

$$r = \frac{G * v^2}{g * (h_a + h_p)}$$

$r = curve\ radius$

$G = gauge\ width$

$g = gravity\ (9.81\ ms^{-1})$

$h_a = cant$

$h_b = cant\ deficciency$

The gauge width used was 2000mm (String Transport Unitksy, 2006). This reflects a light rail vehicle, which will be used for this purpose. The cant and cant deficiency were set to 90mm and 70mm respectively (South Australia - Department of Transport, Planning and Infrastructure, 2008), as these are the maximum and hence worst case scenarios. The corresponding curve maximum velocities were then rounded down to the nearest whole number to remain conservative. These values are also shown in Table 1.

Table 1: Maximum Curve Velocity

Curve Radius (m)	**Maximum Velocity (ms^{-1})**
2200	28.00
1000	28.00
750	24.00
650	22.00
500	19.00
350	16.00
250	14.00
Straight Section	*28.00*

For a straight section of track with the suggested acceleration rate below, the velocity could approach over 200 km/hr. For this route however, maximum velocity will be limited to 100 km/hr ($28ms^{-1}$). North West Rail Link, Sydney's proposed new rail network has a maximum design speed of 130 km/hr (Transport for New South Wales, 2013b) and due to its driverless trains will ultimately form the precedent for a lot of Sydney's and the rest of Australia's rail projects in the future. This will be the case with this route also, and hence why this speed has been considered however the speed will be restricting down to 100 km/hr due to safety reasons relating to the higher levels of urbanisation in the area.

5.2.3.2 Acceleration

For operation, the acceleration and deceleration rates of the vehicle are assumed to be $1ms^{-2}$. This allows for a smooth ride for passengers and is also the acceleration/deceleration rate that current Sydney Train rolling stock (Waratah) use (Transport for New South Wales, 2013c). As well as this, this is also the stipulated rates specified by Yunitskiy in his technical proposals (String Transport Unitksy, 2006). With North West Rail Link to include driverless trains at a GOA4 level (unattended train operation) (Berejiklian, 2013), this route will also assume driverless trains. This means that trains are assumed to accelerate/decelerate at exactly $1ms^{-2}$ and at the right locations, allowing for a more reliable operation than in a car operator. This also allows for more complex acceleration/deceleration patterns to be utilised as shown in Figure 29.

5.2.3.3 Route Time

In the production of the journey time data, the time at each station had to be assumed. A time of 45 seconds was assumed as vehicles have small occupancies and are therefore easily loaded and unloaded. This is a realistic time as there is a maximum of 20 passengers per door, unloaded and loading onto the train. Based on this time at the station, as well as the acceleration/deceleration rates discussed, the route travel time and time to stations could be calculated using basic equations of physics. They are presented in Table 2 below. Key route information has also been graphed and included in Appendix B on page 98. This is where the acceleration/deceleration pattern for the route can be found.

Table 2: Key Performance Indicators of Route

Station	**Chainage (km)**	**Time of Arrival (seconds)**	***(min)***	**Distance to Station (km)**	**Time to Station (seconds)**	***(min)***
Airport Terminus	0.000	-	-	-	-	
East Gardens	4.786	238	*3:58*	4.786	238	*3:58*
Maroubra Junction	6.429	388	*6:28*	1.643	149	*2:29*

Station	Chainage (km)	Time of Arrival (seconds)	*(min)*	Distance to Station (km)	Time to Station (seconds)	*(min)*
Maroubra Beach	8.214	536	*8:56*	1.786	149	*2:29*
Coogee Beach	11.429	762	*12:42*	3.214	226	*3:46*
Randwick	13.714	931	*15:31*	2.286	169	*2:49*
Bondi Junction	17.000	1155	*19:15*	3.286	225	*3:45*
Bondi Beach	19.286	1328	*22:08*	2.286	173	*2:53*
North Bondi Terminus	20.429	1457	*24.17*	1.143	129	*2:09*

From the data presented in Figure 26 to Figure 29 in Appendix B, it is shown that there are straight sections and 7 different sized curve sections. Below presents a table with the curve radius and the subsequent spacing of supports. This will be the information that will be required when costing the route in Chapter 7. The largest curve spacing should be no more than 25 metres in any case to ensure a rigid track structure free from sagging, so if a curve produces a value of greater than 25 metres, it will be rounded down to 25.

The support spacing calculation will be based on basic trigonometric functions using the method shown in Figure 2, Chapter 2.2. The figure shows the curve and associated variables and presents the equation:

$$\Delta = R - \sqrt{R^2 - \frac{L^2}{4}}$$

This can be rearranged to:

$$L = \sqrt{(R^2 - (R - \Delta)^2) * 4}$$

Given the string cross section detailed in Figure 22, the width of the string structure is 120mm encasing 35mm diameter string. There is therefore 42.5mm of concrete filler on each side of the string. This is the delta value. Given the delta and the corresponding radii, the distance between supports, L, could be found. This value is made conservative by rounding down to the nearest metre. Table 3 below presents the support spacing calculated for each of the radii.

Table 3: Maximum Support Spacing

Curve Radius (m)	**Maximum Distance between supports (m)**	**Construction length (m)**
2200	27.34	25
1000	18.43	18
750	15.96	15
650	14.86	14
500	13.03	13
350	10.90	10
250	9.21	9
Straight Section	*25.00*	*25*

The following summary in Table 4 now shows the curves, the length of that curve within the specified alignment, and the subsequent supports number of supports for that curve based on the information above in Table 3. It is noted that tensioning supports are located at 1 km intervals to keep the string tensioned. Where this has fallen in one of the following curve radius sections, an intermediate support is excluded and replaced with a tensioning support. This table will form the basis for information regarding the volume of material when costing has been calculated in Chapter 7.

Table 4: Number of Supports Required

Curve Radius (m)	Number of Curves	Total Length (m)	Number of Tensioning Supports	Number of Intermediate Supports
2200	1	1,142.857	2	44
1000	1	714.2857	1	39
750	3	2,571.429	1	171
650	2	928.5714	1	66
500	5	2,714.286	2	207
350	6	2,571.429	4	254
250	4	1,214.286	3	132
0	10	8,571.429	8	335

5.2.4 Demand Estimation

To determine the approximate demand for the above route, the current airport rail and bus services will be considered along with Australian Bureau of Statistic population information. The Eastern suburbs population, as a percentage of Sydney's total population will be applied to the current hourly services from the airport for an approximate of the demand.

There are currently 131 train services from the airport to central between the hours of 4.56 AM and 0.54 AM (AirportLink, 2013). These services are 8 carriage sets and are capable of carrying 1000 passengers each (Sydney Trains, 2013). There are also 54 bus services to Sydney's eastern suburbs each day on the 400 bus route (Sydney Buses, 2013b) between 5.29 AM and 11.58 PM, each with a capacity of 58 passengers (Sydney Buses, 2013a).

Table 5 below was used to estimate the population of Sydney's eastern suburbs and in turn, this as a percentage of Sydney's total population. Each population statistic was provided by the Australian Bureau of Statistics (Australian Bureau of Statistics, 2012). Population statistics were however only provided for council areas, so each council which falls within the route designed will be included.

Table 5: Sydney Population Data

Area	2011 Population	Growth rate (Average Last 5 Years)	2013 Estimated Population
Botany Bay	40,871	1.60%	42,189
Sydney (East)	53,429	1.40%	54,935
Randwick	133,945	1.20%	137,179
Waverley	70,238	1.70%	72,646
Eastern Suburbs (Total)	*298,033*	*1.41%*	306,950
Sydney (Total)	4,627,345	1.60%	4,776,604
		Eastern Suburbs (% of Total)	**6.426%**

To determine the number of services per hour using String Transport Systems, the current services were kept at the same ratio of services per hour, however with only 6.426% of the capacity when compared to current capacity. That produced the following demand per hour.

Table 6: Estimated Demand (per hour)

Time	**4am**	**5am**	**6am**	**7am**	**8am**	**9am**	**10am**
	64	437	688	688	688	624	682
Time	**11am**	**12pm**	**1pm**	**2pm**	**3pm**	**4pm**	**5pm**
	560	560	560	560	560	624	746
Time	**6pm**	**7pm**	**8pm**	**9pm**	**10pm**	**11pm**	**12am**
	746	688	688	444	437	379	129

With this demand in mind, it was decided to use 5 carriage sets in Chapter 5.2.5, with each train having a capacity of 100. This results in 8 trains being required between 5 and 7 pm.

The maximum services per hour, discussed in Chapter 5.2.5 calculated to be 10 services per hour, fitting within the demand calculated in Table 6.

Based on this information, a suggested weekday timetable has been produced and is included in Appendix C. There are a total of 123 services per day, capable of carrying 12,300 passengers. The timetable suffices the demand estimation carried out and presented in Table 6 with a 4 hour shut down period of a night for scheduled maintenance similar to Sydney Train protocol. A trajectory diagram has also been produced and is presented in Appendix D. The purpose of this is to show the distribution of the 7 trains over the day, specifically showing the effects of morning and afternoon peaks. A section of this trajectory diagram is presented below in Figure 7, showing the train most used, and least used throughout the day. As it can be seen, train one operates for 20 hours of the day, from 4.30 AM to 12.30 AM, however train 7 only operates for 9 hours a day, from 7.00 AM to 11.30 AM and 5.00 PM to 9.30 PM.

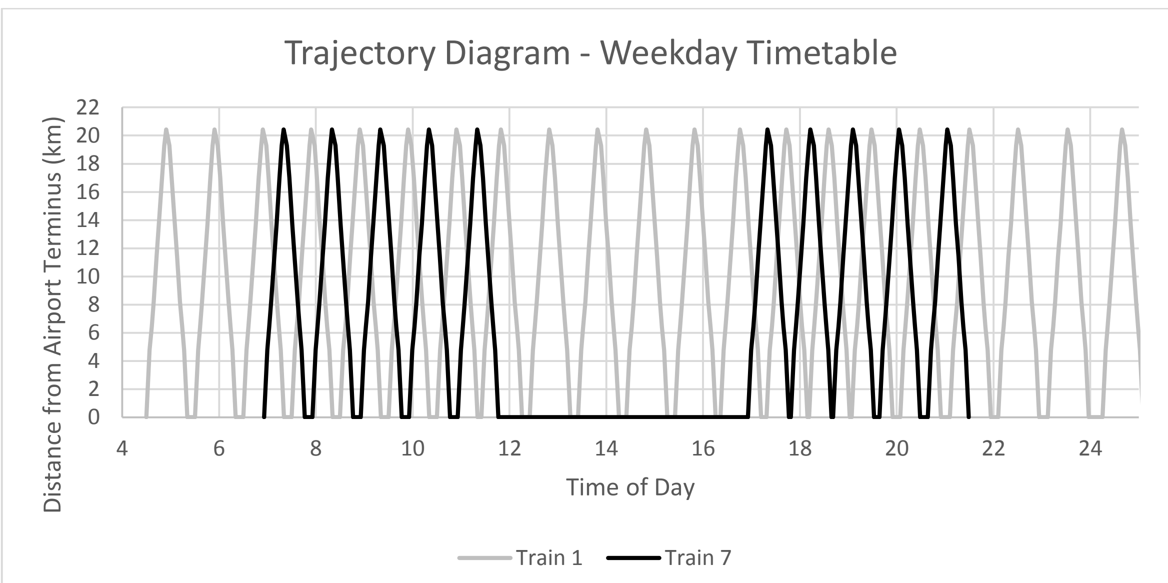


Figure 13: Trajectory Diagram (Train 1 and Train 7)

On any given summer weekend however, up to 50,000 revellers turn out for a day in the sun at Bondi Beach (Aqua Bumps, 2013). This puts a large amount of strain on the roads down to the beach, as well as all other beaches in the area, due to the significant demand on them.

This often results in grid-lock traffic conditions and length traffic delays. With an implemented String Transport Systems route, extra services could be added on such sunny weekend days to help alleviate the traffic congestion to help minimise the time taken to get down to Bondi Beach, as well as other beaches.

5.2.5 Route Capacity

To calculate the route capacity, the maximum number of services per hour needed to be calculated and subsequently the maximum patronage per hour. To determine this, the time the vehicle is stopped at each station was required as well as the time at each terminus. This coupled with the duration of travel between stations is used to determine the time a vehicle takes to travel the out and back route. This then used with the headway information to determine the number of trains that can occupy the route and the number of services per hour.

The headway that will be used between trains will be set at 350 seconds. The longest distance between two stations is the distance between the airport terminus and Eastgardens. The distance between the stations is 4.786 km taking a total of 238 seconds. Allowing for a 45 second time at station, this means a sectional duration of 328 seconds. With headways of 350 seconds, it will be ensured that there will be at most 1 vehicles on each set of strings between any pair of stations. This way, should an incident occur with a train, the following train can be held at the previous station to ensure it avoids the area of danger. Although rolling stock and subsequent evacuation methods are out of the scope of this dissertation, the evacuation methodology would obviously be difficult and require to be quite complex. Therefore it would be imperative that the rolling stock and the route be designed to a very high standard, however this headway will help in the very unlikely event of an emergency.

Headways of 350 seconds will allow for 10 trains per hour, as previously discussed. As Sydney’s eastern suburb’s population ultimately grows, and the demand for this route increases, this number will need to be increased. North West Rail Link, again acting as a precedent for this dissertation, has been designed to cater for up to 20 trains per hour (Barry O'Farrell, 2012).

Ultimately the decision on number of carriages per vehicle and number of passengers per carriage is up to the designer and the purpose of the specific route. For an indicative measure below, 5 carriages per train and 20 passengers per carriage will be assumed. This allows for 100 passengers to be on-board each train.

The total duration of the route is 1,457 seconds. Allowing for a return journey and 120 seconds at each terminus, this is a duration of $1{,}457 * 2 + 120 * 2 = 3{,}154\ seconds$ for one complete trip of the route. With 350 second headways, this allows for 9 trains to occupy the route. With a 100 person limit, this gives the route a capacity of 900 passengers, per 3,154 seconds, or per return journey. This gives a maximum hourly patronage of 1,000 passengers per hour.

Detailed analysis would be required to determine the patronage numbers, but at a start, the data suggest that this is feasible value. With 10 carriage sets and 3 minute headways, the volume of passengers per hour could be increased to 4,000, quadrupling the current value, allowing for a lot of growth in the area as well as a large contingency.

5.2.6 Turnouts/Crossovers

Given the route presented above, there is no need for a turnout or a crossover for regular operation. Granted this, there may be a need should a train break down between stations. Trains are not excessively heavy and can be removed from the track by a crane. Until this could happen however, trains may need to cross on to the opposite line to pass the failed train and turnouts could be used.

Turnouts within a string transport network are possible (String Transport Unitksy, 2006) however the structure is changed around the area of the turnout and in this case, it is likely not necessary to include.

5.3 INTERCHANGE

Each station located along this route is aimed to be located at a public transport interchange. Due to no trains operating in the eastern suburbs (excluding the train to Bondi Junction), each interchange is a major bus stop, often a route terminus, or a key demand centre such as a beach or shopping centre.

Table 7 below presents the number of bus routes that stop at (or within 100m) of the rail stations and associated demand centres to determine the usage of the interchange.

Table 7: Bus Routes Interchanging at Each Station

Station	**Demand Centre**	**Number of Bus Routes** (Sydney Buses, 2012)
Airport	Sydney Domestic Airport	1
Eastgardens	Westfield Eastgardens	9
Maroubra Junction	Pacific Square Shopping Centre	14
Maroubra Beach	Maroubra Beach	8
Coogee Beach	Coogee Beach	13
Randwick	Randwick Plaza Shopping Centre	10
Bondi Junction	Westfield Bondi Junction	25+
Bondi Beach	Bondi Beach	5
North Bondi Terminus	North Bondi	7

With large volumes of bus services utilising these current interchanges, it is therefore very appropriate to put the stations in these locations.

5.4 ROUTE SUMMARY

Using the conclusions taken from Chapter 4, an effective route has been developed from Kingsford-Smith Airport to Bondi Beach. The journey only takes 25 minutes, characterised by higher speeds than what is conventionally able to be experienced by light rail vehicles and personal vehicles. This is what Yunitskiy has specified as one of the key advantages of such a technology. Table 8 below compares the travel times experienced by a personal vehicle

(Google, 2013) and current public transport options (NSW Government, 2013) with String Transport Systems to reach each station location from Sydney's Kingsford-Smith Airport. As clearly shown, the travel time on a String Transport System route, is far superior in travel time than current public transport options. The route also outperforms a personal vehicle to all locations, excluding the North Bondi Terminus.

Table 8: Travel Time Comparison

Station	Personal Vehicle (Mins)	Current Public Transport (Mins)	String Transport Systems (Mins)
Eastgardens	11:00	24:00	3:58
Maroubra Junction	13:00	26:00	6:28
Maroubra Beach	17:00	36:00	8:56
Coogee Beach	18:00	36:00	12:42
Randwick	16:00	34:00	15:31
Bondi Junction	20:00	28:00	19:15
Bondi Beach	23:00	42:00	22:08
North Bondi Terminus	24:00	45:00	24:17

With higher speeds, 123 services can be offered per day to satisfy estimated demand of up to 12,300 passengers per day. This allows passengers to connect with `major transportation interchanges within Sydney's eastern suburbs, connecting to over 80 bus routes.

This route, the best application of String Transport Systems, not only services large volumes of passengers, but also helps to fill the rail void within Sydney's Eastern suburbs.

6 DESIGN OF STRUCTURAL ELEMENTS

To assess the feasibility of the system form a technical perspective, a preliminary design has been included below. The design is based on Australian Standards as well load information provided in Yunitskiy's design specifications where gaps exist. Note that the above route mentioned in Chapter 5.2, will form the basis of the design here, and subsequently the cost in Chapter 7.

6.1 LOADS

The loads that will be applied to the structure for design, are the standard loads considered in conventional railways design to provide consistency when comparing String Transport Systems to conventional forms of railway.

6.1.1 Dead Load / Live Load

Loads due to the weight of the structure/tension in the string as well as loads induced by the rolling stock are considered and summarised in the table below. For a full explanation on each of the loads, please refer to Appendix F.

Table 9: Load on Supports

Item	***Mass Experienced on Each Support (kg)***	**Force Experienced on Each Support (kN)**	**Type of load**
Steel in String**	*566.44*	5.551	Dead
Concrete in String**	*1626.82*	15.943	Dead
Total String**	*2193.26*	21.494	Dead
Horizontal support beam*	*687.5*	6.738	Dead
Vertical Column*	*1550*	15.190	Dead
Maximum horizontal string tensioning force (refer Chapter 6.3.2.1)	-	0.772	Dead

Item	*Mass Experienced on Each Support (kg)*	Force Experienced on Each Support (kN)	Type of load
Tensioning of strings (tensioning supports only)**	-	2450	Dead
Rolling stock including all passengers and cargo**	*4375*	42.919	Live
Maximum centrifugal force (refer Chapter 6.3.2.1) **	-	10.976	Live
Car Crash	-	138.889	Live

*Note that the column and beam masses have been assumed at 155kg/m and 125kg/m respectively. This is to reflect the decision to use a 610UB125 and a 508CHS12.7 for preliminary design.

**per string

6.1.2 Dynamic forces

Calculation and detailed analysis of dynamic forces are out of scope of this dissertation and are subject to further investigation. Where gaps exist, information has been taken from String Technologies Unitsky reports, or basic calculations have been performed.

To determine the force on the structure based on the effects of rolling stock, two forces were considered. The centrifugal force exerted by the train was considered and is discussed in Chapter 6.3.2.1. The bending moment exerted on the structure by a passing forward moving train was also included in design calculations, and this was taken from a technical report produced by Yunitskiy to be 25 kN.m (String Transport Systems Limitied, 2010). These loads will be used for the preliminary design.

6.1.3 Wind Loads

Due to the small size of the structure, and the large vertical and horizontal loads experienced, the effects of wind are ignored. It is assumed they are negligible on a structure of this size and this design strength. Numerous wind-tunnel tests however, have been carried out by String Technologies Unitsky at the Krylov Central Scientific Research Institute in St. Petersburg Russia on 1:5 scaled models. The testing showed that a train travelling at 250 km/hr with a 200 km/hr side wind would not break its wheel-rail contact and derail. (String Transport Unitksy, 2006). Given the highest wind gust ever recorded on mainland New South Wales was 174 km/hr (Bureau of Meteorology, 2013), the above assumption is deemed satisfactory.

Albeit, the effects of the wind on the train may be damaging, but this is out of the scope of this dissertation and is subject to further investigation.

6.2 FOUNDATIONS

Basic foundation design methods will be used to design a foundation for a typical support structure. Key considerations include the effect of the foundation under load, foundation type as well as the expected soil properties in Sydney's Eastern suburbs.

6.2.1 Foundation Type

Anatoly Yunitskiy has dictated in his preliminary design work that the foundation should be 4 metres in length and include a diameter of 600mm with a thickness of 10mm. (Yunitskiy, 2000) Figure 14 below shows these geometric properties suggested for a typical support including foundation.

This design however, will include both tracks supported on the one column. Therefore the structure in Figure 17 will be used. This structure will again use a monopole design, but has a 1.0metre diameter base and a length of 7 metres.

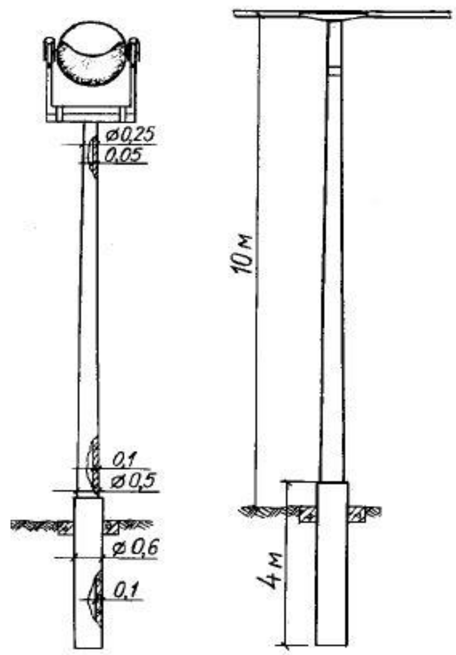


Figure 14: Suggested Foundation and Support - Geometric Properties (Yunitskiy, 2000)

The Australia standard on piles is AS 2159-2009: Piling - design and installation (Standards Australia, 2009c). This standard dictates that loading be factored based on AS1170.1. The standard also dictates that steel piles be designed to AS4100, with an allowance made for corrosion of the pile.

As the steel column has been designed in Chapter 6.3.3.1 and is deemed sufficient, the pile will be assumed to be sufficient as well at this preliminary stage. Simple calculations however have been included on the axial and lateral capacity which can be used as a check for indicative purposes for initial feasibility design. Calculations are based on driven steel piles in medium density sand (Taiebat, 2012). The outcomes of these calculations are presented below in Chapter 6.2.4, and detailed working is found in Appendix F.

6.2.2 Soil Type

Various types of foundations that can be used for design. This preliminary design will be done in medium density Sydney sand, as sand is the most common material found in the region of interest (Sydney Environmental and Soil Laboratory, 2007). Medium density sand is also quite weak, and hence a design will be deemed conservative if it is satisfactory for medium density sand.

Typical Sydney medium density sand was found through triaxial testing to have a cohesion co-efficient of 0 and an angle of friction of 41.42° (Hargraves, 2011). This test was carried out under drained and undrained conditions using mohr-columb failure envelope analysis. Other useful values for medium density sand, using driven piles are $Ktan\delta = 1.0$ and $N_q = 100$ (Taiebat, 2012).

6.2.3 Loads

The loads of interest in this calculation are the moment, horizontal force and vertical force on the top of the pile. These loads are shown acting on the pile in Figure 15 below, with the factored values presented in Table 10. Further loading discussion is in Appendix E.

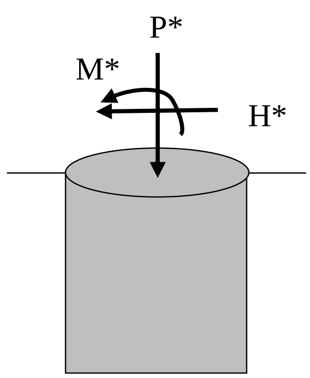


Figure 15: Pile Loads

Table 10: Pile Loads

Load	Value
P*	390.286 kN
M*	721.020 kN.m
H*	270.020 kN

The pile must be designed to deal with a car impact to the structure. Road safety barriers will be likely to be used to deflect a car from impact, however if they fail, this structure will be designed to take the impact of a car colliding with it at 100 km/hr.

$$F = \frac{\Delta p}{\Delta t} = \frac{m * \Delta v}{\Delta t} = \frac{m(v_i - v_f)}{\Delta t} = \frac{1000kg * (27.78 - 0)ms^{-1}}{0.2s} = 138.889\ kN$$

It is assumed to be a 1 tonne car, travelling 100 km/hr, reducing its velocity to 0 in 0.2 seconds, colliding with the structure at a height of 0.5 metres. With modern car crumple zones, the full force of the impact will be damped, however to be conservative, this value will be used. Each support is also isolated from the other supports, so if one support were to fail, disproportionate collapse would not be observed. The result would be a greater span and ultimately a greater sag, however this should not occasion a derailment.

A summary of all the forces used to calculate the key loads in Table 10 is presented below in Table 11. Each load is factored based on Australian Standard 1170.1 (Standards Australia, 2009b).

Table 11: Loads on Pile Summary

Force	Dead load – G (kN)	Live Load – Q (kN)	1.2G+1.5Q	1.35G	Maximum Factored Load (kN)
Each String (Including Rolling Stock)	21.494	42.919	90.171	29.017	90.171
Beam Self-Weight	6.738	0	8.086	9.096	9.096
Column Self-Weight	15.19	0	18.228	20.507	20.507
Train (Centrifugal)	0	10.976	16.464	0	16.464
Horizontal String Tensioning	0.77	0	0.924	1.040	1.040
Car Impact	0	138.889	208.334	0	208.334

$$vertical\ load\ (P^*)$$
$$= force\ on\ string * 4 + beam\ self\ weight + column\ self\ weight$$
$$= 390.286\ kN$$

$horizontal\ load\ (H^*)$
$= centrifugal\ force * 4 + string\ tension * 4 + car\ impact$
$= 270.020\ kN$

$Moment\ (M^*)$
$= (centrifual\ force + string\ tension) * 4 * 10m + car\ impact * 0.5m$
$= 721.020\ kN.m$

6.2.4 Capacities

The axial and lateral capacity of the pile is presented below in Table 12. A complete list of calculations to provide these capacities is presented in Appendix F.

Table 12: Pile Capacities

Capacity	Required	Value	Factor of Safety
Axial Capacity	$P^* \leq \phi_g P_u$	$\phi_g P_u = 2{,}256.29\ kN.m$	5.78
Lateral Capacity	$H^* \leq H_u$	$H_u = 348.291\ kN.m$	1.29

6.3 SUPPORTS

The design of the supports is based on the most unfavourable loading conditions the supports will be exposed to. The design is constructed of steel so design will be carried out to Australian Standard 4100 – Steel Structures (Standards Australia, 1998).

6.3.1 Support Types

There are two types of supports used in String Transport Systems design. The first is used every kilometre and is what the string is tensioned between. These are what will be referred to as a tensioning support. The second type is an intermediate support, spaced every 10-25 metres (refer Chapter 325.2), used to eliminate the effect of sag on the structure.

A singular support will be designed in Chapter 6.3.3.1, designed as a typical support. This support will be designed as the intermediate support, ignoring the ‘tensioning block’ that would be required in a tensioning support. As the tensioning would occur in both directions on such a support, there would be no net horizontal force, the only requirement would be the capacity of the block. There would however be second order effects on the support from rolling stock moving past, but this dynamic analysis is subject to further investigation. The typical support will be assumed to be satisfactory in such supports, however there will be the inclusion of the tensioning block. The structure will act somewhat like a cable stay bridge in this instance.

6.3.2 Loading on Supports

The two support types are exposed to similar loadings. Chapter 6.3.2.2 and 6.3.2.1 aims at exploring these loadings.

6.3.2.1 Intermediate Supports

Intermediate supports are designed to predominantly deal with the vertical loads exerted by the train and the string, preventing sag/vertical deflections. With curves however, there will be some minor horizontal loads induced on the structure from the string tensioning, as well as the possibility of significant centrifugal accelerations.

Figure 16 below shows the loading schematic on a typical intermediate support on a curve. It can be seen that the tensioning force is no longer acting in one direction and is therefore exerting a horizontal force on the structure.

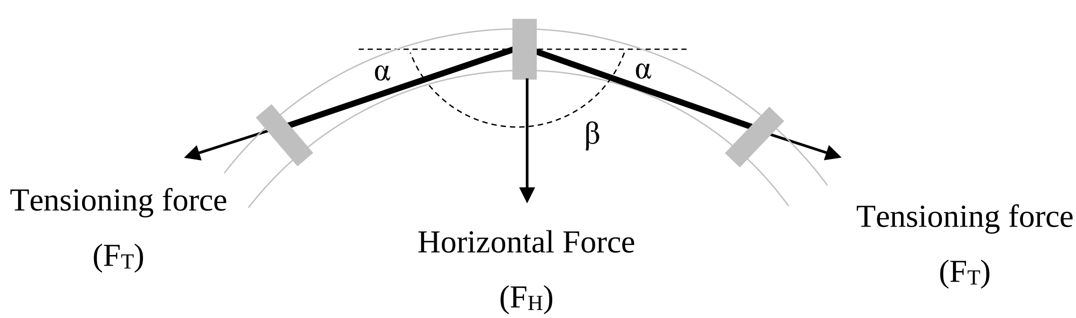


Figure 16: Loading Schematic on Intermediate Supports

A string-rail curve, contains an internal string polygon as shown in Figure 16 above, due to the nature of the strings. To calculate β, the curve radii are used to calculate curve circumference, then this can be divided by the support spacing to find the number of sides to the polygon. This can then be used to calculate the internal angle of each corner of the polygon. Once β is found, α is found and through basic trigonometric functions, the horizontal force on the structure can be found. Table 13 and Table 14 below show these calculations and provide the subsequent horizontal forces on the intermediate supports for each of the 7 curve radii. The tensioning force will not be felt by the intermediate support as the strings are sitting on top of the support. There are held in place to prevent lateral deflection however, and hence this reflects the horizontal forces on the curve. Table 13 and Table 14 below calculate the relevant horizontal and tensioning forces.

Table 13: String Polygon Production

Curve Radius (m)	**Support Spacing (m)**	**Circumference (m)**	**Number of Sides to Polygon**	**$\sum\alpha = (n-2) \times 180°$**
2200	25	13,823.010	552.92	99,165.66
1000	18	6,283.185	349.06	62,471.85
750	15	4,712.389	314.15	56,188.67
650	14	4,084.070	291.71	52,149.48
500	13	3,141.593	241.66	43,138.98
350	10	2,199.115	219.91	39,224.07
250	9	1,570.796	174.53	31,055.93
0	25	-	-	-

Table 14: Horizontal Load Calculation

Curve Radius (m)	β = ∑α /n	B = (180-α)/2	F_T = cos(α)*load (kN)	F_H = sin(α)*load (kN)
2200	179.34	0.32	42.92	0.24
1000	178.96	0.51	42.92	0.39
750	178.85	0.57	42.92	0.43
650	178.76	0.61	42.92	0.46
500	178.51	0.74	42.92	0.56
350	178.36	0.81	42.91	0.61
250	177.93	1.03	42.91	0.77
0	-	-	42.92	0

There is also a centrifugal force exerted by a moving train on the rail and hence the support.

$$F_{centrifugal} = a_{centrifgual} * mass$$

$$a_{centrifugal} = \frac{v^2}{r}$$

$$F_{centrifugal} = \frac{v^2}{r} * mass$$

For each of the curves, the acceleration and subsequent centrifugal force was found based on the maximum allowable curve velocity (refer Chapter 5.2.3.1). This was combined with the estimated rolling stock mass (refer chapter 6.1). This is presented in Table 15.

Table 15: Centrifugal Force Calculations

Curve Radius (m)	Curve Velocity ($m.s^{-1}$)	$a_{centrifugal}$ ($m.s^{-2}$)	$F_{centrifugal}$ ($kg.m.s^{-2}$)
2,200	28	0.36	10,690.91
1,000	28	0.78	23,520.00
750	24	0.77	23,040.00
650	22	0.74	22,338.46
500	19	0.72	21,660.00
350	16	0.73	21,942.86
250	14	0.78	23,520.00
0	28	0	0

Centrifugal forces are in the opposite direction to the horizontal forces shown earlier and will minimises the net force exerted on the structure.

6.3.2.2 Tensioning Supports

The tensioning support is exposed to the same loads as the previously mentioned intermediate support. The extra force that the support is exposed to is a load of 816 kN per string (refer Chapter 6.1). The total tensioning block will therefore be exposed to 9792kN in each direction. Yunitskiy reports suggest tensioning each string to 250 tonnes (250,000 kgf) (String Transport Unitksy, 2006), suggesting that this is an appropriate value to be used for design. The specifics of the tensioning blocks are subject to the ultimate decision on the steel string tensioning and hence the load on each block. This is subject to further investigation.

6.3.3 Structure Design

Suggested maximum heights of the supports are 15-25 metres through analysis by Yunitskiy (String Transport Unitksy, 2006). For conservative design, this structure will only be designed to a height of 10 metres.

6.3.3.1 *Typical Supports*

A typical support structure is simpler in design than a tensioning support. They involve a singular upright structure, with a horizontal beam on top for the string-rails to attach sit on. With a 2 metre gauge width (String Transport Unitksy, 2006), and 2.5m wide carriages (Volvo Buses, 2012) (based on a typical Sydney bus width – wider than a conventional monorail vehicle), the spacing between rail centres needs to be a minimum of 2.5 m to prevent collision by trains in opposing directions. For safety precautions and to minimise the effects of forward rush of air when trains pass each other, the track centres will be spaced at 3 metres. Figure 17 below details the structural dimensions.

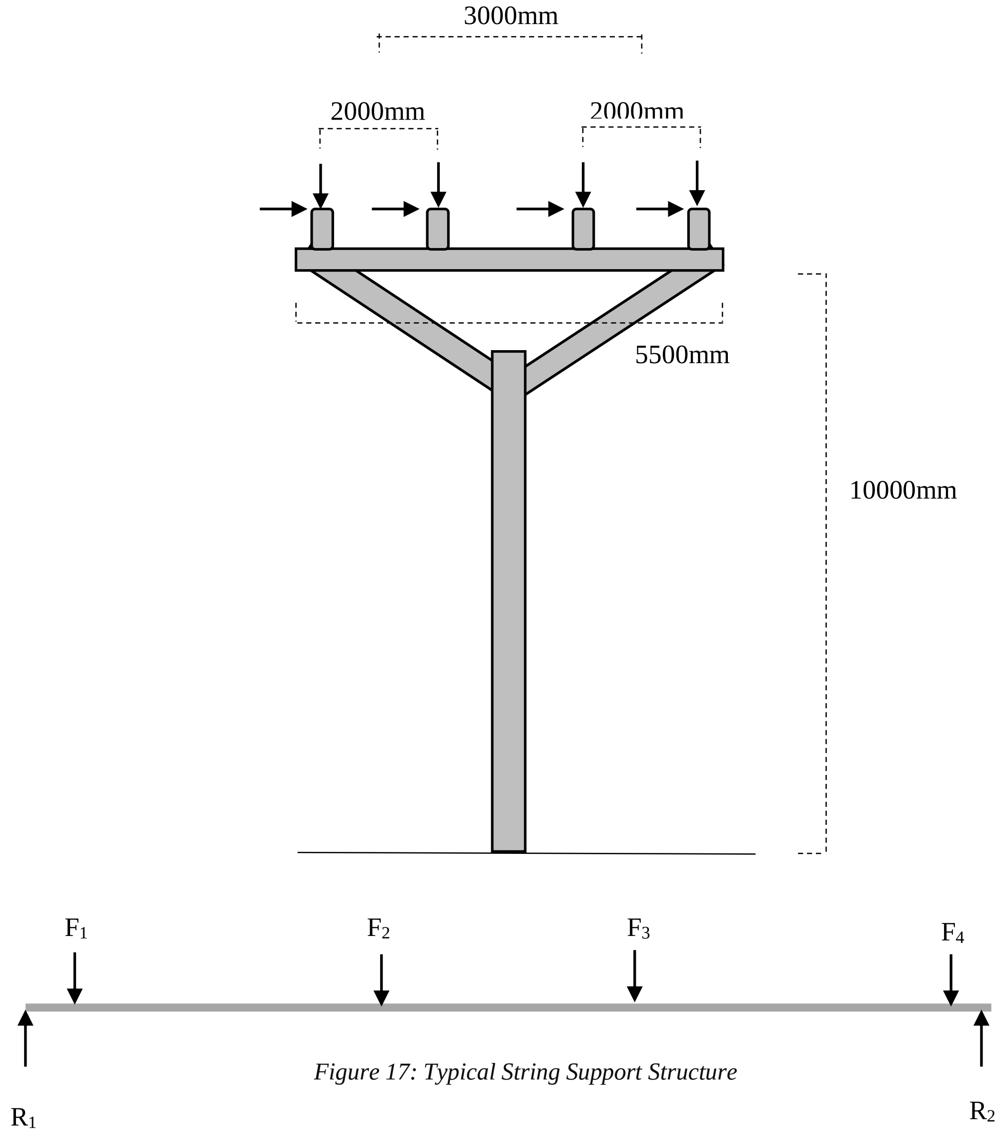


Figure 17: Typical String Support Structure

From the above dimensions, the moments and forces in both the horizontal and vertical directions can be found. This will form the basis of the beam selection. Yunitskiy suggests the usage of circular hollow steel beams for the beams however due to the easier production and availability of Universal Beams (UB), the design will use a 5500mm long one. In terms of the column, Yunitskiy suggests the use of tapered circular hollow sections for the columns however again due to easier production and availability, this will not be used and in this case, a circular hollow section of 10000mm length will be used.

To ensure a conservative design for the typical support, capable of being used in any of the locations along the route, the design will be based on the following;

- Maximum centrifugal force
- Maximum horizontal string tensioning force
- Maximum span

Whilst none of these situations will be encountered at the same location, this will ensure a satisfactory design.

The forces that the beam presented in Figure 17, will be exposed to, are presented in Table 16 below. These loads are based on information provided in Chapter 6.1.1.

Table 16: Beam Loads

Force	**Dead Load – G (kN)**	**Live Load – Q (kN)**	**1.2G+1.5Q**	**1.35G**	**Maximum Factored Load (kN)**
Each string	21.494	42.919	90.171	29.017	90.171
Beam self-weight	1.225 (kN/m)	0	1.47 (kN/m)	1.654 (kN/m)	1.654 (kN/m)

Through static analysis, the values of the shear force and bending moment at any point along the beam can be found. The shear forces on the beam are presented in Table 17, with the subsequent shear force diagram presented in Figure 18 and bending moment diagram presented in Figure 19.

Table 17: Beam Forces

Force	Value (kN)	Location (m)
Beam self-weight	1.225 (kN/m)	0 - 5.5
R_1	184.890	0
F_1	90.171	0.25
F_2	90.171	2.25
F_3	90.171	3.25
F_4	90.171	5.25
R_2	184.890	5.5

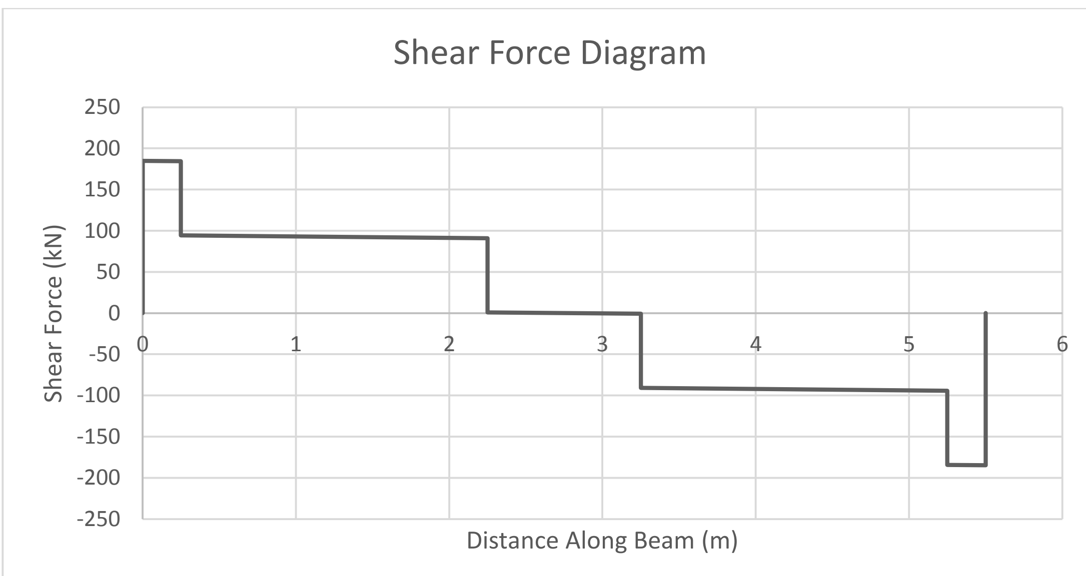


Figure 18: Beam Shear Force Diagram

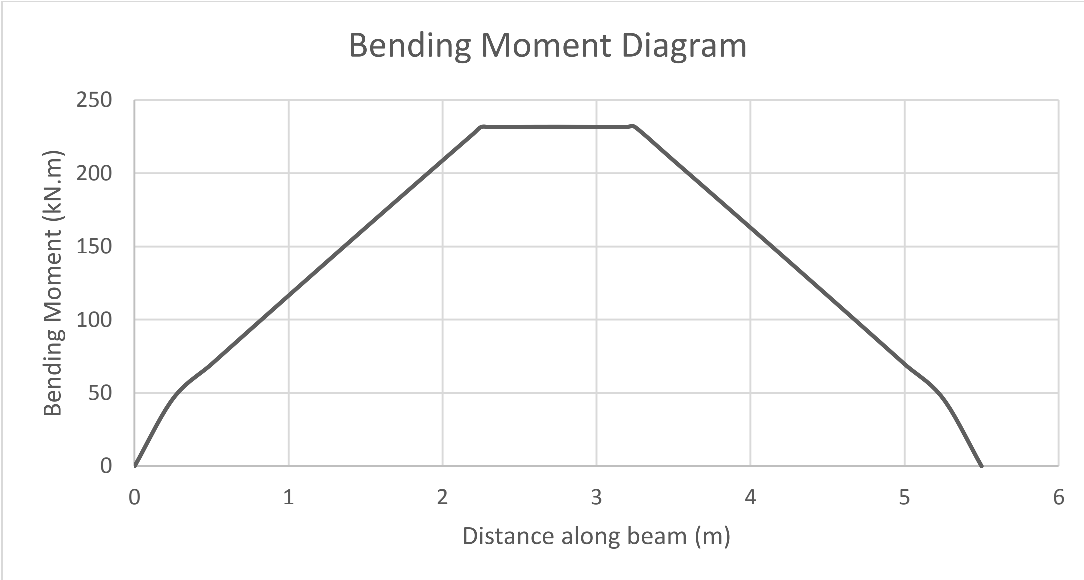


Figure 19: Beam Bending Moment Diagram

The above figures show the following key forces/moments, used for design of the beam

Maximum support reaction, R* = 184.890 kN

Maximum Shear force, V* = 184.890 kN

Maximum moment, M* = 231.681 kN.m

Moment at ¼ beam length, M_2^* = 151.218 kN.m

Moment at ½ beam length, M_3^* = 231.681 kN.m

Moment at ¼ beam length, M_2^* = 151.218 kN.m

Designing to Australian Standard AS4100, capacities were satisfied and are presented below in Table 18. Detailed calculations are presented in Appendix F, should further clarification be required.

Table 18: Beam Design Capacities

Capacity	Required	Value	FOS
Section Capacity	$M_x^* \leq \phi M_{sx}$	$\phi M_{sx} = 1{,}101.643\ kN.m$	4.75
Bending Capacity	$M_x^* \leq \phi M_{bx}$	$\phi M_{bx} = 776.483\ kN.m$	3.35
Web Shear Capacity	$V^* \leq \phi V_v$	$\phi V_v = 1{,}102.702\ kN$	5.96
Bending and Shear Interaction	$V^* \leq \phi V_{vm}$	$\phi V_{vm} = 1{,}102.702\ kN$	5.96
Bearing Capacity	$R^* \leq \phi R_b$	$\phi R_b = 605.797\ kN$	3.28

In design of the column, the loads that it will be exposed to, are presented in Table 19 below. These loads are based on information provided in Chapter 6.1.1.

Table 19: Column Loads

Force	Dead Load – G (kN)	Live Load - Q (kN)	1.2G+1.5Q	1.35G	Maximum Factored Load (kN)
Each String (Including Rolling Stock)	21.494	42.919	90.171	29.017	90.171
Beam Self-Weight	6.738	0	8.086	9.096	9.096
Column Self-Weight	1.519 (kN/m)	0 (kN/m)	1.823 (kN/m)	2.051 (kN/m)	2.051 (kN/m)
Rolling Stock (Centrifugal)	0	10.976	16.464	0	16.464

Force	Dead Load – G (kN)	Live Load - Q (kN)	1.2G+1.5Q	1.35G	Maximum Factored Load (kN)
Horizontal String Tensioning	0.77	0	0.924	1.040	1.040
Rolling stock (Forward Motion)	0 (kN.m)	25 (kN.m)	37.5 (kN.m)	0 (kN.m)	37.5 (kN.m)
Car Crash	0	138.889	208.333	0	208.333

Through static analysis, the axial force and bending moment at any point along the column can be found. The axial forces are presented in Figure 20 and the bending moment diagram in Figure 21.

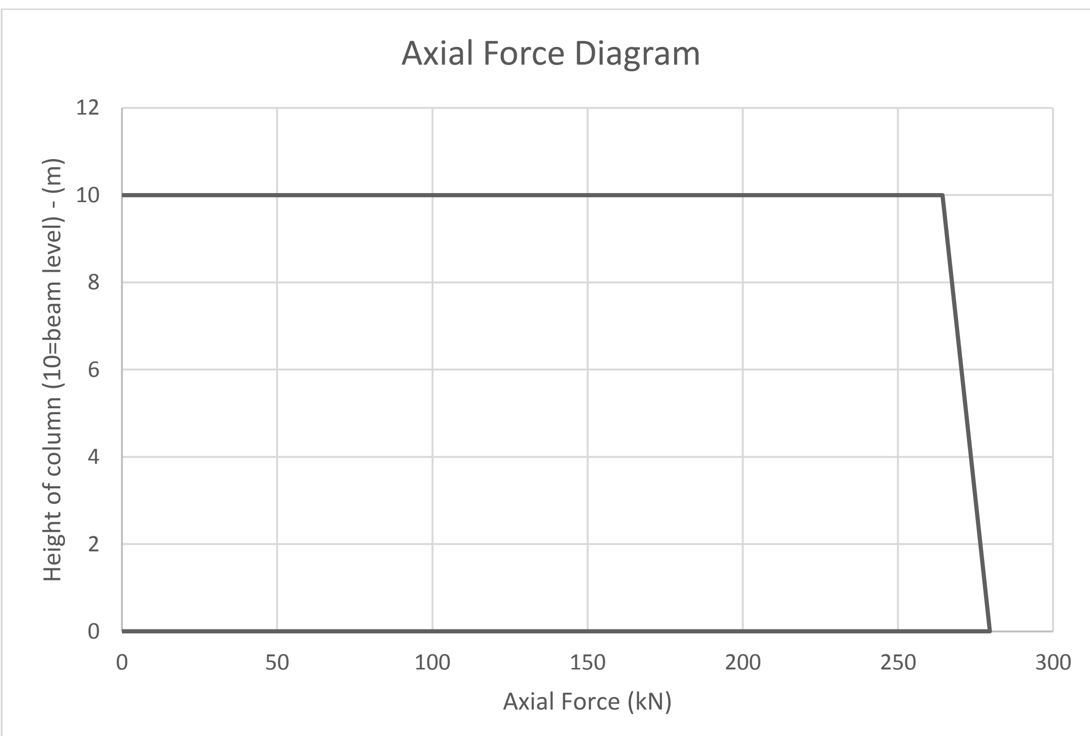


Figure 20: Column Axial Force Diagram

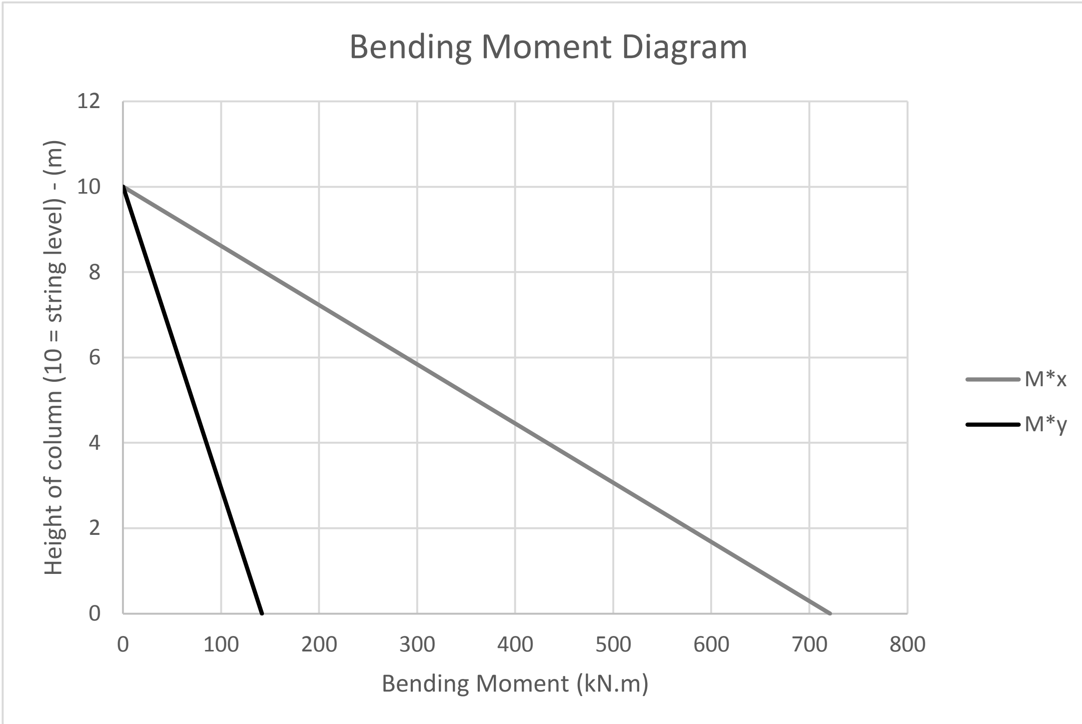


Figure 21: Column Bending Moment Diagram

The above figures show the following key forces/moments, used in design of the column.

Maximum axial force, N* = 390.286 kN

Maximum moment, x-axis, M_x^* = 721.012 kN.m

Maximum moment, y-axis, M_y^* = 141.667 kN.m

Designing to Australian Standard AS4100, capacities were satisfied and are presented below in Table 20. Detailed calculations are presented in Appendix F, should further clarification be required.

Table 20: Column Design Capacities

Capacity	Required	Design	FOS
Section Capacity for Member Exposed to Combined Actions			
Compression	$N^* \leq \Phi N_s$	$\Phi N_s = 6{,}237\ kN$	15.98
Uniaxial Bending about x-axis	$M^* \leq \Phi M_{rx}$	$\Phi M_{rx} = 900.630\ kN.m$	1.25
Uniaxial Bending about y-axis	$M^* \leq \Phi M_{ry}$	$\Phi M_{ry} = 900.630\ kN.m$	6.36
Biaxial Bending Capacity	$\left(\frac{M_x^*}{\Phi M_{rx}} + \frac{M_y^*}{\Phi M_{ry}} + \frac{N^*}{\Phi N_s}\right) \leq 1$	$\left(\frac{M_x^*}{\Phi M_{rx}} + \frac{M_y^*}{\Phi M_{ry}} + \frac{N^*}{\Phi N_s}\right) = 0.905$	-
Member Capacity for Member Exposed to Combined Actions			
Compression	$N^* \leq \phi N_c$	$\phi N_c = 6{,}052.149\ kN$	15.51
In-Plane capacity about x-axis	$M^* \leq \phi M_{ix}$	$\phi M_{ix} = 891.910\ kN.m$	1.24
In-Plane capacity about y-axis	$M^* \leq \phi M_{iy}$	$\phi M_{iy} = 891.910\ kN.m$	6.30
Out of Plane Capacity	$M_x^* \leq \phi M_{ox}$	$\phi M_{ox} = 940.273\ kN.m$	1.30
Biaxial Bending	$\left(\left(\frac{M_x^*}{\Phi M_{cx}}\right)^{1.4} + \left(\frac{M_y^*}{\Phi M_{iy}}\right)^{1.4}\right) \leq 1$	$\left(\left(\frac{M_x^*}{\Phi M_{cx}}\right)^{1.4} + \left(\frac{M_y^*}{\Phi M_{iy}}\right)^{1.4}\right) = 0.754$	-

6.3.3.2 Tensioning Supports

The tensioning supports will be exposed to slightly different loads than those discussed above. The inclusion of the tensioning block for the strings to be tensioned with will add increased axial force down the column and subsequently the pile. Due to the symmetric nature of the structure, this inclusion of this element will not add a moment to the column or the foundation. It will however increase the axial load but as the pile suffices by a factor of safety of 5.78 (refer Chapter 6.2.4) and the column by a factor of safety of 15.98 (refer Chapter 6.3.3.1) this will not be an issue for a typical support.

6.4 STRING-RAILS

As mentioned in the introduction, the string-rails are what makes String Transport Systems so unique. This is the defining characteristic, which differs from conventional rail. This chapter as well as elements of Chapter 5 present the design of the string-rails including the benefits and the constraints of the technology.

6.4.1 What Characterises String-Rail?

String-rail consists of 3 highly tensed steel cables inside a concrete ‘filler’ with a steel rail head on top. These strings are tensioned at 1 kilometre intervals (String Transport Unitksy, 2006), so must be supported along the way with use of intermittent supports. A typical string-rail cross section is shown below in Figure 22. The curve development using this technology is also discussed in chapter 5.2.2 with maximum support spacing provided.

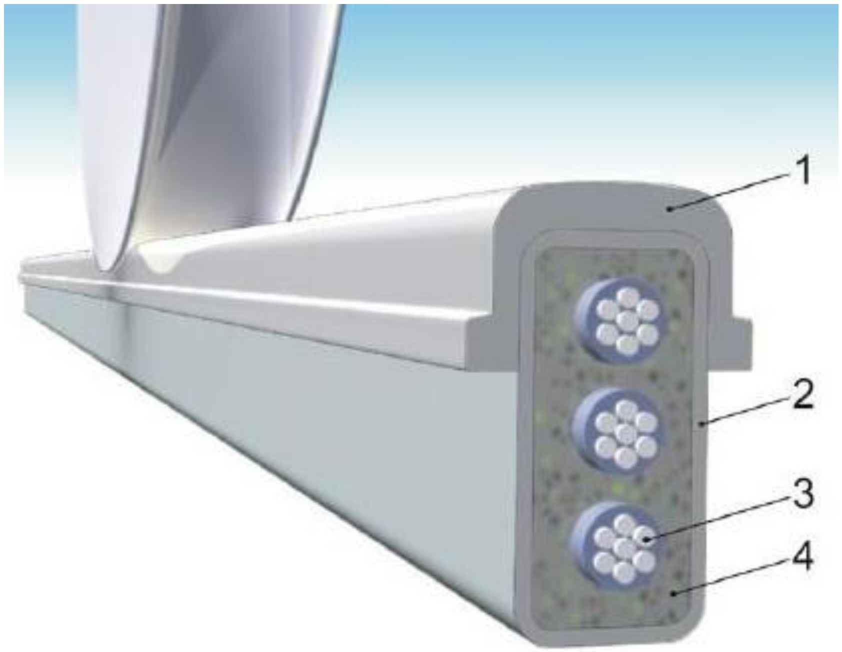


Figure 22: String-Rail Cross-Section (String Transport Unitksy, 2006)

6.4.2 Loads

The steel cables within the string-rail are tensioned at 1 km intervals, each string-rail is tensioned to a total of 250 tonnes (250,000 kg-force) (String Transport Unitksy, 2006). Each string is made up of 3 steel cables. Each will subsequently be tensioned up to a force of 83333.33 kg-force (816.67 kN).

The string are suggested to be 35mm in diameter, but to design to AS 4672.1:2007 - Steel prestressing materials, Part 1: General Requirements (Standards Australa/Standards New Zealand, 2007), 36 mm strings will be used.

Using 7 string strands, with each of these being 11.1 mm strands, a diameter of 36 mm can be achieved with the use of filler;

$$minimum\ breaking\ force\ =\ 7 * 138kN\ =\ 966\ kN$$

The loading on the string in a vertical direction consists of rolling stock and self-weight. Each of these will be considered as a uniform distributed load. Again each load has been factored as per Australian Standard 1170 requirements (Standards Australia, 2009b).

$$Rollingstock \ = \ 1.5 * 1.717 = 2.575 \ kN/m \ per \ string$$

$$String \ (Concrete) \ = \ 1.35 * 0.638 \ = 0.861 \ kN/m$$

$$String \ (Steel \ strand) = \ 1.35 * 0.040 \ = \ 0.054 \ kN/\mathrm{m}$$

6.4.3 Steel String Behaviour

The cables within the string-rail must be high enough in tension to minimise deflection caused by sag and loading. Minimising deflection helps to produce a smooth ride for the rolling stock, and limit the possibility of a derailment.

Two methods of analysis have been used to determine the midspan deflection induced by the rolling stock. One is based on structural equations, assuming the total load is acting at the midspan of the string, and one using MDSolids, a mechanics of materials software, loading the string-rail at the specific locations of wheel-rail contact.

The amount of deflection caused by ‘sag’ in the string is found based on methods of calculation used in HV electric cable calculations, as the string-rail closely mimics the behaviour of such HV wires. The calculation of such sag, only includes the associated steel uniform distributed load, the concrete within the steel rail will be added to deflection calculations later as a dead load.

$$Mid \ Span \ Sag \ (S) = \frac{WL^2}{8T} = 3.98 \ mm$$

$$W = 0.054 \ kN/m$$

$$L = 25 \ m$$

$$T = 816.667 \ kN$$

Temperature does also affect the structure as it is made out of steel. As no dynamic analysis or testing has been carried out and temperature effects are not completely known for this case, data presented by Yunitskiy will be used. It is stated that a 100 degree temperature swing can cause a deflection equal to 1/10,000 of the span (String Transport Unitksy, 2006). 100 degree temperature swings are not observable in Australia, but this value will be used to ensure the design remains conservative.

$$Deflection\ due\ to\ tempereature\ (\Delta) = \frac{1}{10{,}000} * 25 = 2.5mm$$

Assuming the concrete mass and rolling stock mas are a concentrated load at the midspan, the following deflection can be used.

$$Deflection\ (\delta) = \frac{NL}{EA} = 3.720mm$$

$$N = 25 * (2.575 + 0.861) = 85.901\ kN$$

$$L = 25\ m$$

$$E = 2 * 10^5\ MPa\ (typical\ value -\ steel\ modulus\ of\ elasticity)$$

$$A = 3 * \pi * \left(\frac{35}{2}\right)^2 = 2{,}886.338\ mm^2$$

Using MDSolids, the deflection produced from a UDL for the concrete and a series of point loads for the train, the maximum deflection was found to be 7.453mm. Figure 23 below shows the distribution of the loading and the subsequent deflections. As the loading diagram used in MDSolids is the most similar to what will be experienced by the string-rail, the deflection calculated in this case will be used in the calculation of total deflection.

$$Total\ Deflection = 7.453 + 2.5 + 3.98 = 13.759mm$$

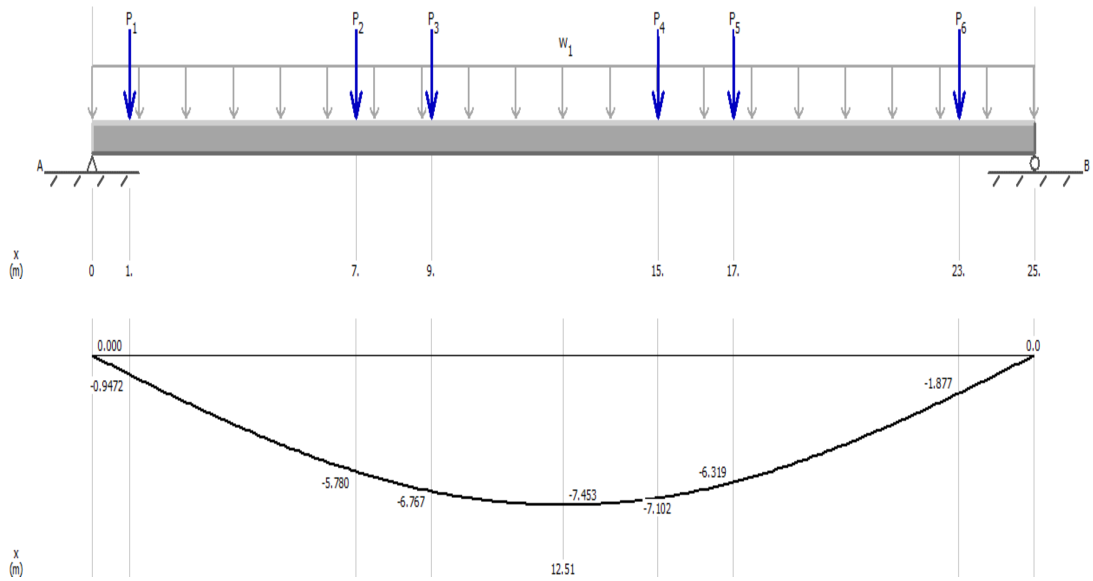


Figure 23: String Deflection Under Load

This total deflection is then used to determine the maximum upward and downward acceleration that the rolling stock will experience as they travel over the support, and down through the deflection of the string-rail. Assuming that a train is travelling at 100 km/hr and is rising and falling through these deflection over each 25 metre span, the following calculation of vertical acceleration can be used. This equation is based on basic equations of physics.

$$a = \frac{s - ut}{0.5 * t^2} = 0.138ms^{-1}$$

$$Horizontal\ distance\ =\ 12.5m$$

$$Vertical\ distance\ (s)\ =\ 0.01376m$$

$$Time\ (t)\ = \frac{12.5}{\left(\frac{100}{3.6}\right)}\ =\ 0.45s$$

$$Initial\ vertical\ velocity\ =\ 0$$

This is deemed a satisfactory deflection for design as this produces a maximum vertical acceleration of $0.138ms^{-2}$. This is slightly above standard railway best practise, with a suggested limit of 0.1ms^2 (Parsons Brinckerhoff Quade & Douglas, inc. , 1999). To ensure a comfortable ride for passengers travelling along the route, the rolling stock would require to be dampened, or the string tension reassessed.

6.5 DESIGN SUMMARY

Based on the most unfavourable loading conditions, the typical support structure was found to be satisfactory when designed to Australian Standards by a factor of safety of between 1.25 and 16. The largest sized standardly available UB and CHS were used, however should design loading increase for any reason, or should the factor of safety be deemed not acceptable, the design can utilise welded beams and welded columns, a stronger alternative.

The foundation also proved to be satisfactory at a feasibility level of design also satisfying by a factor of safety of between 1.3 and 6. This design was only carried out for design in medium density sands, and further investigation is required in regard to the pile behaviour in other soil types such as clay.

The string also produced satisfactory performance measures when designed to Australian Standards, producing minimal mid-span deflections, resulting in a smooth and comfortable ride for rolling stock over the top. The steel cables when tensioned only satisfied by a small factor of safety in regard to breaking tension. Due to the extreme reliance on the string-rail, this may be deemed unacceptable. Designing with marine grade steel cable, instead of general purpose steel cable will increase the breaking tension of the cable, and subsequent factor of safety, eliminating this issue.

When compared to Yunitskiy's designed structures presented in several of his technical papers and in Figure 14, the structure and foundation designed here is slightly larger in size. This is due to the more conservative loadings taken in this design as well as the more conservative design methods used within Australian Standards when compared to Russian design standards.

7 COST ANALYSIS OF THE PROPOSED STRING TRANSPORT SYSTEM

With any government project (ultimately what String Transport Systems will become in this application), one of the key factors on its implementation will be the cost. This chapter aims to breakdown the cost of constructing a String Transport System route, as well as exploring maintenance and operational costs to provide a comparison with other forms of rail currently in use in New South Wales. Key costs considered include; materials, labour, rolling stock, infrastructure, rolling stock, design, commissioning, traffic management and contingency. These will be detailed in the following sub chapters. Where costs are based on information from the past, the Australian Bureau of Statics CPI inflation calculator has been used to convert the values to the equivalent June 2013 Australian Dollar (Australian Bureau of Statistics, 2013). Where costs are not in Australian dollars, they have been converted to Australian dollars at the point history where the costs have been specified with use of the Foreign Currency Exchange website's currency converter (Foreign Currency Exchange, 2013).

All costs below are considered to be conservative for the feasibility stage, and all values are taken at a maximum where multiple possible costs exist.

7.1 COST OF CONSTRUCTION

The cost of construction is typically the largest cost in the implementation of railway. The costs are broken down below into the relevant categories.

7.1.1 Track

The cost of the track will be broken down below into the key areas of; materials, labour and associated traffic works.

7.1.1.1 Materials

The materials in the string track structure is made up of a 610UB152, 502CHS12.1, 1000mm diameter pile, steel cable, concrete and the associated connections between all of the above. The cost for each item, cut and delivered is as follows.

2,076.50 AUD - 610UB152 (Scott Metals Pty. Ltd., 2013)

2,210.00 AUD - 502CHS12.1 (Parker Steel, 2013)

2,275.00 AUD - 1000 diameter, 7000mm long, driven pile
(US Department of Transportation, 2011)

49.00 AUD/metre - 35mm diameter steel cable (Shane's Stainless Store, 2013)

100.75 AUD/Cubic Metre - Concrete (Boral, 2012)

1,000.00 AUD - Connections/other material (estimated)

It is noted that the cost of steel is volatile and hence these costs presented above are likely to experience large deviations as with the price of steel

7.1.1.2 Labour

The cost of labour including hire of equipment to construct the string transport system has been estimated as 4,000,000 AUD/kilometre based on similar works suggested for Australia’s High-Speed Rail Network (AECOM Australia Pty Ltd, 2013)

7.1.1.3 Traffic Works

The infrastructure suggested for this design is to be constructed down the centreline of key roads in Sydney’s East. There will be traffic works required to direct traffic around construction works as well as potential realignment of roads. The costs of these works is estimated as 1,400,000 AUD/kilometre based on similar works designed for a Hobart light rail (Parsons Brinckerhoff, 2009). This cost also includes the likes of road barriers around the columns, to deflect and prevent impact with vehicles.

7.1.2 Infrastructure

The cost of the stations and terminus' also need to be considered when assessing the cost of railway construction. This route has 7 stations, as well as a depot/terminus at each end. Costs for stations and depot's/interchanges is based on CPI adjusted values of the light rail development previously mentioned for construction in Hobart.

133,500 AUD – Station (Parsons Brinckerhoff, 2009)

5,562,750 AUD - Depot/Terminus (Parsons Brinckerhoff, 2009)

Due to each station being located at a current bus interchange location, the cost of constructed a bus interchange to connect the transport mediums is ignored as it is already in place.

7.1.3 Land Acquisition

String Transport Systems have a very small physical footprint due to the nature of elevated structures. There are however columns and piles which will need to be constructed/installed along the alignment. Whilst it is idealised that the structure be constructed along road centrelines or footpaths, costing is included as though each column requires a portion of land to be acquired. Table 21 below outlines the cost of acquisitions for each of the 1270 columns. Land prices are based on 2013 average house price for varying suburbs (Australian Property Monitors, 2013), with the average land size being 400m^2 (Randwick City Council, 2013). It is assumed that the land acquisition required for each pile or column would be 1 m^2 (the pile diameter).

Table 21: Land Acquisition Costs

Suburb	Mean house price (AUD)	Mean house price per m^2 (AUD)	Number of piles/columns	Acquisition costs (AUD)
Botany bay	786,000	1,965	186	365,490
Eastgardens	1,035,000	2,588	93	240,638
Maroubra	1,090,000	2,725	310	844,750
Coogee	1,565,000	3,913	124	485,150

Suburb	Mean house price (AUD)	Mean house price per m^2 (AUD)	Number of piles/columns	Acquisition costs (AUD)
Randwick	1,515,000	3,788	248	939,300
Waverly	1,670,000	4,175	93	388,275
Bondi Junction	1,400,000	3,500	93	325,500
Bondi	1,618,000	4,045	123	497,535
			TOTAL	**4,086,638**

7.1.4 Rolling Stock

The cost of rolling stock will be based on the Yunitskiy specified design. Rolling stock will ultimately be up to the detailed designer and constructed offshore and shipped to Australia, so this is the approach that will be used for calculations. Chapter 7.1.4.1 to 7.1.4.3 outline costs of typical String Transport Rolling stock, however 'MiniSTU' rolling stock will be used in calculations going forward.

7.1.4.1 MicroSTU

MicroSTU is rolling stock applicable to personal rapid transit. It involves small vehicles of 4-6 seats travelling independently around a network. Costs of these vehicles are typical of standard electric/diesel passenger vehicles (String Transport Unitksy, 2006). This value will be assumed to be 20,000 AUD.

7.1.4.2 MiniSTU

MiniSTU is rolling stock applicable to light rail applications. It involves carriages of 10-20 seats in a train formation. This is the rolling stock applicable to this route choice. Very conservative estimates by Yunitskiy put the cost of these carriages to be 75,638 AUD, with the combined train cost of 348,190 AUD (String Transport Unitksy, 2006).

7.1.4.3 MegaSTU

MegaSTU is rolling stock applicable to high speed or intercity rail passenger vehicles. It involves large carriage sets of over 100 passengers per carriage. Costs for this rolling stock is around 50% higher than the MiniSTU modules with a cost of 113,457 AUD per carriage, or 567,285 AUD per train (String Transport Unitksy, 2006).

7.1.5 Project Development Costs

Project Development costs include costs that are associated with pre-phase and preliminaries, planning, design and procurement, construction oversight and commissioning. Costs associated with project development typically take the value of 9% of the total project construction costs (AECOM Australia Pty Ltd, 2013). In this case, the value is 148,543,444 AUD (refer Table 22).

7.1.6 Contingency

Feasibility level of design and analysis is inherently high level and thus the costing's reflect this lack of detail. Whilst costs are attempted to be calculated conservatively, it is acknowledged that there are likely to be large variances with these values. Figure 24 below shows the contingency levels throughout project progression.

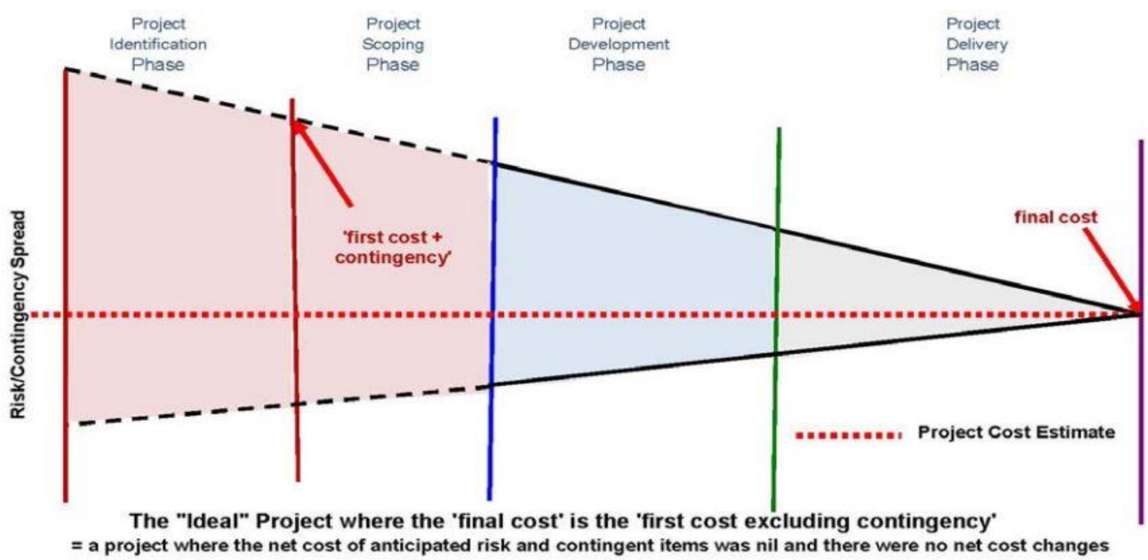


Figure 24: Acceptable Contingency Levels during Project Development (Evens & Peck , 2008)

This figure was included in a report by Evens & Peck for Best Practice Cost Estimation for Publicly Funded Road and Rail Construction. It stipulated an acceptable contingency level to 90% confidence (P90) at the project identification stage to be 40-60% as per Federal

Infrastructure Notes on Administration. (Evens & Peck , 2008). In this case, a value of 50% will be used, due to the already highly conservative costing. This provides a contingency value of 80,960,270 AUD.

7.1.7 Construction Cost Summary

All the costs presented in Chapter 7.1 are summarised below in Table 22. The table summarises the total cost of construction of the route under consideration.

Table 22: STS Construction Cost

Item	**Unit Price (AUD)**	**Number of Units**	**Total Cost (Million AUD)**
610UB152	2,076.50	1,270 pieces	2.64
502CHS12.1	2,210.00	1,270 pieces	2.81
1000x7000 Pile	2,275.00	1,270 pieces	2.89
35mm Cable	49.00	245,142.86 metres	12.01
Concrete	100.75	2,215.57 m^3	0.22
Materials (Extra)	1,000.00	1,270 pieces	1.27
Construction Labour	4,000,000.00	20.43 km	81.71
Stations	133,506	7 pieces	0.93
Terminus	5,562,750.00	1.5 pieces	8.34
Traffic/Site Management Etc.	1,400,000.00	20.43 km	28.60
Design and Commissioning	148,543,444.58	9%	13.37
Land Acquisition	-	-	4.09
Total	-	-	**161.91**
Contingency	161,912,354.59	50%	80.96
Total including Contingency	-	-	**242.87**

7.2 Cost of Operation

To consider whole of life costs, to effectively represent the cost of implementing this system, the cost of operation needs to be considered. Detailed costing of such operation is subject to selection of rolling stock and subsequent interaction with the rail. Detailed costing of operation is out of scope and subject to further investigation, however String Technologies Unitsky have specified indicative costs, which will be used to compare with conventional rail to provide a comparison.

7.2.1 Rolling Stock Operation

There are numerous forms of rolling stock suggested by Yunitskiy, running off a variety of fuels, including diesel, natural gas and electric. Natural gas or electric are the ideal options, due to the quieter operation given the routes location. Yunitskiy has specified fuel consumption for diesel engine rolling stock, so this will be explored further. Yunitskiy rolling stock is capable of using a minimal 0.04 litres of diesel per 100 passengers per kilometre (String Transport Unitksy, 2006). This equates to less than 3% of the fuel per person compared to a passenger vehicle.

The engines are also operating at 90% efficiency compared to only 30% for an internal combustion engine (String Transport Unitksy, 2006). Considering conventional rail is more efficient than road travel, and uses only one third of the fuel (CSX, 2012), this means String Transport Systems will use approximately 10% of the fuel of conventional rail. With the given demand estimation presented in Chapter 5.2.4 and the price of diesel at $1.60 per litre (Australian Institute of Petroleum, 2013), the cost of fuel per year has been estimated for three modes of transport. This costs is presented in Table 23 below. The cost will have high volatility though as it is directly correlated with the price of diesel, however the cost ratio between modes will be the same.

Table 23: Fuel Cost Comparison

Mode of Transport	Fuel Required Per Year (Litres)	Cost of Fuel Per Year (AUD)
String Transport Systems	73,371.26	117,394.00
Conventional Rail	733,712.60	1,173,940.00
Passenger Vehicle	2,445,709.00	3,913,134.00

Given the above information, String Transport System rolling stock can operate in terms of fuel at only 10% of the cost of conventional rail and at 3% the cost of passenger vehicles. This results in savings of over 1 million AUD per year, given the route and patronage presented in Chapter 5. With driverless trains and full automated operation (refer Chapter 5.2.3.2), the total cost of rolling stock operation will be very low in this case, and less than the available alternatives.

7.2.2 Maintenance Cost

Associated maintenance costs at a feasibility stage of design, are still subject to further investigation. This chapter aims to provide indicative costs for comparative purposes.

7.2.2.1 Rollingstock

The cost of rolling stock maintenance has not been specified by Yunitskiy due to no network currently existing to benchmark from. With this in mind, the associated maintenance costs are going to be similar to that of conventional rail rolling stock, specified at approximately $1.50 per km for the life of the lead engine powered wagon, and $0.05 for the following passenger wagons. (Parsons Brinckerhoff, 2010).

7.2.2.2 Part Replacement and Refurbishment

As with any light rail project, there will be associated infrastructure such as stations and depots. Considering these would expect similar traffic as with any form of rail, the associated maintenance cost would be the same.

This route will also use automated operation, and hence line side infrastructure will not be required, again; using the North West Rail Link as a precedent. There will therefore be no maintenance costs associated with this.

It is therefore assumed that maintenance costs of infrastructure will be similar if not less than conventional rail.

7.2.2.3 String-rail

A report based on the freight based applications of String Transport Systems has shown that the string is capable 5,000,000 cycles before replacement is required (String Transport Systems Limitied, 2010). With a maximum of 20 services per hour (3 minute headways) and 20 hour a day operation (refer Chapter 5.2.4), this would require replacement once in every 35 years. With conventional rail requiring track replacement every 10-30 years in well maintained railways this again provides savings when using String Transport Systems.

The cost of the below-rail maintenance costs would also be reduced when using String Transport systems due to the reduction in required infrastructure. Conventional track requires ballast and sleepers etc. however String Transport Systems only have the intermediate and tensioning supports to maintenance.

7.3 Construction Cost Comparison with Rail Alternatives

As it can be seen, the total cost for this 20.42 km out and back route is 242.87 million AUD. This equates to 11.89 million AUD per km of track. Table 24 below presents typical values for conventional rail, light rail, monorail and personal rapid transit projects around the New South Wales and Greater Australia Region. Each price is again converted to 2013 AUD.

Table 24: Cost Comparison

Rail Type	Average Cost per km (million AUD)	Saving with STS (%)
Conventional Rail	*48* (New South Wales Parliament Legislative Council - General Purpose Standing Committee No. 33, 2012)	*75.23*
Light Rail (Tram)	*31.64* (Parsons Brinckerhoff, 2009)	*62.42*
Monorail	*18.26* (Parkz, 2010)/ (Grzesiakowski, 2013)	*34.89*
Personal Rapid Transit	*11.72* (Jones, 2009)	*-0.01%*
String Transport Systems (Australian design)	*11.89*	-

Figure 25 below provides a visual representation of the saving when using String Transport Systems as opposed to other forms of rail.

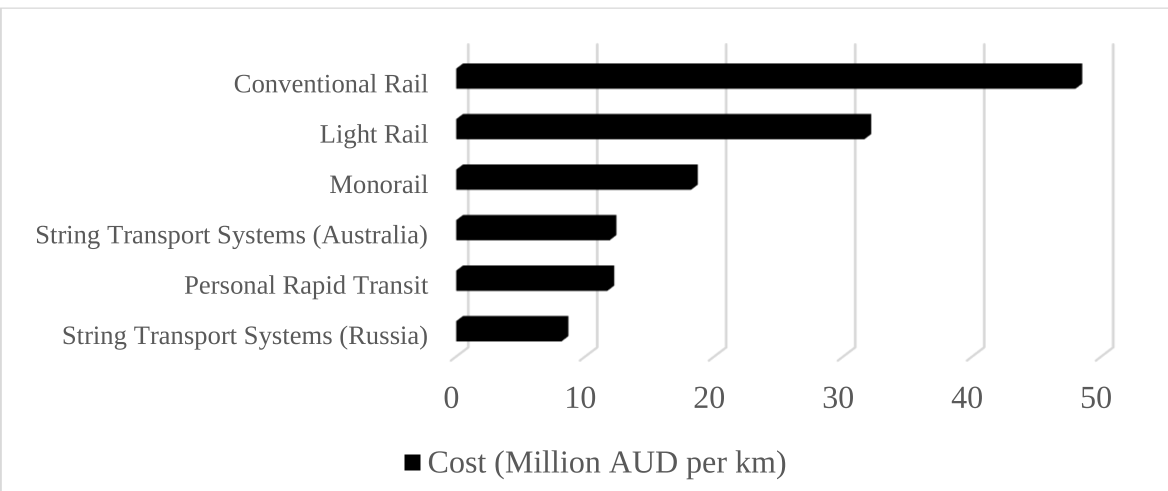


Figure 25: STS Construction Cost Comparison

As it can be seen, there are huge savings in using String Transport Systems. With conservative costing, and a large contingency value, the cost is still cheaper than all methods of transport excluding personal rapid transit. Personal Rapid Transit is however a very differing technology and in the circumstances of the above route, it would not be a feasible design due to the large land requirements.

7.4 COST SUMMARY

The costs associated with string transport system construction for the selected route in eastern Sydney are far lower than other rail alternatives as presented in Table 24. With smaller construction costs, also comes shorter construction times, allowing a project like this to be up and running earlier, achieving a positive NPV in a shorter period of time.

Yunitskiy specified his construction costs for a miniSTU network, the equivalent application to what is designed here to cost 8.17 million AUD per kilometre (String Transport Unitksy, 2006). The differences in cost between this, and the value of 11.89 million AUD per km shown in Table 22, are put down to a variety of reasons. For one, the structure is designed to Australian Standards, a more conservative standard, and is therefore larger than the one designed to Russian standards, resulting in an increased material cost. The cost of labour is also higher in Australia than in Russia. The route designed in this case is also made up of flowing curves through highly urbanised environments. When compared to straight track, in areas with minimal land acquisition costs, the costs can be seen to really blow out.

PART 3: CONCLUSIONS AND SUPPORTING MATERIAL

8 RECOMMENDATIONS/FEASIBILITY

The New South Wales' passenger rail network is in need of alternate technologies to assist in servicing areas of high urbanisation and reduced capacity public transport. In this dissertation, is it recommended that String Transport Systems be used as this alternative to conventional rail systems.

The methodology followed in this dissertation has provided an effective platform for concluding on the feasibility of implementing String Transport Systems for Passenger Rail in New South Wales. Analysis of needs before designing of the route allowed for the most appropriate route to be designed, and with the detailed information of this route, estimated costing could be undertaken. This coupled with skills in civil engineering and project management to undertake the feasibility study, have allowed for a report to be completed, similar to the style of that prepared in industry.

The proposed route for String Transport System application is from Sydney's Kingsford-Smith Airport to Bondi Beach. This decision is based on the current needs of New South Wales' passenger rail network when considering rural rail, high-speed rail and urban rail. The route has been designed to carry 12,300 passengers per day based on demand estimation with provisions to increase this to 80,000 passengers per day. These capabilities suggest that the route would satisfy Sydney's growing population into the future as well as the demand on Sydney's Eastern suburb's beaches during the summer months.

The 20.42 km route also has superior performance, reaching Bondi Beach in under 25 minutes, faster than other public transport options as well as personal travel. The route consists of 7 stations between two terminuses, with curves ranging in radius from 250m to 2,200m. These 7 stations connect public transport interchanges with the route, with stations spaced between 1.1 km and 4.8 km.

The typical support structure of the String Transport System, designed to Australian Standards was deemed to be satisfactory. A typical support utilised a 610UB152, 502CHS12.1 as well as 1000mm diameter piles, and was designed conservatively allowing these elements to be optimised for a more cost effective design. Although differences exist from the specification initially provided by Yunitskiy, and this proposed design to Australian Standards, the increased size of the structure can be attributed to conservative design and loading. Further dynamic analysis as well as testing in Australia could provide more efficient solutions in this case.

The cost analysis of the construction of 1km of String Transport System route was found to be 11.89 million AUD. This was a saving of over 75% when compared to conventional rail and 35-62% when compared with monorail and light rail. This independent analysis has produced a cost 40% higher than that specified by Yunitskiy. This discrepancy is again put down to conservative design, and the increased materials and labour cost in Australia when compared to Russia. In terms of operation, String Transport Systems also have savings when compared to conventional rail with 90% less fuel consumption per passenger and 70% less emissions. The potential financial benefits of using this technology, contribute to the decision of the feasibility of implementation of String Transport Systems for passenger rail within New South Wales.

Based on the need for an alternative form of technology within the Sydney urban rail network, as well as the associated demand, design of the structures and the costing of String Transport Systems, it is feasible for implementation. The performance in terms of travel time and demand servicing, is greater than current methods available and the financial and environmental benefits make this a more superior choice for an alternative rail technology.

It is concluded that further research can now be commenced on the design of a full scale route for implementation of this technology across a variety of rail applications within Australia.

9 REFERENCES

AECOM Australia Pty Ltd, 2011. *High Speed Rail Study - Phase 1,* Canberra: Department of Infrastructure and Transport.

AECOM Australia Pty Ltd, 2013. *High Speed Rail Study Phase 2 Report,* Canberra: Australia Government Department of Infrastructure and Transport.

AirportLink, 2013. *Airport to City - Weekdays.* [Online]
Available at: http://www.airportlink.com.au/time-table-to-city-weekdays.php
[Accessed 10 10 2013].

Aqua Bumps, 2013. *Bondi 24th May 2013.* [Online]
Available at: http://www.aquabumps.com/2013/05/24/b-o-n-d-i/
[Accessed 05 09 2013].

Australian Bureau of Statistics, 2012. *3128.0 Regional Population Growth, Australia,* Canberra: Australian Bureau of Statistics.

Australian Bureau of Statistics, 2013. *Consumer Price Index Inflation Calculator.* [Online]
Available at:
http://www.abs.gov.au/websitedbs/d3310114.nsf/home/consumer+price+index+inflation+calculator
[Accessed 10 10 2013].

Australian Institute of Petroleum, 2013. *Weekly Diesel Price Report.* [Online]
Available at: http://www.aip.com.au/pricing/facts/Weekly_Diesel_Prices_Report.htm
[Accessed 20 10 2013].

Australian Property Monitors, 2013. *Home Price Guide.* [Online]
Available at: http://www.homepriceguide.com.au/Default.aspx?source=DOMAIN
[Accessed 05 10 2013].

Barry O'Farrell, G. B., 2012. *New Trains, More Choice For North West as Multi-Billion Dollar Tender Process Begins, media release.* [Online]

Available at: http://northwestrail.com.au/document/show/72
[Accessed 01 10 2013].

Berejiklian, G., 2013. *North West Rail Link to be state of the art* [Interview] (06 06 2013).

Bombardier Transportation, 2010. *Automated Monorail System,* Berlin: Bombardier Incorporated.

Boral, 2012. *Boral Construction Materials - Fees and Surcharges Sheet: General.* [Online]
Available at: http://www.boral.com.au/concrete/termsandconditions/Fees-Surcharges-Scehedule-Sydney.pdf
[Accessed 06 10 2013].

Bureau of Meteorology, 2013. *Facts on Severe Wind Gusts in NSW.* [Online]
Available at: http://www.bom.gov.au/nsw/sevwx/windfact.shtml
[Accessed 12 10 2013].

Churchman, G. B., 1995. *Railway Electrification in Australia and New Zealand.* Wellington: IPL Books.

CountryLink, 2012. *Counry Link Train and Coach Network.* [Online]
Available at:
http://www.countrylink.info/__data/assets/pdf_file/0019/2692/CountryLink_network.pdf

CSX, 2012. *Fuel Efficiency.* [Online]
Available at: http://www.csx.com/index.cfm/about-csx/projects-and-partnerships/fuel-efficiency/
[Accessed 10 10 2013].

Ergon Energy, 2009. *NETWORK LINES STANDARD - Guidelines for overhead line design* , Maryborough: Ergon Energy Queensland.

Evens & Peck , 2008. *Best Practice Cost Estimation for Publicly Funded Road and Rail Construction,* Sydney : Department of Infrastructure, Transport, Regional Development and Local Government.

Federation, U. P., 2012. *Ambassador for Peace Award.* Seoul: s.n.

Foreign Currency Exchange, 2013. *Foreign Currency Exchange Rates and Currency Converter Calculator.* [Online]
Available at: http://www.fx-exchange.com/
[Accessed 10 10 2013].

Ginn, S., 1998. *An Overview of Light Rail Technology and it's Potential Within an Australian Environment,* Perth: Western Australian Planning Commission.

Google, 2013. *Google Maps.* [Online]
Available at: maps.google.com.au
[Accessed 20 10 2013].

Grzesiakowski, T., 2013. *End of the Line for the Sydney Monorail.* [Online]
Available at: http://www.metroplanning.org/news-events/blog-post/6761
[Accessed 10 10 2013].

Hargraves, A., 2011. *CVEN2201 Soil Mechanics - Laboratory Test 5 - Triaxial Testing,* Sydney: University of New South Wales.

Hotlz, R. D., Kovacs, W. D. & Sheahan, T. C., 2011. *An Introduction to Geotechnical Engineering.* 2nd ed. Upper Saddle River NJ: Pearson Higher Education.

International Forum on Sustainable Development, 2008. *Diploma - Sustainable development of the Eurasian continent.* Astana: s.n.

Japan California High Speed Rail Consortium, 2012. *Technolog.* [Online]
Available at: http://www.jchighspeedrail.com/technology/

Jones, H. M., 2009. Personal Rapid Transit for Canberra. *Telecommunications Journal of Australia,* 59(1), p. 6.1 to 6.10.

Lewis, D. M. J. T., 2000. *RAILWAYS IN THE GREEK AND ROMAN WORLD,* Hull: University of Hull.

Muhametdinov, A., 2012. *The Use of High-Speed String for Passenger Transport in the Metropolitan Area of Yekaterinburg [Translated]*, Yekaterinburg: The Ministry of Education and Science of the Russian Federation.

New South Wales Parliament Legislative Council - General Purpose Standing Committee No. 33, 2012. *Rail Infrastructure Project Costing in New South Wales*, Sydney: New South Wales Parliament Legislative Council.

NSW Government, 2013. *Greater Sydney Transport Information - Trains, Buses & Ferries.* [Online]
Available at: https://131500.com

NSW Government, 2013. *TransportInfo - Plan Your Trip.* [Online]
Available at: www.131500.com.au
[Accessed 20 10 2013].

OneSteel Market Mills, 2003. *Hot Rolled and Structural Steel Products.* 3rd Edition ed. Newcastle: OneSteel Market Mills.

Oxford Dictionaries, 2013. *Definition of rolling stock in English.* [Online]
Available at: http://www.oxforddictionaries.com/definition/english/rolling-stock#m_en_gb0716410?view=aus
[Accessed 10 05 2013].

Parker Steel, 2013. *Circular Hollow Section.* [Online]
Available at: http://www.parkersteel.co.uk
[Accessed 05 10 2013].

Parkz, 2010. *Sea World Monorail System.* [Online]
Available at: http://www.parkz.com.au/parks/AU/Gold_Coast/Sea_World/rides/31-Sea_World_Monorail_System.html
[Accessed 05 10 2013].

Parsons Brinckerhoff Quade & Douglas, inc. , 1999. *Track Design Handbook for,* Washington: Transportation Research Board, National Research Council.

Parsons Brinckerhoff, 2009. *Hobart Light Rail Cost Estimate: Desktop System Design and Service Model,* Brisbane: Department of Infrastructure, Energy and.

Parsons Brinckerhoff, 2010. *Melbourne-Brisbane Inland Rail Alignment Study - Preliminary Operating and Maintenance Cost Analysis,* Sydney: Australian Rail Track Corporation.

Rail Express, 2011. *Australian Technology wins Transport Project of the Year.* [Online] Available at: http://www.railexpress.com.au/archive/2011/september/september-28th-2011/other-top-stories/australian-technology-wins-transport-project-of-the-year

Randwick City Council, 2013. *Residential Discussion Paper - Summary Document,* Sydney: 2011.

Rogers, P., 1995. *The Mumbles Train.* [Online]
Available at: http://www.welshwales.co.uk/mumbles_railway_swansea.htm

Saulwick, J., 2012. Tilt trains seen as way to lure users to rural rail. *Sydney Morning Herald*, 15 8, p. 1.

Scott Metals Pty. Ltd., 2013. *Scott Metals Steel Supply.* [Online]
Available at: http://www.scottmetals.com.au/beams.php
[Accessed 05 10 2013].

Sea World, 2013. *Sea World Monorail.* [Online]
Available at: http://seaworld.com.au/rides-and-attractions/rides/sea-world-monorail.aspx
[Accessed 08 07 2013].

Shane's Stainless Store, 2013. *Stainless Steel Wire 7x7 316 Marine Grade.* [Online]
Available at: http://www.shanesstainless.com.au/cart.php
[Accessed 05 10 2013].

South Australia - Department of Transport, Planning and Infrastructure, 2008. *PART 1025: Track Geometry Specifications,* Adelaide: South Australia - Department of Transport, Planning and Infrastructure.

Standards Australa/Standards New Zealand, 2007. *AS/NZS 4672.1:2007 - Steel Prestressing Materials, Part 1: General Requirements,* Sydney: Standards Australia.

Standards Australia, 1998. *AS4100:1998 Steel Structures,* Sydney: SAI Global Limited.

Standards Australia, 2009a. *AS 3600-2009 Concrete Structures,* Sydney: SAI Global Limited.

Standards Australia, 2009b. *AS/NZS 1170.1:2002 Structural Design Actions - Part 1: Permenant, Imposed and Other Actions,* Sydney: Standards Australia.

Standards Australia, 2009c. *AS2159-2009: Piling - Design and Installation,* Sydney: Sai Global Limited.

String Transport Systems Limitied, 2010. *Technical Specifications of Freight String Transport System for Highly Efficient Transportation of Bulk Commodities,* Sydney: s.n.

String Transport Unitksy, 2006. *String Transport Unitksy in Questions and Answers,* Moscow: Anatoly Yunitskiy.

Sydney Airport, 2012. *Long Term Development of Aviation in the Sydney Region,* Sydney: Sydney airport.

Sydney Buses, 2012. *Network Interchange Maps (East Map).* [Online]
Available at: http://www.sydneybuses.info/network-interchange-maps/east_map.pdf
[Accessed 10 10 2013].

Sydney Buses, 2013a. *Chartering a Bus.* [Online]
Available at: http://www.sydneybuses.info/chartering-a-bus
[Accessed 15 09 2013].

Sydney Buses, 2013b. *Sydney Buses Timetable - Burwood to Bondi Junction,* Sydney: Sydney Buses.

Sydney Environmental and Soil Laboratory, 2007. *Soils of the Sydney Basin – the Quaternary alluvium deposits.* [Online]

Available at: http://www.sesl.com.au/fertileminds/201009/Quaternary_alluviums.php
[Accessed 06 06 2013].

Sydney Trains, 2013. *Facts and stats.* [Online]
Available at: http://www.sydneytrains.info/about/environment/
[Accessed 09 09 2013].

Taiebat, H. A., 2012. *Applied Geotechnics CVEN3201 - Student Notes,* Sydney: University of New South Wales.

Tourisminternet, 2013. *Sydney to Albury.* [Online]
Available at: http://www.tourisminternet.com.au/howsyd.htm

Transnet, 2012a. *Transnet,* Moscow: Anatoly Yunitksiy.

Transnet, 2012b. *Unitsky String Technologies - Overground Transport System,* Moscow: String Technologies Unitksy.

Transport For New South Wales, 2012. *SYDNEY'S LIGHT RAIL FUTURE,* Sydney: NSW Government.

Transport for New South Wales, 2013a. *North West Rail Link.* [Online]
Available at: http://northwestrail.com.au/
[Accessed 21 05 2013].

Transport for New South Wales, 2013b. *Submissions Report: Stage 2 – Stations, Rail Infrastructure and Systems,* Sydney: Transport for New South Wales.

Transport for New South Wales, 2013c. *Waratah Public Private Partnership.* [Online]
Available at: http://www.transport.nsw.gov.au/projects-waratah-public-private-partnership-frequently-asked-questions
[Accessed 10 08 2013].

Transport NSW TrainLink, 2013. *Our Regional Network.* [Online]
Available at: http://www.nswtrainlink.info/destinations/network
[Accessed 08 09 2013].

Transportation Research Board, 1977. *Rail Research at TRB.* [Online]
Available at: http://www.trb.org/Railroads/Railroads2.aspx

US Department of Transportation, 2011. *Cost Data of Driven Piles.* [Online]
Available at: http://www.fhwa.dot.gov/engineering/geotech/pubs/05159/chapter5.cfm
[Accessed 06 10 2013].

VicSig.net, 2013. *D1 Class Trams.* [Online]
Available at: http://www.vicsig.net/index.php?page=trams&section=class&class=D1

Volvo Buses, 2012. *VOLVO B7Rle 4x2 Data Sheet.* [Online]
Available at:
http://www.volvobuses.com/SiteCollectionDocuments/VBC/United_Kingdom_and_Ireland/Downloads/B7RLE%204x2%20Data%20sheet%2006.09.12.pdf
[Accessed 10 10 2013].

Yunitksiy, A., 2013a. *Summary of Technology, String Technologies Unitksy,* Moscow: String Technologies Unitsky.

Yunitksiy, A., 2013b. *The upcoming reality.* [Online]
Available at: http://www.yunitskiy.com/
[Accessed 25 04 2013].

Yunitskiy, A., 2000. *TECHNICAL PROPOSAL - Ring High Speed String, Transport Links [translated],* Moscow: String Transport Unitsky.

Yunitskiy, A., 2004. Eurasian, Patent No. 006,112.

Yunitskiy, A., 2009. *STU Presentation to Russian President Dmitry Medvedev.* Ulyanovsk City(Ulyanovsk): Anatoly Yunitskiy.

Yunitskiy, A., 2010. *The Biography of Dr. Anatoly Yunitskiy.* [Online]
Available at: http://www.yunitskiy.com/author/biography_en.pdf

Yunitskiy, A., 2013c. *Benefits of Unitsky String Transport,* Moscow: String Technologies Unitsky.

Yunitskiy, A., 2013d. *Unitsky String Technologies* - *Section in English.* [Online] Available at: http://www.yunitskiy.com/author/english.htm

APPENDIX A – CURVE RADII AND VELOCITY

Table 25: Alignment Velocity

Start Chainage (km)	End Chainage (km)	Curve Radius (km)	Allowable Velocity (ms^{-1})
0.0000	0.7143	1	28
0.7143	1.4286	0.5	19
1.4286	1.7857	0.25	14
1.7857	2.3571	0	28
2.3571	2.9286	0.65	22
2.9286	4.5000	0	28
4.5000	4.7857	0.35	16
4.7857	5.2143	0.35	16
5.2143	5.5714	0.35	16
5.5714	6.8571	0	28
6.8571	7.2143	0.65	22
7.2143	7.6429	0	28
7.6429	8.2143	0.5	19
8.2143	9.1429	0	28
9.1429	9.7143	0.35	16
9.7143	10.0000	0	28
10.0000	10.3571	0.5	19
10.3571	10.8571	0.75	24
10.8571	11.2857	0.5	19
11.2857	11.8571	0.35	16
11.8571	13.0000	0.75	24
13.0000	14.1429	2.2	28
14.1429	14.7857	0.5	19

Start Chainage (km)	End Chainage (km)	Curve Radius (km)	Allowable Velocity (ms^{-1})
14.7857	15.0714	0	28
15.0714	15.3571	0.25	14
15.3571	16.8571	0	28
16.8571	17.1429	0.25	14
17.1429	18.5000	0	28
18.5000	18.7857	0.25	14
18.7857	19.7143	0.75	24
19.7143	20.0714	0.35	16
20.0714	20.4286	0	28

APPENDIX B – STS ROUTE SCHEMATICS

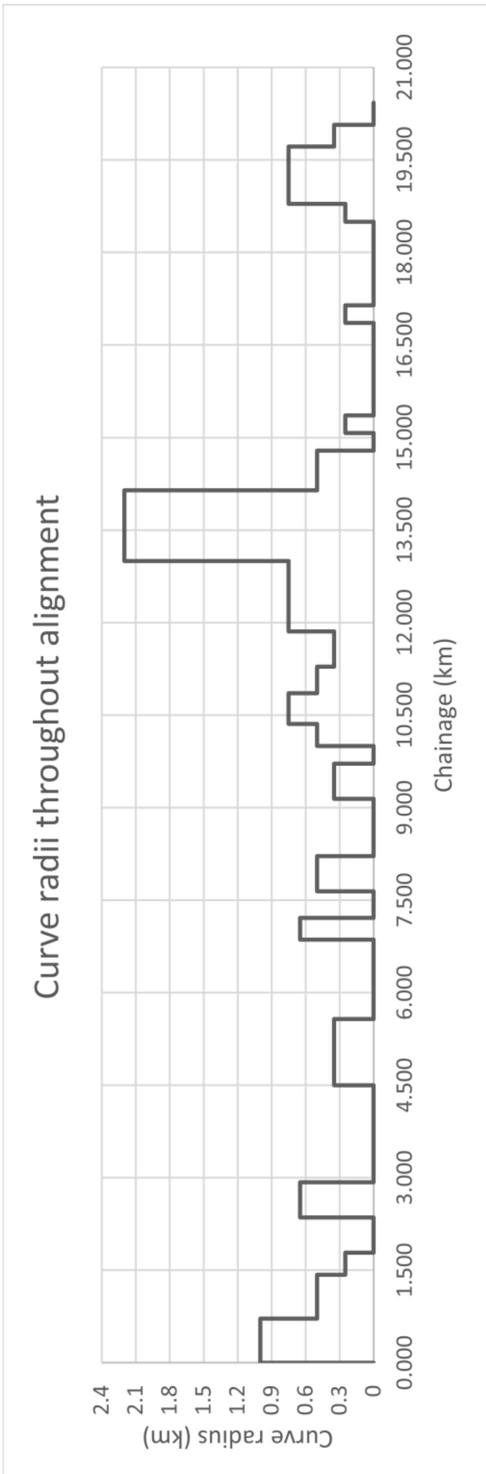


Figure 26: Curve Radii along Route

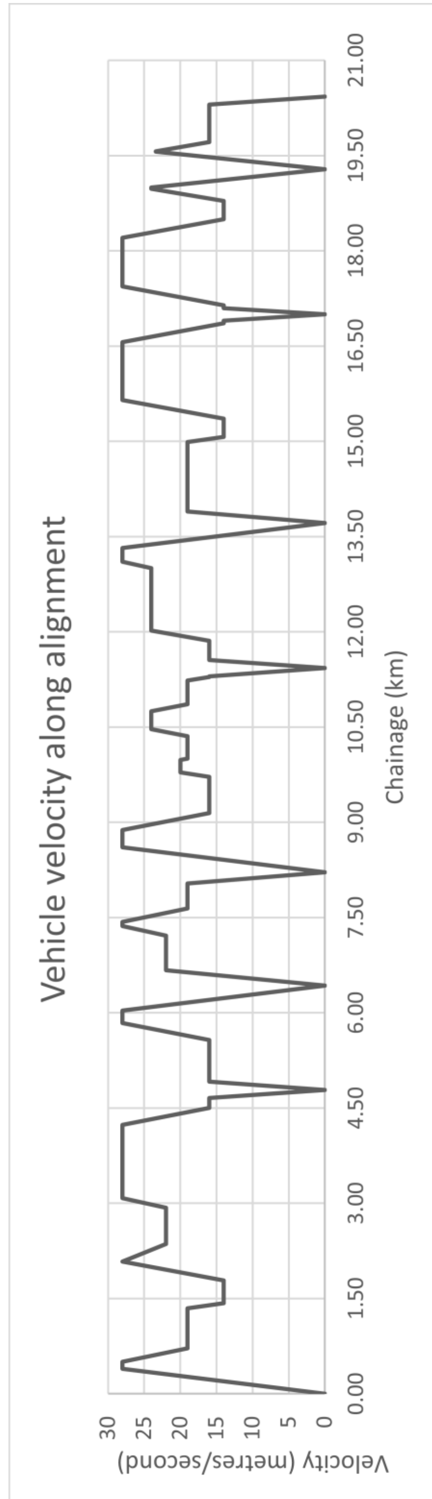


Figure 27: Vehicle Velocity along Route

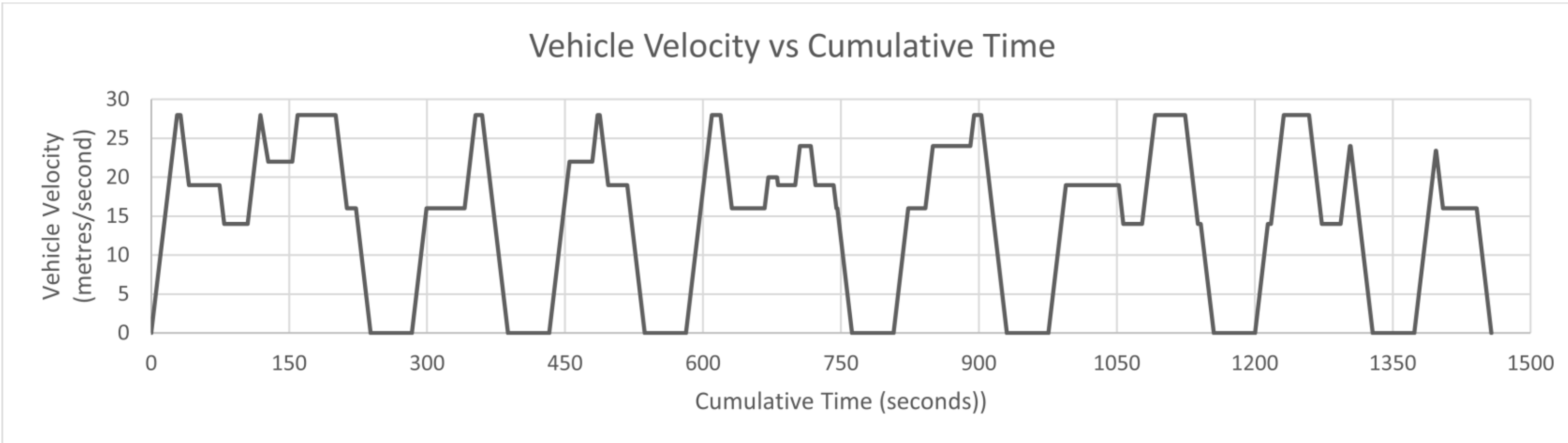


Figure 28: Vehicle Velocity over Duration of Route Travel

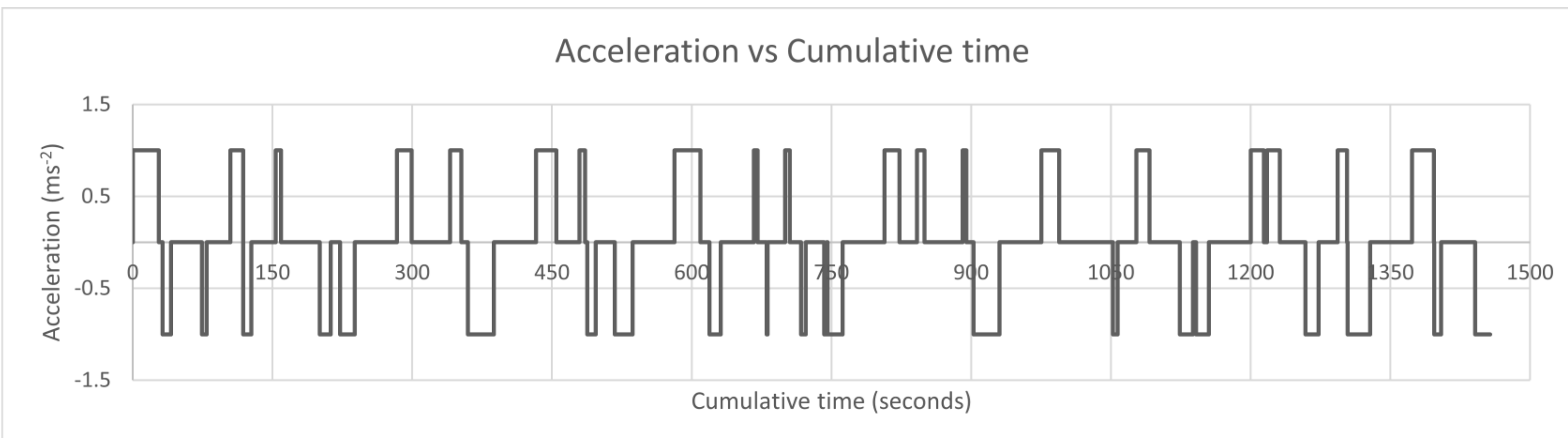


Figure 29: Rolling Stock Acceleration over Duration of Route Travel

APPENDIX C – SUGGESTED WEEKDAY STS TIMETABLE

Table 26: Weekday STS Timetable

Airport	Eastgardens	Maroubra Junction	Maroubra Beach	Coogee Beach	Randwick	Bondi Junction	Bondi Beach	North Bondi Terminus	Bondi Beach	Bondi Junction	Randwick	Coogee Beach	Maroubra Beach	Maroubra Junction	Eastgardens	Airport
4.30	4.34	4.36	4.39	4.43	4.46	4.49	4.52	4.54	4.58	5.01	5.05	5.08	5.12	5.14	5.17	5.21
5.06	5.10	5.12	5.15	5.19	5.22	5.25	5.28	5.30	5.34	5.37	5.41	5.44	5.48	5.50	5.53	5.57
5.18	5.22	5.24	5.27	5.31	5.34	5.37	5.40	5.42	5.46	5.49	5.53	5.56	5.60	6.02	6.05	6.09
5.30	5.34	5.36	5.39	5.43	5.46	5.49	5.52	5.54	5.58	6.01	6.05	6.08	6.12	6.14	6.17	6.21
5.42	5.46	5.48	5.51	5.55	5.58	6.01	6.04	6.06	6.10	6.13	6.17	6.20	6.24	6.26	6.29	6.33
5.54	5.58	6.00	6.03	6.07	6.10	6.13	6.16	6.18	6.22	6.25	6.29	6.32	6.36	6.38	6.41	6.45
6.04	6.08	6.11	6.13	6.17	6.20	6.24	6.26	6.29	6.33	6.36	6.39	6.42	6.46	6.48	6.51	6.55
6.13	6.17	6.19	6.22	6.26	6.28	6.32	6.35	6.37	6.41	6.44	6.48	6.51	6.54	6.57	6.59	7.03
6.21	6.25	6.28	6.30	6.34	6.37	6.41	6.44	6.46	6.50	6.53	6.56	6.59	7.03	7.06	7.08	7.12
6.30	6.34	6.36	6.39	6.43	6.46	6.49	6.52	6.54	6.58	7.01	7.05	7.08	7.12	7.14	7.17	7.21
6.39	6.43	6.45	6.48	6.51	6.54	6.58	7.01	7.03	7.07	7.10	7.14	7.16	7.20	7.23	7.25	7.29
6.47	6.51	6.54	6.56	6.60	7.03	7.06	7.09	7.11	7.16	7.18	7.22	7.25	7.29	7.31	7.34	7.38
6.56	6.60	7.02	7.05	7.08	7.11	7.15	7.18	7.20	7.24	7.27	7.31	7.34	7.37	7.40	7.42	7.46
7.04	7.08	7.11	7.13	7.17	7.20	7.24	7.26	7.29	7.33	7.36	7.39	7.42	7.46	7.48	7.51	7.55
7.13	7.17	7.19	7.22	7.26	7.28	7.32	7.35	7.37	7.41	7.44	7.48	7.51	7.54	7.57	7.59	8.03
7.21	7.25	7.28	7.30	7.34	7.37	7.41	7.44	7.46	7.50	7.53	7.56	7.59	8.03	8.06	8.08	8.12
7.30	7.34	7.36	7.39	7.43	7.46	7.49	7.52	7.54	7.58	8.01	8.05	8.08	8.12	8.14	8.17	8.21
7.39	7.43	7.45	7.48	7.51	7.54	7.58	8.01	8.03	8.07	8.10	8.14	8.16	8.20	8.23	8.25	8.29
7.47	7.51	7.54	7.56	7.60	8.03	8.06	8.09	8.11	8.16	8.18	8.22	8.25	8.29	8.31	8.34	8.38
7.56	7.60	8.02	8.05	8.08	8.11	8.15	8.18	8.20	8.24	8.27	8.31	8.34	8.37	8.40	8.42	8.46
8.04	8.08	8.11	8.13	8.17	8.20	8.24	8.26	8.29	8.33	8.36	8.39	8.42	8.46	8.48	8.51	8.55
8.13	8.17	8.19	8.22	8.26	8.28	8.32	8.35	8.37	8.41	8.44	8.48	8.51	8.54	8.57	8.59	9.03
8.21	8.25	8.28	8.30	8.34	8.37	8.41	8.44	8.46	8.50	8.53	8.56	8.59	9.03	9.06	9.08	9.12
8.30	8.34	8.36	8.39	8.43	8.46	8.49	8.52	8.54	8.58	9.01	9.05	9.08	9.12	9.14	9.17	9.21
8.39	8.43	8.45	8.48	8.51	8.54	8.58	9.01	9.03	9.07	9.10	9.14	9.16	9.20	9.23	9.25	9.29
8.47	8.51	8.54	8.56	8.60	9.03	9.06	9.09	9.11	9.16	9.18	9.22	9.25	9.29	9.31	9.34	9.38
8.56	8.60	9.02	9.05	9.08	9.11	9.15	9.18	9.20	9.24	9.27	9.31	9.34	9.37	9.40	9.42	9.46
9.04	9.08	9.11	9.13	9.17	9.20	9.24	9.26	9.29	9.33	9.36	9.39	9.42	9.46	9.48	9.51	9.55
9.13	9.17	9.19	9.22	9.26	9.28	9.32	9.35	9.37	9.41	9.44	9.48	9.51	9.54	9.57	9.59	10.03
9.21	9.25	9.28	9.30	9.34	9.37	9.41	9.44	9.46	9.50	9.53	9.56	9.59	10.03	10.06	10.08	10.12
9.30	9.34	9.36	9.39	9.43	9.46	9.49	9.52	9.54	9.58	10.01	10.05	10.08	10.12	10.14	10.17	10.21
9.39	9.43	9.45	9.48	9.51	9.54	9.58	10.01	10.03	10.07	10.10	10.14	10.16	10.20	10.23	10.25	10.29
9.47	9.51	9.54	9.56	9.60	10.03	10.06	10.09	10.11	10.16	10.18	10.22	10.25	10.29	10.31	10.34	10.38
9.56	9.60	10.02	10.05	10.08	10.11	10.15	10.18	10.20	10.24	10.27	10.31	10.34	10.37	10.40	10.42	10.46
10.04	10.08	10.11	10.13	10.17	10.20	10.24	10.26	10.29	10.33	10.36	10.39	10.42	10.46	10.48	10.51	10.55
10.13	10.17	10.19	10.22	10.26	10.28	10.32	10.35	10.37	10.41	10.44	10.48	10.51	10.54	10.57	10.59	11.03
10.21	10.25	10.28	10.30	10.34	10.37	10.41	10.44	10.46	10.50	10.53	10.56	10.59	11.03	11.06	11.08	11.12
10.30	10.34	10.36	10.39	10.43	10.46	10.49	10.52	10.54	10.58	11.01	11.05	11.08	11.12	11.14	11.17	11.21
10.39	10.43	10.45	10.48	10.51	10.54	10.58	11.01	11.03	11.07	11.10	11.14	11.16	11.20	11.23	11.25	11.29
10.47	10.51	10.54	10.56	10.60	11.03	11.06	11.09	11.11	11.16	11.18	11.22	11.25	11.29	11.31	11.34	11.38
10.56	10.60	11.02	11.05	11.08	11.11	11.15	11.18	11.20	11.24	11.27	11.31	11.34	11.37	11.40	11.42	11.46
11.05	11.09	11.11	11.14	11.18	11.21	11.24	11.27	11.29	11.33	11.36	11.40	11.43	11.47	11.49	11.52	11.56

Airport	Eastgardens	Maroubra Junction	Maroubra Beach	Coogee Beach	Randwick	Bondi Junction	Bondi Beach	North Bondi Terminus	Bondi Beach	Bondi Junction	Randwick	Coogee Beach	Maroubra Beach	Maroubra Junction	Eastgardens	Airport
11.15	11.19	11.21	11.24	11.28	11.31	11.34	11.37	11.39	11.43	11.46	11.50	11.53	11.57	11.59	12.02	12.06
11.25	11.29	11.31	11.34	11.38	11.41	11.44	11.47	11.49	11.53	11.56	12.00	12.03	12.07	12.09	12.12	12.16
11.35	11.39	11.41	11.44	11.48	11.51	11.54	11.57	11.59	12.03	12.06	12.10	12.13	12.17	12.19	12.22	12.26
11.45	11.49	11.51	11.54	11.58	12.01	12.04	12.07	12.09	12.13	12.16	12.20	12.23	12.27	12.29	12.32	12.36
11.55	11.59	12.01	12.04	12.08	12.11	12.14	12.17	12.19	12.23	12.26	12.30	12.33	12.37	12.39	12.42	12.46
12.05	12.09	12.11	12.14	12.18	12.21	12.24	12.27	12.29	12.33	12.36	12.40	12.43	12.47	12.49	12.52	12.56
12.15	12.19	12.21	12.24	12.28	12.31	12.34	12.37	12.39	12.43	12.46	12.50	12.53	12.57	12.59	13.02	13.06
12.25	12.29	12.31	12.34	12.38	12.41	12.44	12.47	12.49	12.53	12.56	13.00	13.03	13.07	13.09	13.12	13.16
12.35	12.39	12.41	12.44	12.48	12.51	12.54	12.57	12.59	13.03	13.06	13.10	13.13	13.17	13.19	13.22	13.26
12.45	12.49	12.51	12.54	12.58	13.01	13.04	13.07	13.09	13.13	13.16	13.20	13.23	13.27	13.29	13.32	13.36
12.55	12.59	13.01	13.04	13.08	13.11	13.14	13.17	13.19	13.23	13.26	13.30	13.33	13.37	13.39	13.42	13.46
13.05	13.09	13.11	13.14	13.18	13.21	13.24	13.27	13.29	13.33	13.36	13.40	13.43	13.47	13.49	13.52	13.56
13.15	13.19	13.21	13.24	13.28	13.31	13.34	13.37	13.39	13.43	13.46	13.50	13.53	13.57	13.59	14.02	14.06
13.25	13.29	13.31	13.34	13.38	13.41	13.44	13.47	13.49	13.53	13.56	14.00	14.03	14.07	14.09	14.12	14.16
13.35	13.39	13.41	13.44	13.48	13.51	13.54	13.57	13.59	14.03	14.06	14.10	14.13	14.17	14.19	14.22	14.26
13.45	13.49	13.51	13.54	13.58	14.01	14.04	14.07	14.09	14.13	14.16	14.20	14.23	14.27	14.29	14.32	14.36
13.55	13.59	14.01	14.04	14.08	14.11	14.14	14.17	14.19	14.23	14.26	14.30	14.33	14.37	14.39	14.42	14.46
14.05	14.09	14.11	14.14	14.18	14.21	14.24	14.27	14.29	14.33	14.36	14.40	14.43	14.47	14.49	14.52	14.56
14.15	14.19	14.21	14.24	14.28	14.31	14.34	14.37	14.39	14.43	14.46	14.50	14.53	14.57	14.59	15.02	15.06
14.25	14.29	14.31	14.34	14.38	14.41	14.44	14.47	14.49	14.53	14.56	15.00	15.03	15.07	15.09	15.12	15.16
14.35	14.39	14.41	14.44	14.48	14.51	14.54	14.57	14.59	15.03	15.06	15.10	15.13	15.17	15.19	15.22	15.26
14.45	14.49	14.51	14.54	14.58	15.01	15.04	15.07	15.09	15.13	15.16	15.20	15.23	15.27	15.29	15.32	15.36
14.55	14.59	15.01	15.04	15.08	15.11	15.14	15.17	15.19	15.23	15.26	15.30	15.33	15.37	15.39	15.42	15.46
15.05	15.09	15.11	15.14	15.18	15.21	15.24	15.27	15.29	15.33	15.36	15.40	15.43	15.47	15.49	15.52	15.56
15.15	15.19	15.21	15.24	15.28	15.31	15.34	15.37	15.39	15.43	15.46	15.50	15.53	15.57	15.59	16.02	16.06
15.25	15.29	15.31	15.34	15.38	15.41	15.44	15.47	15.49	15.53	15.56	16.00	16.03	16.07	16.09	16.12	16.16
15.35	15.39	15.41	15.44	15.48	15.51	15.54	15.57	15.59	16.03	16.06	16.10	16.13	16.17	16.19	16.22	16.26
15.45	15.49	15.51	15.54	15.58	16.01	16.04	16.07	16.09	16.13	16.16	16.20	16.23	16.27	16.29	16.32	16.36
15.55	15.59	16.01	16.04	16.08	16.11	16.14	16.17	16.19	16.23	16.26	16.30	16.33	16.37	16.39	16.42	16.46
16.04	16.08	16.11	16.13	16.17	16.20	16.24	16.26	16.29	16.33	16.36	16.39	16.42	16.46	16.48	16.51	16.55
16.13	16.17	16.19	16.22	16.26	16.28	16.32	16.35	16.37	16.41	16.44	16.48	16.51	16.54	16.57	16.59	17.03
16.21	16.25	16.28	16.30	16.34	16.37	16.41	16.44	16.46	16.50	16.53	16.56	16.59	17.03	17.06	17.08	17.12
16.30	16.34	16.36	16.39	16.43	16.46	16.49	16.52	16.54	16.58	17.01	17.05	17.08	17.12	17.14	17.17	17.21
16.39	16.43	16.45	16.48	16.51	16.54	16.58	17.01	17.03	17.07	17.10	17.14	17.16	17.20	17.23	17.25	17.29
16.47	16.51	16.54	16.56	16.60	17.03	17.06	17.09	17.11	17.16	17.18	17.22	17.25	17.29	17.31	17.34	17.38
16.56	16.60	17.02	17.05	17.08	17.11	17.15	17.18	17.20	17.24	17.27	17.31	17.34	17.37	17.40	17.42	17.46
17.04	17.08	17.10	17.13	17.16	17.19	17.23	17.26	17.28	17.32	17.35	17.39	17.42	17.45	17.48	17.50	17.54
17.11	17.15	17.18	17.20	17.24	17.27	17.31	17.33	17.36	17.40	17.43	17.46	17.49	17.53	17.55	17.58	18.02
17.19	17.23	17.25	17.28	17.31	17.34	17.38	17.41	17.43	17.47	17.50	17.54	17.57	18.00	18.03	18.05	18.09
17.26	17.30	17.33	17.35	17.39	17.42	17.46	17.48	17.51	17.55	17.58	18.01	18.04	18.08	18.10	18.13	18.17
17.34	17.38	17.40	17.43	17.46	17.49	17.53	17.56	17.58	18.02	18.05	18.09	18.12	18.15	18.18	18.20	18.24
17.41	17.45	17.48	17.50	17.54	17.57	18.01	18.03	18.06	18.10	18.13	18.16	18.19	18.23	18.25	18.28	18.32
17.49	17.53	17.55	17.58	18.01	18.04	18.08	18.11	18.13	18.17	18.20	18.24	18.27	18.30	18.33	18.35	18.39
17.56	18.00	18.03	18.05	18.09	18.12	18.16	18.18	18.21	18.25	18.28	18.31	18.34	18.38	18.40	18.43	18.47
18.04	18.08	18.10	18.13	18.16	18.19	18.23	18.26	18.28	18.32	18.35	18.39	18.42	18.45	18.48	18.50	18.54
18.11	18.15	18.18	18.20	18.24	18.27	18.31	18.33	18.36	18.40	18.43	18.46	18.49	18.53	18.55	18.58	19.02
18.19	18.23	18.25	18.28	18.31	18.34	18.38	18.41	18.43	18.47	18.50	18.54	18.57	19.00	19.03	19.05	19.09

Airport	Eastgardens	Maroubra Junction	Maroubra Beach	Coogee Beach	Randwick	Bondi Junction	Bondi Beach	North Bondi Terminus	Bondi Beach	Bondi Junction	Randwick	Coogee Beach	Maroubra Beach	Maroubra Junction	Eastgardens	Airport
18.26	18.30	18.33	18.35	18.39	18.42	18.46	18.48	18.51	18.55	18.58	19.01	19.04	19.08	19.10	19.13	19.17
18.34	18.38	18.40	18.43	18.46	18.49	18.53	18.56	18.58	19.02	19.05	19.09	19.12	19.15	19.18	19.20	19.24
18.41	18.45	18.48	18.50	18.54	18.57	19.01	19.03	19.06	19.10	19.13	19.16	19.19	19.23	19.25	19.28	19.32
18.49	18.53	18.55	18.58	19.01	19.04	19.08	19.11	19.13	19.17	19.20	19.24	19.27	19.30	19.33	19.35	19.39
18.56	19.00	19.03	19.05	19.09	19.12	19.16	19.18	19.21	19.25	19.28	19.31	19.34	19.38	19.40	19.43	19.47
19.04	19.08	19.11	19.13	19.17	19.20	19.24	19.26	19.29	19.33	19.36	19.39	19.42	19.46	19.48	19.51	19.55
19.13	19.17	19.19	19.22	19.26	19.28	19.32	19.35	19.37	19.41	19.44	19.48	19.51	19.54	19.57	19.59	20.03
19.21	19.25	19.28	19.30	19.34	19.37	19.41	19.44	19.46	19.50	19.53	19.56	19.59	20.03	20.06	20.08	20.12
19.30	19.34	19.36	19.39	19.43	19.46	19.49	19.52	19.54	19.58	20.01	20.05	20.08	20.12	20.14	20.17	20.21
19.39	19.43	19.45	19.48	19.51	19.54	19.58	20.01	20.03	20.07	20.10	20.14	20.16	20.20	20.23	20.25	20.29
19.47	19.51	19.54	19.56	19.60	20.03	20.06	20.09	20.11	20.16	20.18	20.22	20.25	20.29	20.31	20.34	20.38
19.56	19.60	20.02	20.05	20.08	20.11	20.15	20.18	20.20	20.24	20.27	20.31	20.34	20.37	20.40	20.42	20.46
20.04	20.08	20.11	20.13	20.17	20.20	20.24	20.26	20.29	20.33	20.36	20.39	20.42	20.46	20.48	20.51	20.55
20.13	20.17	20.19	20.22	20.26	20.28	20.32	20.35	20.37	20.41	20.44	20.48	20.51	20.54	20.57	20.59	21.03
20.21	20.25	20.28	20.30	20.34	20.37	20.41	20.44	20.46	20.50	20.53	20.56	20.59	21.03	21.06	21.08	21.12
20.30	20.34	20.36	20.39	20.43	20.46	20.49	20.52	20.54	20.58	21.01	21.05	21.08	21.12	21.14	21.17	21.21
20.39	20.43	20.45	20.48	20.51	20.54	20.58	21.01	21.03	21.07	21.10	21.14	21.16	21.20	21.23	21.25	21.29
20.47	20.51	20.54	20.56	20.60	21.03	21.06	21.09	21.11	21.16	21.18	21.22	21.25	21.29	21.31	21.34	21.38
20.56	20.60	21.02	21.05	21.08	21.11	21.15	21.18	21.20	21.24	21.27	21.31	21.34	21.37	21.40	21.42	21.46
21.06	21.10	21.12	21.15	21.19	21.22	21.25	21.28	21.30	21.34	21.37	21.41	21.44	21.48	21.50	21.53	21.57
21.18	21.22	21.24	21.27	21.31	21.34	21.37	21.40	21.42	21.46	21.49	21.53	21.56	21.60	22.02	22.05	22.09
21.30	21.34	21.36	21.39	21.43	21.46	21.49	21.52	21.54	21.58	22.01	22.05	22.08	22.12	22.14	22.17	22.21
21.42	21.46	21.48	21.51	21.55	21.58	22.01	22.04	22.06	22.10	22.13	22.17	22.20	22.24	22.26	22.29	22.33
21.54	21.58	22.00	22.03	22.07	22.10	22.13	22.16	22.18	22.22	22.25	22.29	22.32	22.36	22.38	22.41	22.45
22.06	22.10	22.12	22.15	22.19	22.22	22.25	22.28	22.30	22.34	22.37	22.41	22.44	22.48	22.50	22.53	22.57
22.18	22.22	22.24	22.27	22.31	22.34	22.37	22.40	22.42	22.46	22.49	22.53	22.56	22.60	23.02	23.05	23.09
22.30	22.34	22.36	22.39	22.43	22.46	22.49	22.52	22.54	22.58	23.01	23.05	23.08	23.12	23.14	23.17	23.21
22.42	22.46	22.48	22.51	22.55	22.58	23.01	23.04	23.06	23.10	23.13	23.17	23.20	23.24	23.26	23.29	23.33
22.54	22.58	23.00	23.03	23.07	23.10	23.13	23.16	23.18	23.22	23.25	23.29	23.32	23.36	23.38	23.41	23.45
23.08	23.11	23.14	23.16	23.20	23.23	23.27	23.30	23.32	23.36	23.39	23.43	23.45	23.49	23.52	23.54	23.58
23.23	23.26	23.29	23.31	23.35	23.38	23.42	23.45	23.47	23.51	23.54	23.58	0.00	0.04	0.07	0.09	0.13
23.38	23.41	23.44	23.46	23.50	23.53	23.57	23.60	0.02	0.06	0.09	0.13	0.15	0.19	0.22	0.24	0.28
23.53	23.56	23.59	0.01	0.05	0.08	0.12	0.15	0.17	0.21	0.24	0.28	0.30	0.34	0.37	0.39	0.43
0.15	0.19	0.21	0.24	0.28	0.31	0.34	0.37	0.39	0.43	0.46	0.50	0.53	0.57	0.59	1.02	1.06

APPENDIX D – STS TRAJECTORY DIAGRAM

APPENDIX E – DESIGN LOADING

E1 LOAD PRODUCED FROM STRING

The cross sectional structure of the string is shown in Chapter 6.4.1. This forms the basis of the vertical string loading on the supports. Calculations below show the forces that are applied to the structure from each individual string.

This structure consists of 3 steel strings of 35mm diameter, encased in concrete of dimensions 120mm x 250mm (String Transport Unitksy, 2006).

Cross sectional area of string – 2,886.338mm²

(Assumes solid string to be conservative as steel has greater density than concrete)

Cross sectional area of concrete – 27,113.66mm²

Density of Steel= 7,850kg/m³ (OneSteel Market Mills, 2003)

Density of concrete = 2,400kg/m³ (Standards Australia, 2009a)

Length of maximum span = 25 metres

Length of string effecting each support = 2 ½ * 25 = 25 metres*

*Mass steel = density * length * area = 566.44kg*

*Mass concrete = density * length * area = 1,626.82 kg*

*Force of steel = mass * 9.8ms⁻² = 5.551 kN*

*Force of concrete= mass * 9.8ms⁻² = 15.943 kN*

Force from string = 21.494 kN

Maximum horizontal force from string = 0.772 kN (refer Figure 16)

E2 Load Produced from Rolling Stock

Rolling stock data is generalised in this instance as rolling stock selection will ultimately be the designer's decision. For this case a 2800kg mass for a 20 person carriage is assumed, based on the mass specified by Yunitskiy for a 50 person carriage (String Transport Unitksy, 2006).

Mass of carriage = 2,800kg

Length of carriage = 8 metres

Maximum carriages effecting support at one time = 25/8 = 3.125

*Mass per support = 2,800 * 3.125 = 8,750kg*

*Force per string = 8750 / 2 * 9.8ms-2 = 42.919kN*

Maximum centrifugal acceleration = $v^2/r = 14^2/250 = 0.78ms^{-2}$

*Maximum centrifugal force = mass * acceleration = 10.976 kN*

(This force is in the opposite direction to the horizontal string tensioning force)

E3 Load Produced from Beam

For calculation of the beam self-weight force, a mass of 125kg/m was assumed. This is conservative as this is the maximum value for a standard sized universal beam, exhibited in a 610UB125 (OneSteel Market Mills, 2003).

*Mass of beam = 125*5.5 = 687.5kg*

*Force from beam = 687.5 * 9.8 = 6.738 kN*

E4 LOAD PRODUCED FROM COLUMN

For calculations of column self-weight force, 155kg/m was assumed. This is conservative as this is the maximum value for a standard sized circular hollow section, exhibited in a 508CHS12.7 (OneSteel Market Mills, 2003).

*Mass of column= 155*10 = 1,550kg*

*Force from column = 1550 * 9.8 = 15.2 kN*

E5 LOAD PRODUCED FROM IMPACT BY MOTOR VEHICLE

The typical support structures suggested for design in this route, will be placed along road centrelines and are subsequently exposed to collisions with motor vehicles. The force below is an approximate force that the structure will be exposed to, with a 1 tonne car, colliding with it at 100 km/hr, the maximum speed limit along the alignment.

$$Mass\ of\ vehicle = 1{,}000kg$$

$$initial\ velocity = 27.78ms^{-1}$$

$$final\ velocity = 0ms^{-1}$$

$$time\ of\ collision = 0.2s$$

$$Force = \frac{\Delta p}{\Delta t} = \frac{m * \Delta v}{\Delta t} = \frac{m(v_i - v_f)}{\Delta t} = 138.889kN$$

A summary of all of the above mentioned forces is provided in Chapter 6.1.1

APPENDIX F – DESIGN CALCULATIONS

F1 TYPICAL SUPPORT BEAM – 610UB125

Table 27: 610UB125 Section Properties (OneSteel Market Mills, 2003)

Section Property	Value	Units
A_g	16,000	mm^2
t_f	19.6	mm
t_w	11.9	mm
b_f	229	mm
d	612	mm
d_1	572	mm
$(b_f-t_w)/2$	108.55	mm
I_x	986,000,000	mm^4
Z_x	3,230,000	mm^3
S_x	3,680,000	mm^3
I_y	39,300,000	mm^4
Z_y	343,000	mm^3
S_y	536,000	mm^3
I_w	3,450,000,000,000	mm^6
f_{yw}	300	MPa
f_{yf}	280	MPa
E	200,000	MPa
G	80,000	MPa
J	1,560,000	mm^4
k_f	0.95	-
R_y	49.6	mm
R_x	249	mm
Weight	125	kg/m

Section Property	Value	Units
Factored load (1.35G)	1.655	kN/m
L	5,500	mm

The design method used here is based on Australian Standard (AS) 4100, Steel Structures (Standards Australia, 1998) and the loadings are based on AS 1170.1, structural design actions (Standards Australia, 2009b). Beam sectional properties are based on data provided by OneSteel Market Mills (OneSteel Market Mills, 2003).

F1.1 Design for Bending Moment

F1.1.1 Section Capacity $(\boldsymbol{M_x^*} \leq \phi \boldsymbol{M_{sx}})$

$$\lambda_{ef} = \frac{b_f - \frac{t_w}{2}}{t_f} * \sqrt{\frac{f_{yf}}{250}} = 12.365$$

$$\lambda_{ew} = \frac{b_w}{t_w} * \sqrt{\frac{f_{yw}}{250}} = 52.655$$

$$\lambda_{eyf} = 16\ for\ hot\ rolled\ UB$$

$$\lambda_{epf} = 9\ for\ hot\ rolled\ UB$$

$$\lambda_{eyw} = 115\ for\ hot\ rolled\ UB$$

$$\lambda_{epw} = 82\ for\ hot\ rolled\ UB$$

$$\lambda_{epf} < \lambda_{ef} < \lambda_{eyf} \quad \rightarrow flange\ is\ compact$$

$$\lambda_{ew} < \lambda_{epw} < \lambda_{eyw} \quad \rightarrow web\ is\ non\ compact$$

The non-compact web now governs design

$M_{sx} = z_{ex} * f_y = 1224.048\ kN.m$

$$z_{ex} = z_x + \left(\frac{\lambda_{eyw} - \lambda_{ew}}{\lambda_{eyw} - \lambda_{epw}}\right) * (z_c - z_x) = 4080158.97 mm^3$$

$$z_c = \min(s_x, 1.5z_x) = 3680000\ mm^3$$

$\phi = 0.9\ for\ a\ member\ subject\ to\ bending\ or\ shear\ in\ web$

$\phi M_{sx} = 1101.643\ kN.m$

$M_x^* \leq \phi M_{sx} \quad \rightarrow satisfied\ for\ section\ capacity$

F1.1.2 Bending Capacity $(M_x^* \leq \phi M_{bx})$

$$L = r_y * (80 + 50\beta_m) * \sqrt{\frac{250}{f_{yw}}} = 1406.03mm$$

$$\beta_m = -1 \quad \rightarrow end\ moments\ are\ both\ zero\ and\ there\ is\ negative\ curvature$$

As L < length of beam, the beam is unable to be fully laterally restrained, hence is only fully restrained at both ends

$M_b = \alpha_s \alpha_m M_s = 862.759\ kN.m$

$$\alpha_S = 0.6 * [\sqrt{\left(\frac{M_{SX}}{M_{OA}}\right)^2 + 3} - \frac{M_{SX}}{M_{OA}} = 0.564$$

$$M_{OA} = \sqrt{\left(\frac{\pi^2 EI_y}{l_e^2}\right) * \left(GJ + \left(\frac{\pi^2 EI_w}{l_e^2}\right)\right)} = 979.366\ kN.m$$

$$l_e = k_l * k_t * k_r * L = 5.39m$$

$$k_l = 1.4 \quad \rightarrow FF\ as\ load\ on\ top\ flange\ within\ segment$$

$$k_t = 1.0 \quad \rightarrow FF\ as\ ends\ fully\ restrained$$

$$k_r = 0.7 \quad \rightarrow FF\ with\ end\ lateral\ rotation\ restraint$$

$$\alpha_m = \max\left(\frac{1.7M_{max}^*}{\sqrt{(M_2^*)^2 + (M_3^*)^2 + (M_4^*)^2}}, 1\right) = 1.249$$

$$\phi M_b = 776.483\ kN.m$$

$$M_x^* \leq \phi M_b \quad \rightarrow satisfied\ for\ bending\ capacity$$

$$Moment\ capcity = \min(\phi M_{sx}, \phi M_b) = 776.483$$

$$M_x^* \leq moment\ capacity \quad \rightarrow satisfied\ for\ moment\ capacity$$

F1.2 Web Shear Capacity ($V^* \leq \phi V_v$)

$$t_{w,min} = \frac{d_1}{180} * \sqrt{\frac{f_{yw}}{250}} = 3.481mm$$

Web thickness > minimum web thickness so this beam is satisfactory for shear loading

$$\frac{d_1}{t_w} = 48.067$$

$$\frac{82}{\sqrt{\frac{f_{yw}}{250}}} = 74.855$$

$$\frac{82}{\sqrt{\frac{f_{yw}}{250}}} > \frac{d_1}{t_w} \quad \rightarrow \quad V_v = V_w$$

$$v_w = 0.6 * f_{yw} * A_w = 1{,}225.224\ kN$$

$$A_w = d_1 * t_w = 6808.6mm^2$$

$$V_v = V_w = 1{,}225.224\ kN$$

$$\phi V_v = 1{,}102.702\ kN$$

$$V^* \leq \phi V_v \quad \rightarrow satisfied\ for\ web\ shear\ capacity\ and\ no\ stiffeners\ required$$

F1.3 Bending and Shear Interaction ($\boldsymbol{V^*} \leq \phi \boldsymbol{V_{vm}}$)

$$0.75\ \phi M_s = 826.232\ kN.m$$

$$0.75\ \phi M_s \geq M^* \quad \rightarrow V_{vm} = V_v$$

$$V_{vm} = V_v = 1{,}225.224\ kN$$

$$\phi V_{vm} = 1{,}102.7016\ kN$$

$$V^* \leq \phi V_{vm} \quad \rightarrow satisfied\ for\ shear\ with\ bending$$

F1.4 Bearing Capacity ($\boldsymbol{R^*} \leq \ \phi \boldsymbol{R_b}$)

$R_b = \min(R_{bb}, R_{by}) = 673.108\ kN$

$R_{by} = 1.25 b_{bf} t_w f_{yw} = 1{,}240.575 kN$

$b_{bf} = b_S + \ 2.5 t_f = 278 mm \quad \rightarrow \ for\ end\ bearing, where\ b_s$
$= stiff\ bearing\ length$

$R_{bb} = N_c = 673.108\ kN$

$N_c = \ \min(\alpha_c N_s, N_s) = 673.108\ kN$

$N_s = k_f * A_n * F_{yw} = 2{,}013.48\ kN$

$A_n = A_w = t_W * b_b = \ 6{,}711.6\ mm^2$

$b_b = b_{bf} + \frac{d_1}{2} = 564\ mm$

$k_f = 1$

$$\alpha_c = \ \xi \left(1 - \sqrt{1 - \left(\frac{90}{\lambda \xi}\right)^2}\right) = 0.334$$

$$\xi = \frac{\left(\frac{\lambda}{90}\right)^2 + 1 + \eta}{2\left(\frac{\lambda}{90}\right)} = 0.796$$

$\eta = 0.00326(\lambda - 13.5) = 0.408$

$\lambda = \ \lambda_n + \alpha_a * \alpha_b = 138.781$

$$\lambda_n = \left(\frac{l_e}{r}\right) * \sqrt{k_f} * \sqrt{\frac{f_y}{250}} = 131.638$$

$$l_e = d_1$$

$$\alpha_a = \frac{2{,}100(\lambda_n - 13.5)}{\lambda_n^2 - 15.3\lambda_n + 2{,}050} = 14.287$$

$$\alpha_b = 0.5 \quad \rightarrow for\ an\ i - section\ with\ no\ stiffener$$

$\phi R_b = 605.797$ kN

$R^* \leq \phi R_b \quad \rightarrow satisfied\ for\ bearing\ capacity$

F2 TYPICAL SUPPORT COLUMN – 508CHS12.7

Table 28: 508CHS12.7 Section Properties (OneSteel Market Mills, 2003)

Section Property	Value	Units
d_o	508	mm
t	12.7	mm
F_y	350	MPa
F_u	430	MPa
A_g	19800	mm^2
I	606,000,000	mm^4
Z	2,390,000	mm^3
S	3,120,000	mm^3
R	175	mm
J	1,210,000	mm^4
C	4,770,000	mm^3
k_f	1	-
Z_e	3,050,000	mm^3
Weight	155	kg/m
Factored load (1.35G)	2.050	kN/m
L	10,000	mm

The design method used here is based on Australian Standard (AS) 4100, Steel Structures (Standards Australia, 1998) and the loadings are based on AS 1170.1, structural design actions (Standards Australia, 2009b). Beam sectional properties are based on data provided by OneSteel Market Mills (OneSteel Market Mills, 2003)

F2.1 Section Capacity for Member Exposed to Combined Actions

Note that sectional properties are the same in both the x and y direction for a CHS, and hence the subscript $_{x/y}$ will be used.

F2.1.1 Compression ($N^* \leq \Phi N_s$)

$N_s = k_f A_n f_y = 6{,}930\ kN$

$A_n = A_g$

$\Phi = 0.9\ for\ member\ subject\ to\ axial\ compression\ and\ bending$

$\Phi N_s = 6{,}237$ kN

$\boldsymbol{N^*} \leq \Phi N_s$ → section capacity satisfied for compression

F2.1.2 Uniaxial Bending about Major Principal (x) and Minor Principal (y) Axis ($M^* \leq \Phi M_{rx/y}$)

$$M_{rx/y} = M_{sx/y}\left(1 - \frac{N^*}{\Phi N_s}\right) = 1{,}000.700\ kN.m$$

$$M_{sx/y} = z_e f_y = 1{,}067.5\ kN.m$$

$\Phi M_{rx/y} = 900.630\ kN.m$

$M_x^* \leq \Phi M_{rx/y}\ and\ M_y^* \leq \Phi M_{rx/y}$

→ section capacity satisfied for uniaxial bending in major and minor principal axis′

F2.1.3 Biaxial Bending $\left(\left(\frac{M_x^*}{\Phi M_{rx}} + \frac{M_y^*}{\Phi M_{ry}} + \frac{N^*}{\Phi N_s}\right) \leq \mathbf{1}\right)$

$$\frac{M_x^*}{\Phi M_{rx}} + \frac{M_y^*}{\Phi M_{ry}} + \frac{N^*}{\Phi N_s} = 0.905 \quad (assuming\ car\ crash\ only\ in\ one\ direction\ not\ both)$$

$$\frac{M_x^*}{\Phi M_{rx}} + \frac{M_y^*}{\Phi M_{ry}} + \frac{N^*}{\Phi N_s} \leq 1 \quad \rightarrow \quad section\ capacity\ satisfied\ for\ biaxial\ bending$$

F2.2 Member Capacity for Member Exposed to Combined Actions

F2.2.1 Compression $(N^* \leq \phi N_c)$

$\mathrm{N_c} = \alpha_c * N_s = 6{,}052.149\ kN$

$$\alpha_c = \xi\left(1 - \sqrt{1 - \left(\frac{90}{\lambda\xi}\right)^2}\right) = 0.873$$

$$\xi = \frac{\left(\frac{\lambda}{90}\right)^2 + 1 + \eta}{2\left(\frac{\lambda}{90}\right)} = 2.512$$

$$\eta = 0.00326(\lambda - 13.5) = 0.110$$

$$\lambda = \lambda_n + \alpha_a * \alpha_b = 47.273$$

$$\lambda_n = \left(\frac{l_e}{r}\right) * \sqrt{k_f} * \sqrt{\frac{f_y}{250}} = 67.612$$

$$l_e = k_e * l = 10\text{m}$$

$$k_e = 1$$

$$\alpha_a = \frac{2{,}100(\lambda_n - 13.5)}{\lambda_n^2 - 15.3\lambda_n + 2{,}050} = 20.339$$

$$\alpha_b = -1 \quad \rightarrow for\ a\ CHS$$

$\phi\mathrm{N_c} = 5{,}446.934\ kN$

$\mathrm{N}^* \leq \phi\mathrm{N_c} \quad \rightarrow member\ capacity\ satisfied\ for\ compression$

F2.2.2 In-Plane Capacity ($M^* \leq \phi M_{ix/y}$)

$$M_{ix/y} = M_{sx/y}\left(1 - \frac{N^*}{\Phi N_c}\right) = 991.011\ kN.m$$

$$\phi \mathrm{M}_{\mathrm{ix/y}} = 891.910\ kN.m$$

$$M_{\mathrm{x}}^* \leq \Phi M_{ix/y}\ and\ M_{\mathrm{y}}^* \leq \Phi M_{\mathrm{ix/y}}$$

$$\rightarrow \text{member capacity satisfied for in} - \text{plane capacity for x and y axis}'$$

F2.2.3 Out of Plane capacity ($M_x^* \leq \phi M_{ox}$)

$$M_{ox} = M_{bx}\left(1 - \frac{N^*}{\Phi N_{cy}}\right) = 1{,}044.748\ kN.m$$

$$M_b = \alpha_s \alpha_m M_s = 1{,}125.384\ kN.m$$

$$\alpha_S = 0.6 * [\sqrt{\left(\frac{M_{SX}}{M_{OA}}\right)^2 + 3} - \frac{M_{SX}}{M_{OA}} = 0.602$$

$$M_{OA} = \sqrt{\left(\frac{\pi^2 E I_y}{l_e^2}\right) * \left(GJ + \left(\frac{\pi^2 E I_w}{l_e^2}\right)\right)} = 979.366\ kN.m$$

$$l_e = k_e L = 10m$$

$$k_e = 1.0$$

$$\alpha_m = \max\left(\frac{1.7 M_{max}^*}{\sqrt{(M_2^*)^2 + (M_3^*)^2 + (M_4^*)^2}}, 1{,}1.7\right) = 1.7$$

$$\phi M_{ox} = 940.273\ kN.m$$

$M_{\mathrm{x}}^* \leq \Phi M_{ox}$ → member capacity satisfied for out of plane capacity

F2.2.3 Biaxial Bending $\left(\left(\left(\frac{M_x^*}{\Phi M_{cx}}\right)^{1.4} + \left(\frac{M_y^*}{\Phi M_{iy}}\right)^{1.4}\right) \leq 1\right)$

$$\left(\frac{\mathrm{M_x^*}}{\Phi M_{cx}}\right)^{1.4} + \left(\frac{\mathrm{M_y^*}}{\Phi M_{iy}}\right)^{1.4} = 0.754 \qquad (assuming\ car\ crash\ only\ in\ one\ direction)$$

$$M_{cx} = \min(M_{ox}, M_{ix}) = 991.011$$

$$\left(\frac{\mathrm{M_x^*}}{\Phi M_{cx}}\right)^{1.4} + \left(\frac{\mathrm{M_y^*}}{\Phi M_{iy}}\right)^{1.4} \leq 1 \quad \rightarrow \quad member\ capacity\ satisfied\ for\ biaxial\ bending$$

F3 FOUNDATION – MONOPILES IN SAND

The Australia standard on piles is AS 2159-2009: Piling - design and installation (Standards Australia, 2009c). This standard dictates that loading be factored based on AS1170.1. The standard also dictates that steel piles be designed to AS4100, with an allowance made for corrosion of the pile.

As the steel column has been designed and is deemed sufficient, the pile will be as well (refer Chapter 6.2), however, simple calculations of axial and lateral capacity can be used as a check for indicative purposes for initial feasibility design. Calculations are based on driven steel piles in medium density sand (Taiebat, 2012).

F3.1 Axial Capacity ($\boldsymbol{P^*} \leq \phi_{\boldsymbol{g}} \boldsymbol{P_u}$)

$$P_u = f_s A_s + f_b A_b = 5{,}013.982\ kN$$

$$f_s = (Ktan\delta)\sigma_v' = 28$$

$$Ktan\delta = 1.0\ for\ driven\ pile\ in\ medium\ density\ sand$$

$$\sigma_v' = depth_{middle\ of\ pile} * (\gamma_{sand} - \gamma_{water}) = 28\frac{kN}{m^2}$$

$$\gamma_{sand} = 18\frac{kN}{m^3} \quad \text{(Hotlz, et al., 2011)}$$

$$\gamma_{water} = 10\frac{kN}{m^3} \quad \text{(Hotlz, et al., 2011)}$$

$$A_s = \pi BL = 21.991\ m^2$$

$$f_b = \sigma_{vb}' * N_q = 5{,}600$$

$$N_q = 100\ for\ driven\ pile\ in\ medium\ density\ sand$$

$$\sigma_v' = depth_{base\ of\ pile} * (\gamma_{sand} - \gamma_{water}) = 56\frac{kN}{m^2}$$

$$A_b = \pi\left(\frac{B}{2}\right)^2 = 0.785m^2$$

$\phi_g = 0.45$

$\rightarrow conservative\ value\ for\ static\ analysis, with\ soil\ properties\ based\ on\ laboratry\ data$

$\phi_g P_u = \ 2{,}256.292\ kN$

$P^* \leq \phi_g P_u \qquad \rightarrow satisfied\ for\ axial\ capactiy$

F3.2 Lateral Capacity ($\boldsymbol{H^*} \leq \ \boldsymbol{H_u}$)

$$H_u = \frac{\sigma'_{vb} K_p B L^2}{2(e+L)} = \ 348.291\ kN \quad \rightarrow for\ free\ head\ piles\ in\ sand$$

$$K_p = \tan^2(45 + 0.5 * \emptyset') = 4.910$$

$$\emptyset' = 41.42^o$$

$$H = \sum horizontal\ forces\ at\ top\ of\ pile\ = 270.018\ kN$$

$$M = \sum moments\ at\ top\ of\ pile = 721.012\ kN.m$$

$$e = \frac{M}{H} = 2.670\ m$$

$H^* \leq \ H_u \qquad \rightarrow satisfied\ for\ lateral\ capacity$