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Bachelor of Engineering Thesis

Comparative analysis of the Hyperloop against High Speed Rail for commuting between Sydney, Canberra and Melbourne

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Abstract

In 2013, Elon Musk proposed a conceptual new form of transportation called “*The Hyperloop*” which would involve transporting passengers through reduced-pressure tubes, in capsules, at more than three times the speed of modern rail. The feasibility and cost of the initial design has been heavily criticised, with varying degrees of bias. To better understand and contextualise the Hyperloop system, this study utilises axiomatic design to investigate and compare the implementation of both High Speed Rail and the Hyperloop along the eastern coast of Australia. Axiomatic design allowed quantification of the inherent uncertainty in both systems and a cost assessment determined the capital cost and annual revenue of both systems. The findings, based on design feasibility and financial metrics, suggest that High Speed Rail is the better design option. However, the development of new technology in the coming years may justify the implementation of the Hyperloop in Australia.

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1 Study Overview

1.1 Introduction

To accommodate the immense volume of commuters travelling between capital cities daily, the Australian government has investigated the feasibility of constructing a High Speed Rail (HSR) traversing the East coast of Australia, connecting highly populated capital cities, with a priority on Sydney, Canberra and Melbourne. A feasibility study conducted at the request of the government in 2013, estimated this project to cost 114 billion AUD (\$50 billion for Sydney-Melbourne-Canberra and \$64 billion for Brisbane-Sydney) and take up to 50 years to construct. (AECOM, 2013) The findings of this study led to the stalling of project advancement due to the large cost and construction duration. Similar projects have been discussed and proposed in Australia since as early as 1984 and have been rejected due to analogous timelines and disproportionate investment with low potential returns. (Huggan, 1990; Laird & Bachels, 2001)

In 2013, Elon Musk and a team of engineers at SpaceX, in opposition to a similar HSR proposal in the United States, proposed a conceptual new form of transportation called "*The Hyperloop*" which would involve transporting passengers through reduced-pressure tubes, in capsules, at near Mach speeds. The 2013 Hyperloop Alpha study recommended a route from Los Angeles to the San Francisco Bay Area and estimated total project cost as 6 billion USD, equivalent to approximately 6.6 billion AUD as of August, 2013 (Musk, 2013). The straight line distance between Melbourne and Sydney is approximately 25% greater than the straight line distance between Los Angeles and San Francisco of 570km. Hence, even with highly pessimistic financial estimates, the Hyperloop could cost significantly less than the HSR proposal of 2013. In addition to the reduced expense, the Hyperloop also travels at far greater speeds, up to 1200 km/hr, compared to the typical HSR top speed of 300 km/hr; is powered through solar panels along the tube length and would therefore reduce transport related carbon emissions; is less disruptive to the environment as it can be routed alongside existing roads and is more immune to weather variability. If found to be feasible, the Hyperloop should provide a highly attractive alternative to the current HSR proposal for Australia.

1.2 Problem Definition

This project's primary objective is to provide a comprehensive, comparative analysis between the existing HSR proposal and the Hyperloop. This will involve a technical and financial comparison of the two technologies, which will require explicit description of route, materials, subsystem design and other various financial considerations. As the Hyperloop is a recent, unproven form of transport, an analytical assessment of its various components will need to be conducted, including but not limited to: tube and capsule dimensions, fluid flow analysis, propulsion mechanics, suspension and energy storage. This analysis will provide a more robust cost estimation and allow qualitative assessment of the feasibility of implementing this design in Australia. HSR is an internationally realised technology and is expected to be feasible; however, it will be assessed in the same manner as the Hyperloop to ensure validity of the comparison.

The Sydney, Canberra and Melbourne alignment will be assessed for both systems. The HSR Phase 2 study (the report completed by AECOM in 2013) also included a passage to Brisbane; however, the Brisbane to Sydney alignment follows a more complicated route, with a variety of bends, making it less suitable for the Hyperloop (AECOM, 2013).

1.3 High Speed Rail Background

1.3.1 History

At the beginning of the 19th century, during the Industrial Revolution, the need for shorter travel times gave impetus to high speed passenger trains. Companies competed to produce the fastest possible trains and, at an operational level, trains had an average speed of 135 km/hr and a top speed of 180 km/hr by the 1930s, utilising steam, diesel or electric power. The introduction of private cars and aviation stunted the growth of the rail industry and it was forced to adapt to the new market (International Union of Railways, 2015).

Japan's introduction of the Tokaido Shinkansen rail line, which operated at 210 km/hr, to accommodate the rapid growth of the Japanese economy and populace, reignited global interest in rail transport as the first official High Speed Rail. The success of the Shinkansen line drove European development and by 1981, France introduced a high speed line, the TGV, travelling at a maximum speed of 260 km/hr and with the additional advantage that it was compatible with existing railways, which further invigorated the rail market. In the years following the introduction of the TGV, a number of nations introduced their own high speed rail, including Germany, the United Kingdom, China, Taiwan and South Korea. In particular, the Chinese HSR system has developed enormously, with an additional 20,000 km of high speed line, carrying 800 million passengers per year (as of 2014). New HSR systems are currently under development in Morocco, Saudi Arabia, the USA and a number of other countries, following the example of the successful Chinese HSR (International Union of Railways, 2015).

Discussions of an Australian HSR have also been gaining significant political and media attention in recent years (Steketee, 2016; Carey & Dow, 2016; McMahan, 2016). Australia's involvement with HSR, began in June, 1984, with a proposal by the CSIRO to the Hawke Government, founded on the French TGV technology; upon review by the Bureau of Transport Economics, it was found that CSIRO vastly underestimated construction costs and the proposal was rejected in September, 1984. Two years later, the Very Fast Train (VFT) Joint Venture was established which conducted a major feasibility study regarding an inland route between Melbourne, Sydney and Canberra. The study's results released in 1990 estimated five years' construction time and a total cost of 6.6 billion AUD (11.9 billion AUD in 2013). It was established that major tax breaks would be required to make the project economically viable which the Hawke Cabinet rejected, leading to the dissolution of the VFT Joint Venture (Williams, 1998).

The Howard government, in the late 1990s and early 2000s, investigated two successive proposals, denoted the *Speedrail* proposal and the *East Coast Very High Speed Train Scoping Study*, respectively. Both ventures failed because it was discovered they required subsidies and consequently enormous public funding (Laird & Bachels, 2001). In late 2008, the Rudd Government enlisted AECOM to conduct a feasibility study investigating HSR along the East coast, from Brisbane to Melbourne. The report study was completed in two phases; where the second phase provided a more comprehensive scope and improved the estimates of demand, cost and construction timeline. The Phase 2 report, released in 2013, estimated the system would be fully operation by 2065, carrying approximately 84 million passengers per year and costing 114 billion AUD for construction (AECOM, 2013). Due to the turbulent nature of the Australian government in recent years, no further development has been made regarding the High Speed Rail; however, it has been raised by the Turnbull government in the lead up to the 2016 election generating media speculation (Iggulden, 2016).

The Phase 2 report will be referred to frequently throughout this study and forms the basis of the High Speed Rail components as well as assisting in project scope and definition.

1.3.2 Considerations

There are a number of factors which need to be considered when implementing HSR. HSR provides a safe and reliable alternative to road and aviation transport, which consequently reduces both air and road congestion, as well as reducing the transport related carbon emissions (Canberra Business Council, 2008). The addition of HSR in Australia would help to account for the increasing demand for travel between Brisbane, Sydney, Canberra and Melbourne. According to The International Air Transport Association, as of 2014, the air route between Melbourne and Sydney is the fourth busiest in the world, and Sydney and Brisbane is the thirteenth, suggesting a high speed rail service would be a beneficial alternative to aviation as the demand continues to increase (IATA, 2015). The project would also generate a large number of jobs, as well as sourcing materials from the struggling mining sector of Australia (Carey & Dow, 2016).

HSR is a large scale infrastructure project typically implemented to reduce commuting time, address regional imbalance and reduce the pressure on growing urban areas through decongestion, but is unlikely to make much, if any, profit. Historically, the restrictive factor on the development of HSR in Australia has been the enormous capital investment required for construction, which would undoubtedly require public funding and tax reform, with no foreseeable return. The most recent report, from the Phase 2 study, estimates a capital cost of 114 billion AUD, which is the highest predicted cost of any similar proposal in Australia to date. If this considerable financial obstacle is overcome, the environmental impact of constructing the route, as well as the social impact, will then need to be discussed, which could potentially derail the project. HSR will likely become a political movement in the upcoming months, but it is unclear at this stage whether it will develop any further or be discarded similar to the previous ventures.

This study will only have a minor emphasis on the financial aspects of HSR and will instead concentrate on the technical feasibility of the HSR and estimate the uncertainty in the design in comparison to the Hyperloop. An example of this uncertainty is that the maximum design speed of a given HSR design is typically not met by the operational maximum speed and consequently, the duration estimates in the Phase 2 study may not be realised (Gourvish, 2010).

1.4 Hyperloop Background

1.4.1 History

In August 2013, Elon Musk (CEO of Tesla & SpaceX) and SpaceX released an Alpha study detailing a new form of transportation called the Hyperloop. The Alpha study was intended to promote an alternative transportation system, after the California High Speed Rail, suggested to be one of the slowest and most expensive per kilometre in the world, was approved (Rogowsky, 2013). Due to the bold claims of the Alpha study and Musk's fame and following, the study garnered a lot of media attention, both positive and negative. Among various innovative design concepts, the study claimed that the Hyperloop could travel up to 1200 kilometres per hour, which would equate to a thirty-five-minute journey time between San Francisco and Los Angeles. The Hyperloop capsules are able to reach near Mach speeds by travelling through a low pressure tube (approximately 100Pa) and thereby minimising the influence of drag and resistive forces.

The technology was first postulated by Robert Goddard, credited with creating and building the first liquid-fuelled rocket, who suggested a very similar design using magnetic levitation, rather than air bearings described in the Alpha study, under a design called a 'Vac-Train'. A patent for the design was filed on 21 May, 1945, by his wife Esther Goddard (USA Patent No. US2511979 A, 1945).

The design was largely ignored due to the technical difficulties and uncertainty in the design; however, Musk et al.'s (2013) study revived interest in the concept. The validity of the design, outlined in the Alpha study, specifically the air bearings, understatement of the tube diameter and the power requirements of the system, which Musk et al. (2013) claimed could be entirely powered by on-board batteries and solar panels lining the outside of the tubing, was widely reviewed by scientists and engineers in the media resulting in conflicting opinions and no distinct conclusion regarding the validity of the design (Staley, 2013; Pedestrian Observations, 2013). The main doubt, however, surrounded Musk et al.'s (2013) projected cost 6 billion USD (6.6 billion AUD as of August, 2013), which is less than 10% of the proposed California Rail cost (Musk, 2013; Nichols, 2015).

From a technical standpoint, a variety of developments have arisen recently regarding the Hyperloop. Two Hyperloop companies have formed in the US, Hyperloop One and Hyperloop Transportation Technologies (HTT) and both are in the process of constructing a test tube and refining the components that will make up the final system (Grothaus, 2016). French Railways, the SNCF, pioneers of the TVG high speed rail, have recently invested 80 million Euros in Hyperloop One, and the Slovakian government have signed an agreement with Hyperloop Transportation Technologies to develop a high-speed tube system linking Bratislava, Budapest and Vienna; both these cases indicate growing international interest in the technology (Lichfield, 2016). The companies seem to be inclined more to a magnetic levitation method, rather than air bearings; this supports the view that the Alpha study was not intended to be a final design, merely a proposal to reinvigorate interest in what Musk believed to be a stagnating form of transportation. Along with the introduction of two Hyperloop companies and the growing investor interest, SpaceX is hosting a pod design competition between an ensemble of university teams worldwide, with a pod testing day expected for January, 2017 (SpaceX, 2016). The outcome of this competition will indicate how much further the technology needs to be developed as well as testing the feasibility of the concept.

Whether the Hyperloop becomes a reality is difficult to predict, but it is clear that there is public desire for new transportation and investors are willing to support the technology even in its infancy. There is not much Hyperloop interest in Australia at this time; however, as HSR is discussed in the upcoming months it is likely that the Hyperloop will get some media attention and potentially influence the development of both technologies.

1.4.2 Considerations

The Hyperloop would satisfy the same fundamental premise as HSR, which is to provide a safe and reliable alternative to air and road travel. It would similarly reduce the demand on aviation, decongest roads, reduce carbon emissions and stimulate the economy by generating a large number of jobs. The Hyperloop, even with the projected costs being considerably lower than that of the HSR, is still a major infrastructure project and will cost the government and investors a large amount of capital investment.

Furthermore, the Hyperloop is an unproven technology, hence, there is a high amount of risk associated with the development of this project. Before construction of the Hyperloop, there

will need to be considerable research and development of the technology which will cost additional money and time. If a government or company intends to develop this technology, they need to accept the inherent risk associated with investing money in a project which may not ever be physically realised.

The Hyperloop has two geographical dependent design criteria; firstly, a very small radius of curvature to prevent turbulent movement and strong G-forces and secondly, solar panels situated along the external wall of the tube would ideally be used to power the system. Both of these design criteria are challenging to satisfy for difficult routes in “non-sunny” areas; however, the Australian east coast offers great solar potential and has generally straight-line routes between Melbourne, Canberra, Sydney and Brisbane (AECOM, 2013; Energy Matters, 2016).

This study will concentrate on the technical feasibility of the Hyperloop, critically addressing criteria similar to the two previously stated, and estimate the uncertainty in the design in comparison to HSR. Due to the infancy of the technology, there is predicted to be greater uncertainty in the Hyperloop design.

1.5 Study Methodology

In this study, I will design both the Hyperloop and HSR system for implementation in Australia. These designs will then be evaluated to estimate the inherent uncertainty in each design, as well as to determine each system’s associated costs.

I will employ axiomatic design to ensure rigour and provide a quantitative assessment of the design’s capability to satisfy the functional requirements (Suh, 2001). Axiomatic design provides a structured approach to design, which is described in *Figure 1*.

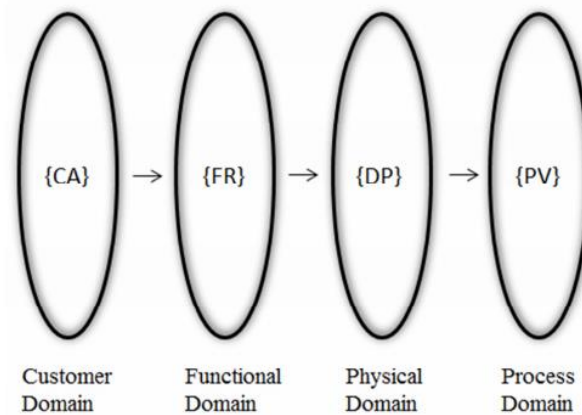


Figure 1: Axiomatic design domain maps (Gurgenci, 2016)

The axiomatic design strategy outlined in *Figure 1* shows the client, or customer, requirements mapping to a set of functional requirements, which then map to a physical design which maps to the process variables. Process variables are production, or manufacturing considerations, and are out of scope of this study (Suh, 2001).

Axiomatic design is based on two fundamental axioms: the independence axiom and the information axiom. The independence axiom requires the independence of the functional requirements (FRs) and the information axiom stipulates that the information content of the design should be minimised. Information content describes the ability of a design to satisfy the functional requirements. An information content of zero implies that the design is assured to meet the functional requirements of the system. A value greater than zero indicates the amount

of extra information that is required before the design is guaranteed to meet the functional requirements. As such, the design which minimises the information content is considered the best design (Suh, 2001).

The first step in axiomatic design is to define the customer domain to ensure that the aims of the product or design are achieved. In this study, the customer domain definition will include the average number of commuters, the preferred time and duration of commute, locations of non-capital city stations along route, comfort of passengers, safety requirements, etc. Examples of the functional requirements (FRs) in this design include trip duration, noise generation and on-board vibrations, which are each influenced by design parameters (DPs), including acceleration mechanism, route and tube/track specifications. Evidently, there are a variety of FRs and DPs which will need to be manipulated to minimise the information content and produce a robust design (Suh, 2001).

Using axiomatic design provides a fundamental strategy to approach the research and ensures that the final design and recommendations reflect the customer demands and satisfy the functional requirements. It is also a more rigorous approach than alternative design methods and allows the designer to arrive at a high level of confidence in the ability of their design to satisfy the functional requirements (Gurgenci, 2016).

The second aspect of the design evaluation involves a financial assessment of each system. The cost of an Australian HSR system can be readily sourced from the Australian HSR Phase 2 Study (AECOM, 2013). Each of the cost components described in the Phase 2 study will be evaluated and adjusted to produce an equivalent cost for the Hyperloop system. There is greater uncertainty in the cost estimates for the more complex Hyperloop components and as a result there will be a greater uncertainty in the overall Hyperloop cost estimate. However, this approach will provide a more robust cost comparison of the two systems than speculative, or unsupported, articles.

Using the aforementioned methods, a comparison of the Hyperloop and HSR in Australia can then be conducted based on design feasibility and cost metrics.

1.6 Scope

The in-scope study aspects are described in *Table 1*.

Table 1: In-scope components

In-scope	Comment
Commuter demand	Commuter demand is explicitly detailed in <i>Section 2.2</i> .
Route analysis	An analysis of the route (i.e. route breakdown) is included in <i>Section 3.1.6</i> and <i>3.2.8</i> .
Customer requirements	Customer requirements are explicitly detailed in <i>Section 2.1</i> and <i>2.3</i> .
Functional requirements	Functional requirements are explicitly detailed in <i>Section 2.4</i> and <i>2.5</i> .
Design of sub-systems	Subsystem component breakdown and design is explicitly detailed in <i>Section 3</i> . Only subsystems which directly affect a functional requirement were included.
Alternatives	All reasonable alternatives to included subsystems were investigated and are detailed in <i>Section 3</i> .
Information content	Information content is explicitly detailed in <i>Section 4</i> .
Cost analysis	Cost analysis is explicitly detailed in <i>Section 5</i> .

The out of scope study aspects are described in *Table 2*.

Table 2: Out of scope components

Out of scope	Comment
Detailed design of each subsystem	This study serves as a preliminary design, primarily scoping high-level design options. Specific, detailed design is not included due to time constraints.
Subsystems which do not influence system ranges	Any subsystem designs which did not directly map or influence a functional requirement (e.g. station design, tube vacuum design), were not included in the study. This was a limitation of axiomatic design, discussed in <i>Section 3.2.10</i> .
Subsystem designs which do not influence performance	Any subsystem designs which did not directly map or influence the performance or operation of the transportation (e.g. comfort, accessibility, station convenience, security), were not included in the study. This was a limitation of axiomatic design, discussed in <i>Section 3.2.10</i> .
Route definition	The route described in the Phase 2 study will be used for both systems.
Operational parameters	Operational aspects, such as carriages/capsules adhering to schedules, are out of scope.
Process Domain	Production or manufacturing of the design is out of scope.
Independent computational analysis	Due to time constraints, independent finite-element modelling and computational fluid dynamics will not be conducted. External sources will provide the necessary computational analysis.
Civil components	This is a mechanical engineering project, therefore, civil components (e.g. pylons, land-clearing) are out of scope.
Electrical components	This is a mechanical engineering project, therefore, electrical components (e.g. sensors, wiring) are out of scope.
Ground-borne vibrations	The analysis of ground-borne vibrations is an important aspect in HSR, but was excluded from this study due to axiomatic design limitations.
Environmental analysis	An environmental/sustainability analysis was not conducted due to time constraints.
Safety and emergency systems	Emergency systems (e.g. emergency braking) were not included in this study. Emergency systems, whilst necessary in more developed designs, do not map to any functional requirements.
Landholder analysis	Requires non-engineering related surveying.
Stakeholder analysis	Not included due to time constraint and lack of significance.

2 Customer Domain & Functional Requirements

2.1 Customer Domain

An important aspect of axiomatic design is a comprehensive understanding of the customer's requirements, formally encompassed by the Customer Domain. The Customer Domain can effectively be described as understanding what we, as engineers, need to achieve out of the design process. This allows us to consider the customers' needs as the functional requirements are scoped; thus ensuring that the final design satisfies essential client criteria. For both the Hyperloop and HSR, the customer domain will be the same to ensure consistency of the study and validity of the comparison; hence, the following scope effectively defines the customer requirements for any new transportation technology.

2.1.1 Alternative

The primary requirement is that the new transportation system acts as an effective alternative to flight or road travel, as these are the only common modes of transport available along the eastern coast of Australia. The system, by the problem definition (see *Section 1.2*), must connect Melbourne, Canberra and Sydney, thus alleviating road congestion and air traffic between these extremely busy routes.

2.1.2 Reliable, convenient & comfortable

In order to ensure reliability, the transportation must establish and adhere to a strict schedule, with very little deviation in journey durations. Although reliability is one of the essential criteria of any transportation system, it is dependent on a variety of operational factors and will therefore not be ensured by the design outlined in this study. Rather than directly assessing reliability in this study, it is assumed that by designing a robust system, this requirement will be easier to satisfy during operation; or conversely, if a design has a high degree of uncertainty in the design phase there is likely to be uncertainty in the operation of the system and therefore the system will be less reliable.

Further, the system must also be convenient and comfortable. The convenience of the system will be primarily described by the location of stations and the duration of travel, as well as the time spent through security checks and obtaining tickets. The comfort of passengers is dependent on the experienced vibrations, air flow and temperature regulation, seat comfort, lavatory access, food and water availability, baggage room, disability access and entertainment services. Some of these requirements will not be explored in this study, as outlined in the scope, because they do not affect the operation of the system; however, they would need consideration if either design progressed to a more detailed phase.

2.1.3 Sufficient capacity

It is essential that either transportation system can provide for the vast number of commuters expected to travel in the future. The system must not only account for the number of commuters at completion of construction, but also increased demand due to population growth and increases in the travel market share. A detailed analysis of the expected demand on both transport systems is described in *Section 2.2*.

2.1.4 Health & Safety standards satisfied

As with any new technology, the transportation system must meet the health and safety requirements governed by legislation. This involves a variety of factors including thorough security regulation to prevent external influences on the system, as well as intrinsic system properties that may influence the commuters, including dangerous vibration or noise levels and

insufficient spacing between carriages or capsules. The factors intrinsic to the system can be accounted for in the design phase and will be considered during the scoping of the functional requirements. There will be safety and emergency systems in place, but these are out of scope of this study, as defined in *Section 1.6*.

2.1.5 Environmentally friendly

Due to an increasing global focus on environmental impact, it is important that the environmental impact of the new transportation system produces a net reduction in climate damage. The construction of the route will require land clearing and tunnelling which will locally impact the environment. Additionally, the final system will require energy from the grid or some alternative source, both of which will produce carbon emissions as a by-product of either fossil fuel burning or construction of alternative energy supplies, such as wind turbines or solar panels. There is substantial difference in the operational emissions of these different methods, which will need consideration. It is important that the carbon emissions of either system be below the emissions produced by aviation or road travel, normalised by distance and number of passengers. In this study, the environmental impact will not be formally analysed as there would be a high degree of uncertainty at this early stage; however, it will be considered throughout the design phase of both systems and considered when making design decisions.

2.1.6 Affordable

Any new mode of transport can only effectively compete if it offers either substantial time reduction or a reduction in cost; hence, it is important that the transport system offers a competitive cost per kilometre travelled. Although the new system will take a portion of the road market share, its primary competitor will be aviation travel and, therefore, ticket prices should be chosen based on domestic plane journeys between Sydney, Canberra and Melbourne. The cost of constructing each system will be assessed in *Chapter 5*, as well as ticketing prices and the estimated returns of the system.

2.2 Expected Demand

2.2.1 Methodology

The HSR Phase 2 report had a detailed assessment of the expected number of commuters travelling between inter-city and regional stations, with the HSR implemented, and without it, by 2065. The report's rigorous study, which included international surveys and a detailed analysis of population and commuter growth, was used as a basis for the demand on Hyperloop predictions (AECOM, 2013). There is more variability in this study, due to limited resources and an inability to predict customer reaction to the Hyperloop; however, by making reasonable assumptions, I postulate the predicted volume of commuters to be sufficiently accurate for the purposes of a comparison study.

2.2.2 Assumptions & Justification

1. The improved transport accessibility will induce more commuters. The HSR induction percentage was calculated from the HSR Phase 2 Study and the Hyperloop was predicted to have from 0-10% greater induction capacity (see *Appendix 1.1*). The additional anticipated increase was due to the Hyperloop being a new technology with greater performance potential.
2. For short regional trips, automobiles hold the monopoly (see *Figure 2*), which will likely remain the case, even with the inclusion of a new transportation method, as the journey time is not significantly reduced over short distances due to boarding requirements, including security checks and ticketing. Hence, it was assumed that the market shares

- of HSR and Hyperloop will be low for short regional trips, with Hyperloop only expecting to hold a greater market share of 0-5%.
3. For inter-city transport and long regional trips, air transport holds the monopoly of the market (see *Figure 2*) and due to comparative travel times, the HSR and Hyperloop are predicted to acquire a significant portion of this market. The Phase 2 HSR study forecast how much the market share would be between each section of the route and, from these results, the Hyperloop was predicted to be 0-15% greater than HSR due to shorter journey durations and greater convenience.
 4. The number of commuters travelling in one direction is equivalent to the number of commuters travelling in the opposite direction. For instance, if the number of commuters travelling between Melbourne and Sydney is 18.8 million per year, 9.4 million commuters board at Sydney to travel to Melbourne every year, and vice versa. This assumption will not be true at all times, but should be accurate when averaging over the duration of a year.
 5. There will be no significant changes to the air travel industry, such as electric planes or significantly cheaper flights.

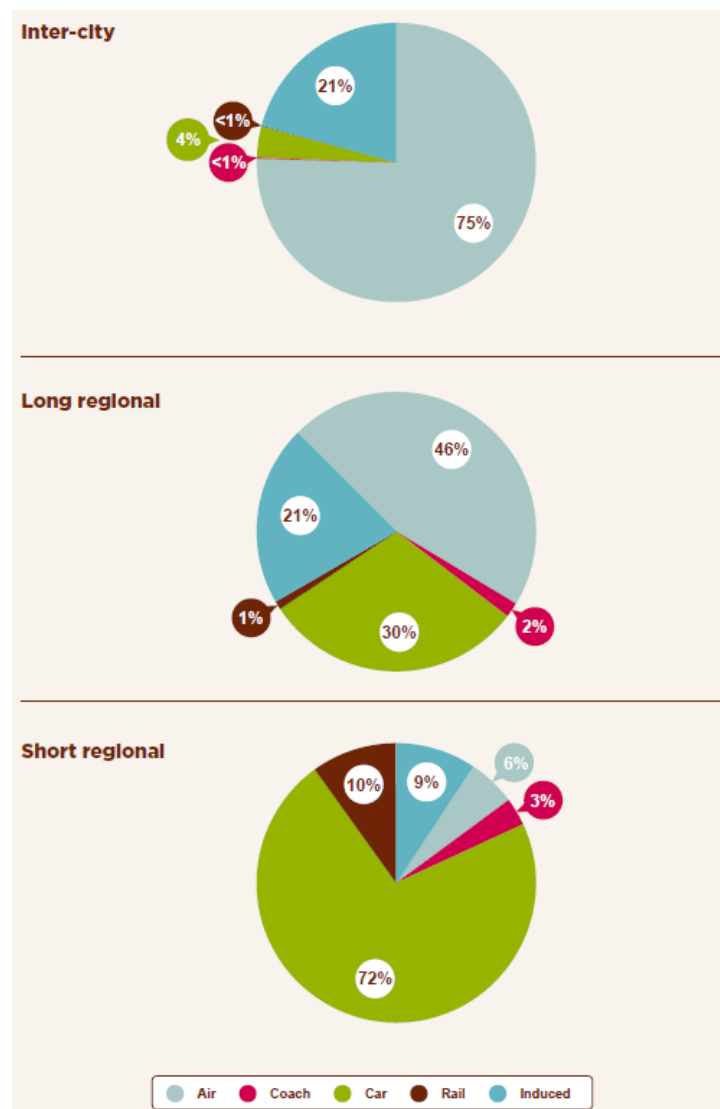


Figure 2: Source of HSR travel demand (trips) in 2065 by distance segment (AECOM, 2013)

2.2.3 Results

2.2.3.1 High Speed Rail

The predictions for the number of commuters travelling per day between each area using HSR are given in *Table 3* below.

Table 3: HSR commuter transfer breakdown by region (AECOM, 2013)

Station	No. of million commuters boarding per year	No. of million commuters disembarking per year	On-board commuters [million]	No. of commuters per day
<i>Sydney</i>	14.465	0	14.465	39630
<i>Intermediate 1*</i>	1.490	1.345	14.610	40027
<i>Canberra</i>	1.680	2.835	13.455	36863
<i>Intermediate 2*</i>	2.330	1.515	14.270	39096
<i>Melbourne</i>	<i>END OF LINE</i>	14.270		

* Intermediate 1 and Intermediate 2 represent the collection of stations between Sydney and Canberra and between Canberra and Melbourne, respectively.

The HSR Phase 2 Study performed a risk and sensitivity analysis and found the 95% confidence interval of the commuter numbers to have a low case of -22% and a high case of +33% deviation from the predictions outlined in *Table 4*. Hence, the HSR must have a daily capacity between the ranges outlined in *Table 2*, by 2065.

Table 4: HSR commuters per day breakdown by region

Station	No. of commuters per day
<i>Sydney</i>	30912-52708
<i>Intermediate 1</i>	31221-53236
<i>Canberra</i>	28753-49028
<i>Intermediate 2</i>	30495-51998
<i>Melbourne</i>	<i>END OF LINE</i>

2.2.3.2 Hyperloop

The lower predictions for the Hyperloop demand are equivalent to the number of commuters travelling by the HSR (see *Table 4*) because the Hyperloop is anticipated to induce more commuters as well as acquire a larger market share than HSR due to the reduction in journey duration.

The upper predictions for the Hyperloop demand are given in *Table 5* below (see *Appendix 1.2* for justification).

Table 5: Hyperloop commuter transfer breakdown by region

Station	No. of million commuters boarding per year	No. of million commuters disembarking per year	On-board commuters [million]	No. of commuters per day
<i>Sydney</i>	20.679	0.000	20.679	56656
<i>Intermediate 1*</i>	2.380	2.722	20.337	55719
<i>Canberra</i>	2.432	4.324	18.445	50535
<i>Intermediate 2*</i>	5.075	2.306	21.214	58122
<i>Melbourne</i>	END OF LINE	21.214		

Therefore, the Hyperloop must have a capacity between the ranges outlined in Table 6, by 2065.

Table 6: Hyperloop commuters per day breakdown by region

Station	No. of commuters per day
<i>Sydney</i>	39630-56656
<i>Intermediate (SC)</i>	40027-55719
<i>Canberra</i>	36863-50535
<i>Intermediate (CM)</i>	39096-58122
<i>Melbourne</i>	END OF LINE

2.3 System Constraints

There are a number of requirements, defined by the project definition, which both the Hyperloop and the HSR must satisfy; these are as follows:

1. The route defined in the Phase 2 study for the HSR will be used for both transportation systems, this ensures that the construction costs, the trip duration and a variety of other aspects are consistent between each method and thus the comparison maintains validity. The Hyperloop has constraints on the maximum radius of curvature and inclination which it can traverse which may not be satisfied by the Phase 2 route; however, this constraint will be neglected in this study and recommended as a future investigation.
2. The stations outlined in the Phase 2 study must also be the same for both transportation systems for consistency of the comparison.
3. The Phase 2 Study estimates a variety of values, including commuter predictions, based on an operational date of 2065, so this operational date will be assumed for both systems.
4. The system must be reliable and consistent, in regards to scheduled departures, arrival times, passenger comfort, etc.
5. The capsule or carriage must satisfy typical transport requirements, such as baggage room, disability allowances, lavatory availability, comfort, hygiene, etc.
6. Safety mechanisms will need to be in place, such as emergency braking and exits, security checks and available assistance in emergencies.

Requirements 4, 5 and 6 are difficult to evaluate in an early phase design study, especially in regards to the Hyperloop, but they will be essential in future development of both systems and are mentioned here for completeness. These requirements will be addressed again during concluding remarks to ensure they were not violated during the design phase of the study.

2.4 High Speed Rail Functional Requirements

The second stage in Axiomatic design, following the analysis of the customer domain, is to create a list of functional requirements that each system must satisfy. The functional requirements of both systems are assessed below.

2.4.1 Trip Duration

The Phase 2 study described a number of requirements which the HSR must satisfy, including the trip duration, which states the duration of a trip between Melbourne to Canberra is 2 hours and 10 minutes and between Canberra and Sydney as 1 hour and 4 minutes. This duration assumes no non-capital city stops (AECOM, 2013). The trip duration requirement for HSR is that it must satisfy a journey time between Sydney and Melbourne of less than or equal to 3 hours and 19 minutes (equivalently 199 minutes), allowing for a 5-minute stopover in Canberra.

2.4.2 G-Forces

There are some physiological effects of high G forces, resulting from acceleration in any of the three spatial dimensions: x, y and z. The increased G acceleration necessitates that the heart and cardiovascular system respond to keep blood flowing and maintain consciousness, potentially leading to feelings of light-headedness or in severe cases, blackout (FAA, 2016). This response is typically a result of G forces in the vertical direction, z, because the human body has a higher tolerance to horizontal G forces, but forces in the x and y direction can also cause discomfort or motion sickness as the body adapts to shifts in applied forces (Beaudette, 1984; Tyson, 2007).

A commuter will be subject to both linear forces during the acceleration and deceleration stages of the trip, as well as radial, or centripetal, acceleration when the pod travels around a curvature in the tube. Assuming that linear acceleration will only occur in straight segments of the tubing, radial and linear forces can be treated as two independent interactions. The maximum horizontal G-force a human can sustain without significant discomfort over short periods of time is 0.5G; hence, this will be the requirement in the linear direction (CNBC, 2013; Musk, 2013). The route is specified by the Phase 2 study and analysis of route curvature is difficult and time exhaustive; therefore, it is out of scope of this study. *Figure 3* below displays the direction of the respective forces in both the x and y-direction.

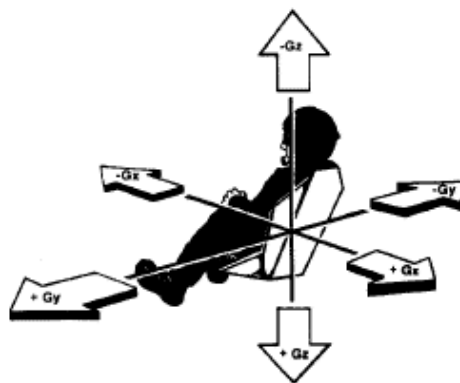


Figure 3: G-Forces in the x, y and z direction (Jedick, 2013)

The assumption that there will be no excessive radial acceleration during curved sections of the route may be an over-simplification. However, as the route is out of the scope of this study (defined by the HSR Phase 2 route), coupling these two interactions is quite complicated in the design phase. Furthermore, one of the design parameters discussed later is route breakdown, which involves separating the route into slow, medium and fast zones, based on location and

route curvature. This affects several functional requirements; hence, the radial acceleration is assessed in this later phase, without creating dependence on different functional requirements.

2.4.3 Vibrations

There are a variety of workplace standards for limitations of vibrations; however, these are typically related to the physical strain the body is under and do not account for motion sickness resulting from prolonged exposure to vibratory forces (BS ISO 2631-1, 1997). Ignoring the effects of noise, temperature and other unaccounted-for travelling conditions that can increase susceptibility to motion sickness, a model can be defined which allows estimation of the motion sickness incidence. Introducing the motion sickness dose value, MSDV, as a function dependent on the frequency weighted accelerations, a_w and the duration of vibration exposure, T_0 (Cheung & Nakashima, 2006)

$$MSDV_z = a_w T_0^{\frac{1}{2}}$$

The experienced vertical accelerations are adjusted by a factor w_k , a frequency dependent weighting provided by an international standard. The *Illness Rating* can then be estimated by (Cheung & Nakashima, 2006)

$$IR = \frac{1}{50} MSDV_z$$

This value allows qualification of the on-board motion sickness responses, per *Table 7*.

Table 7: Illness Rating values to assess motion sickness (Helbling Technik AG, 2013)

IR	Explanation
0	I felt all right
1	I felt slightly unwell
2	I felt quite ill
3	I felt absolutely dreadful

To ensure comfort of the passengers, the chosen requirement is that the IR remain below 1.

Another vibratory requirement is that the frequency is constrained below 0.5 Hz due to the impact of higher frequencies on a commuter's health, comfort and perception. In this study, the *Illness Rating* will be the only functional requirement related to vibration, as it incorporates the comfort and health requirements (i.e. if the *Illness Rating* requirement is satisfied, the health and comfort requirements are also satisfied); thus maintaining independence of the functional requirements (BS ISO 2631-1, 1997; Helbling Technik AG, 2013). This functional requirement helps to satisfy the comfort needs of the customer.

2.4.4 On-board noise

Hearing can be affected by prolonged exposure to moderately high noise levels; accordingly, it is a health requirement of any transportation system that the commuter exposure to noise is monitored and maintained below the established standards. During acceleration, the noise levels are anticipated to be greater than those whilst cruising, but the acceleration period is anticipated to be relatively short, similar to a commercial aircraft, and difficult to assess without experimental measurements; hence, the noise in these stages will be neglected for this study. Workplace standards require that exposure to 85 dBA be no longer than 8 hours in a 24-hour period (U.S. Department of Health and Human Services, 1998); therefore, assuming the only

people exposed to the capsule sound for greater than a single, or return, trip duration are rail technicians who work eight-hour shifts, HSR cabin's internal noise must not exceed an average of 85 dBA.

2.4.5 External noise

To determine a metric for constraining the noise exposure outside of the tubing as the cabin passes, HSR and the Hyperloop will be equated with low flying aircraft, which generate around 100 dBA at ground level. As such, the requirement is that the produced external noise be maintained below 100 dBA (Schulte-Werning, et al., 2007).

2.4.6 Power

High speed trains consume a large amount of power, mainly for propulsion using electric traction motors. The Phase 2 study predicts that by 2065 the high speed line will require 1800 MW of power to operate (AECOM, 2013). Hence, the HSR system must provide at least 1800 MW, by 2065.

2.4.7 Passengers per day

The HSR must cater for a large volume of daily commuters, which is characterised by two components; firstly, the frequency of train departure and secondly, the train passenger capacity. A commuter analysis was undertaken to predict the demand on the HSR in 2065 (see *Section 2.2*) and it was found that the HSR would need to transport an upper limit of roughly 53,200 people per 18-hour operational day. The frequency of travel is difficult to estimate or minimise without operational considerations; consequently, the requirement for HSR is set to the number of passengers per day, rather than the passengers per trip.

The demand expectations offer only a yearly average and do not account for peak seasons of travel, such as before and after national holidays, nor do they account for daily peak commuter traffic, likely to occur early morning and late afternoon. This is a limitation on this requirement; however, a far more detailed survey and analysis will be required to scope these design aspects, and so they were omitted from the study; instead, annual means based on assumptions outlined in *Section 2.2.2* were used.

2.4.8 Summary

The functional requirements outlined above have been summarised in *Table 8* below.

Table 8: HSR Functional Requirements

Function	Requirement
Trip Duration	$T_{\text{SYD-CANB-MELB}} < 199$ minutes
G-forces	$F_G < 0.5G$
Vibrations	$IR < 1$
On-board Noise	On-board Noise < 85 dBA
External Noise	External Noise < 100 dBA
On-board Power	Power available > 200 kW
Passengers per day	53200

Axiom 1 of axiomatic design, the independence axiom, is satisfied because none of the functional requirements are dependent on another requirement. The functional requirements for HSR were significantly easier to interpret and quantify than the Hyperloop as HSR is not a new mode of transport and had less uncertainty in the non-repeated requirements, such as trip duration.

2.5 Hyperloop Functional Requirements

2.5.1 Trip Duration

Musk et al.'s (2013) Alpha study states that the expected duration of a trip between Los Angeles and San Francisco, a 560km journey, is 35 minutes (Musk, 2013). Based on timing assumptions and distance extrapolations, the duration of a trip between Melbourne to Canberra is approximately 40 minutes and between Canberra and Sydney is 25 minutes. Hence, the requirement is that the Hyperloop can travel between Sydney and Melbourne, along the same route as the HSR and with no non-capital city stops, in 70 minutes, allowing for a five-minute stopover in Canberra.

This requirement has a degree of uncertainty because the method used for making the estimations was rather imprecise; however, it is an essential requirement as it provides an objective for the design phase of the study, and must therefore be specified. Furthermore, it is likely that there will be a high degree of uncertainty in the design speed specified in Musk et al.'s (2013) design, due to the immaturity of the technology; hence, it is unreasonable to have a precise duration estimate at this stage.

2.5.2 G-Forces

By the reasoning described in *Section 2.4.2*, the G-forces experienced by the passengers must not exceed 0.5G. The reasoning from *Section 2.4.2* is still valid in the Hyperloop case as the requirement was determined based on verified standards and was independent of HSR itself; this is a similar case to the requirements related to vibrations, on-board noise and external noise.

2.5.3 Vibrations

By the reasoning described in *Section 2.4.3*, the illness rating induced by vibrations must not exceed 1.

2.5.4 On-board noise

By the reasoning described in *Section 2.4.4*, the internal capsule noise must not exceed 85 dBA.

2.5.5 External noise

By the reasoning described in *Section 2.4.5*, the external noise must not exceed 100 dBA.

There is a flaw in this requirement in that the Hyperloop capsules may be departing as frequently as every 30 seconds (see *Section 2.5.7*); as a consequence, people working or living near the Hyperloop line will be subject to these high noise levels regularly. This is a potential health and environmental concern, which would require extensive political debate to resolve issues associated with route selection, landholders, travel speed through cities, and other factors. Proposing a resolution to this issue is therefore beyond the scope of this study.

2.5.6 Capsule Pressure

The capsule must be pressurised due to the low pressure of the tube. The capsule can be pressurised in much the same way as an aircraft, through recirculating capsule air and compressing and cooling external air before mixing it with recirculated air from the cabin (Larson, 2002). This is one of the most important requirements as it ensures that the passengers have sufficient air availability and are not exposed to high pressure differentials which could result in calamitous incidents. There will, of course, be safety contingencies; however, the study will be based on an assumption that if these contingencies are required, the design has failed to fulfil the relevant functional requirement.

Aircraft cabins are pressurised to a typical range of 75 to 81kPa, which is equivalent to atmospheric pressure at altitudes of 2400 m and 1800 m, respectively (World Health Organization, 2016). Again equating the Hyperloop with typical aircraft behaviour, the requirement is that the pressure in the capsule be above 75kPa while not exceeding sea level pressure of 101.25kPa. The pressure must also be stable and not fluctuating between these values, to ensure well-being of the passengers.

2.5.7 Passengers per trip

The Hyperloop must cater for the large volume of daily commuters, which is characterised by two components; firstly, the frequency of capsule departure and, secondly, the capsule passenger capacity. A commuter analysis was undertaken to predict the demand on the Hyperloop in 2065 (see *Section 2.2*) and it was found that the Hyperloop would need to transport an upper limit of roughly 58,100 people per 18-hour operational day. By the constraint of trip frequency, which is specified as every thirty seconds in Musk et al.'s (2013) Alpha Study, the pods must have enough capacity for at least 27 people. This requirement has similar limitations to HSR demand predictions as it neglects peak traffic demand.

2.5.8 Power

There are a variety of on-board energy sinks that will require power, including the compressors, air-conditioning, lighting and passenger entertainment services. The largest energy requirement is the compressors, which firstly provide compression of the tube air to manipulate external flow and through additional compression helps to generate air bearings. From Musk et al.'s (2013) Alpha study, the total compression requires 325 kW of power. Some of the compressed air will be used to cool the capsule-air, potentially using vapour compression refrigeration commonly implemented in aircrafts. The power consumption of this secondary compression is difficult to estimate without design specifications; however, allowing 100 kW of additional compression power should suffice, as the secondary stage should only need a factor of the initial 325 kW. (Cengel & Boles, 2010; Prasad, 2011).

In-flight entertainment systems typically consume 100W of power per passenger (Deluca & Rozenblat, 2008), therefore, assuming the capsule's carry about 30 people, the entertainment systems consume approximately 3 kW of power. Most aircrafts implement LED light bulbs, which consume roughly 1 watt each (McKenna, 2014); as such, lighting, regardless of how many bulbs are needed, will have a minimal impact on power requirements. A similar conclusion can be made regarding radio communication, fans for air circulation, sanitation systems, emergency lighting, automatic doors and various other low energy demand appliances.

To account for unknown variables and uncertainty in the power requirements, an additional 25% of power consumption should be allowed for. Thus, the Hyperloop must provide at least 535 kW of power, whether through solar panelling, batteries, an on-board generator or connection to the grid. This requirement may be an over-estimation of the power requirement of the Hyperloop; however, over-estimating in this stage allows for more certainty that the design will meet power demands as the technology develops and new power sinks are potentially introduced.

2.5.9 Summary

The functional requirements outlined above have been summarised in *Table 9* below.

Table 9: Hyperloop Functional Requirements

Function	Requirement
Trip Duration	$T_{\text{SYD-MELB}} < 65$ minutes
G-forces	$F_G < 0.5G$
Vibrations	$IR < 1$
On-board Noise	On-board Noise < 85 dBA
External Noise	External Noise < 100 dBA
Capsule Pressure	$75 \text{ kPa} < P < 101.25 \text{ kPa}$
Passengers per trip	Capsule Capacity > 27 people
Capsule Power	Power available > 535 kW

Axiom 1 of axiomatic design, the independence axiom, is satisfied because none of the functional requirements are dependent on another requirement. Axiomatic design was challenging to implement for the Hyperloop as there is a high degree of uncertainty in the technology. It is difficult to accurately predict what the system will require when there is such a broad range of potential design ideas. However, by basing most values from literature values for equivalent modes of transport, it was possible to determine meaningful design ranges, which allows a basis for the subsequent design stage.

3 Design Parameters

3.1 High Speed Rail Design Parameters

3.1.1 Overview

A condition of axiomatic design is that the functional requirements can be mapped by the design domain, via a design matrix, A , such that:

$$[FR] = [A][DP]$$

In the case of HSR, the functional requirements defined in *Section 2.4*, can be mapped by the following design parameters:

$$\begin{bmatrix} \text{Power} \\ G - \text{Forces} \\ \text{External Noise} \\ \text{Vibrations} \\ \text{Duration} \\ \text{On-board Noise} \\ \text{Capacity} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & X & X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & X & 0 & 0 \\ 0 & X & X & X & X & X & 0 \\ 0 & X & X & X & X & 0 & X \end{bmatrix} \begin{bmatrix} \text{Power Supply} \\ \text{Acceleration Mechanism} \\ \text{Track/Train Specifications} \\ \text{Carriage Design} \\ \text{Route Breakdown} \\ \text{Active Noise Control} \\ \text{Station Design} \end{bmatrix}$$

The design matrix, A , is lower triangular, which represents a decoupled design. A decoupled design is one which satisfies the independence of FRs, but only through applying the correct design sequence (Suh, 2001). For instance, in this case, the G-forces requirement must be satisfied before the external noise requirement. This is the case because the acceleration mechanism will be designed to satisfy the G-forces condition before being used to satisfy all subsequent requirements.

These design parameters incorporate a variety of physical components of the system, which are described throughout this chapter.

To clarify how each design parameter is relevant to the mapped functional requirements, each parameter is discussed briefly below.

Power Supply:

- The power requirement of HSR can be solely satisfied by the power supply to the system, which will likely be through a traction substation converting power from the grid to an appropriate voltage, current and frequency to supply the railway and trains with traction current.

Acceleration Mechanism:

- This parameter defines how the train will reach maximum speed, as well as how it will decelerate. Consequently, it influences the G-forces requirement, as well as any other speed dependent requirements.

Track/Train Specifications:

- This design component, along with the acceleration mechanism, constrains the top speed of the train. Hence, the external noise requirement, which will only be investigated at max speed (i.e. if it is satisfied at max speed, it is satisfied at all speeds) is wholly described by these two design parameters. The noise generated is dependent only on the speed of travel and the train and rail interaction.

Carriage Design:

- This component details the train's suspension, insulation, seating arrangements and any other internal characteristics.
- By defining the train specifications and carriage design components separately, it will ensure that each of the design parameters is clear, as well as ensuring independence between external noise and vibrations, which are typically coupled together.
- The carriage design will help reduce the vibrations that the passengers experience, which is governed primarily by the speed of travel and the track type. It also incorporates insulation which acts as a passive noise control against external noise and thus reduces on-board noise. Additionally, it defines the seating capacity which helps to define the overall train capacity.

Route Breakdown:

- The route is not a design parameter; rather it is part of the problem definition and hence constrains the system. Each section of the route, however, can be broken down into sections of different speed depending on a variety of factors including the angle of the track, the location relative to cities and the presence of tunnels. As there is some freedom in defining which aspects of the track represent fast, medium or slow areas, the route breakdown can therefore be *designed*.
- This parameter helps describe the duration of the travel; cabin noise, which is louder in tunnelled or faster sections (i.e. unlike external noise which is loudest at max speed, cabin noise needs to be satisfied both at max speed and in tunnels where some sound will be reflected back at passengers); and the minimum distance between trains, which specifies the physical limitation of departure frequency and, consequently, daily capacity.

Active Noise Control:

- Active noise control reduces the on-board noise and is commonly used in high speed trains. It acts in conjunction with the carriage design which passively controls the interior noise.
- This parameter is used to satisfy the cabin noise functional requirement and maps exclusively to this requirement.

Station Design:

- Station design will be kept minimal in terms of detail because the station design does not explicitly affect the train's function; however, for determining trip frequency, which leads to daily commuter capacity, it is essential that the station efficiency is accounted for. This will be defined by the number of tracks and the time to service and redistribute passengers at each station; the latter being similar to a process variable, which is out of scope of this study, but will be estimated based on a literature review.
- The daily capacity is also dependent on the minimum safe distance between trains, which is dependent on the speed of travel (i.e. acceleration mechanism, train/track specifications and route breakdown) and the seating capacity (i.e. carriage design).

As each design component is addressed, in descending order of the DP matrix, a more comprehensive understanding of what each design parameter encompasses will be evident. It

should also be noted that the design outlined in the Phase 2 study encompasses the majority of these components and although various options will be discussed in this study, the components specified in the Phase 2 study will be nominated because they were considered robust by a professional team of engineers. Similarly, for the Hyperloop design parameters, although there is a lot of missing information, the Alpha study design components will be selected if no flaws are apparent throughout the design considerations.

3.1.2 Power Supply

A traction power supply system, comprising traction power substations, switching stations and paralleling stations, is the railway electrical distribution energy network used to power high speed trains. The Phase 2 study specifies a $2 \times 25\text{kV}$ 50Hz autotransformer feed configuration for the traction electrification system since this is the modern standard for HSR. The study assumed that the power supply would be provided by the 25kV 50Hz transformers every ten kilometres, with power feeder stations every 60 kilometres (AECOM, 2013); hence, these design parameters were used in my design. The power requirement and the power supply design were both specified in the Phase 2 report, therefore, it is assumed that the system range of the power supply will be greater than 1800MW by the year 2065.

This design parameter is not as detailed as the subsequent components because it is a standard power supply system, widely established internationally and there are limited, proven alternatives available.

3.1.3 Acceleration Mechanism

3.1.3.1 Acceleration Basics

High speed trains are powered by electric, traction motors, which involve a magnet rotating within a changing magnetic field. The rotating component is a permanent magnetic dipole and is known as a rotor, and the fixed electromagnetic field, generated by either an alternating current (AC) or direct current (DC) electric current, is a stator. Several different traction motors are available on the market; with varying performance characteristics. The first TGV was fitted with a DC motor, with a unit power of 535 kW; later, the synchronous wound motor took over the market with a unit power of 1130 kW. In the early 2000s, the asynchronous motor was introduced, which was more economical and robust than the synchronous motor. Recently, the permanent magnet motor, which offers the highest power density of the aforementioned motor types (Alstom, 2013), has been gaining market share. The properties of these motors are explored more explicitly below.

The fundamental difference between any motor is whether it has DC or AC supply. AC is widely considered better than DC because it can be distributed at high voltages with a small size conductor wire, unlike DC, which requires a larger wire and, commonly, an additional rail. AC also requires fewer feeder substations over the same distance, therefore reducing construction and operational costs. DC motors have historically been the preferred type due to their performance characteristics; however, with the advancement of AC motor technology, the market has shifted towards AC. Recent development of DC permanent magnet motors is threatening to compete with AC motors, but they are currently less established in the high speed market (Railway Technical, 2016).

3.1.3.2 DC Motor

The oldest type of traction motor, DC motors, utilises a direct current which is passed through the motor circuit, generating an electromagnetic field causing the rotor/coil to turn; see *Figure 4*. The stator and rotor are connected in series and referred to as “series wound”. A series wound

circuit has low resistance; hence, by Ohm's Law, when high voltage is applied the circuit current is high. This results in a high torque making it ideal for starting a train. However, the applied current needs to be limited to ensure the motor is not damaged and that the driving wheels do not slip if the adhesion is exceeded (Railway Technical, 2016).

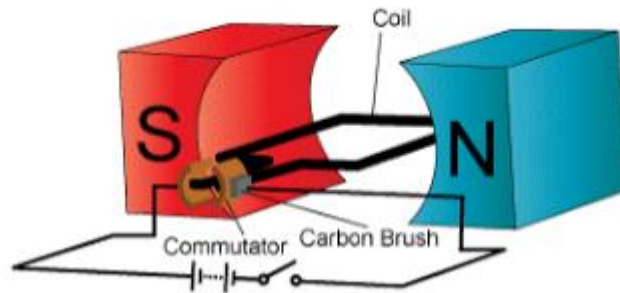


Figure 4: DC Motor Configuration (SPM Physics, 2008)

France's first high speed line, the LGV Sud-Est, used DC traction motors and was capable of speeds up to 380 km/hr, with a nominal speed of 300 km/hr (Revolv, 2016).

3.1.3.3 Synchronous Motor

Synchronous motors use alternating current to feed the stator and are designed such that the speed of the rotor is the same as the rotating magnetic field, hence the term synchronous. As a result, synchronous motors retain their speed irrespective of the driving load. The major benefit of this design is that it is twice as powerful as the DC motor, consequently offering greater performance potential (Alstom, 2013; Teja, 2012). However, synchronous motors are not self-starting and therefore require a primer or an external motor to initially start the rotor rotation until the rotor turns with synchronous speed (Electrical4U, 2016). A generic synchronous motor configuration is shown in Figure 5.

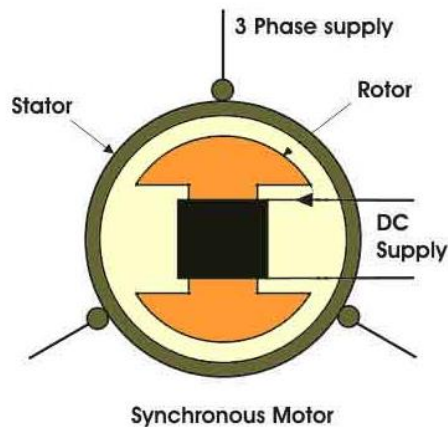


Figure 5: Synchronous Motor Configuration (Electrical4U, 2016)

The synchronous motor was implemented in the TGV Atlantique in 1989 and was capable of speeds up to 300 km/hr (Alstom, 2013).

3.1.3.4 Asynchronous Motor

The asynchronous motor, or the induction motor, superseded the synchronous motor, as it offered a more robust and cheaper design with its rotational speed more easily varied. The asynchronous motor uses alternating current, but the rotor speed is not equivalent to the magnetic field speed. No current flows through the rotor; rather, the current generating the

magnetic field in the stator causes the rotor to turn. This requires three AC conductors, each conducting one third into the cycle period, known as three phase supply, which is the key factor leading to the more robust and economical design, due to more material and design flexibility (Railway Technical, 2016).

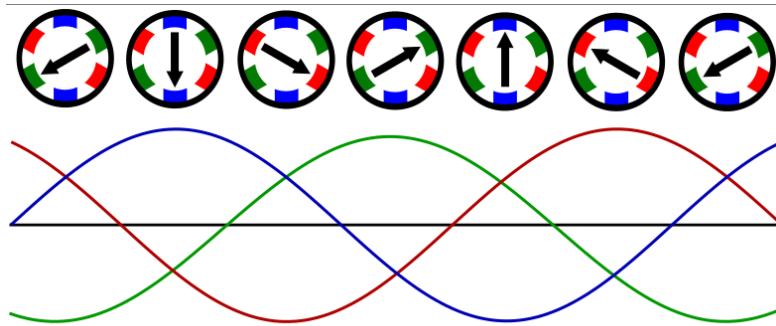


Figure 6: 3-Phase Power Supply

The asynchronous motor has been implemented in a variety of high speed trains, among which are the SNCF TGV POS and the TGV TMST, which both quoted speeds of up to 320-330 km/hr, with the former reaching 574.8 km/hr in 2007 (BBC, 2007; Eurostar, 2003).

3.1.3.5 Permanent Magnet Motor

The synchronous motor recently made a return to the market in the form of the permanent magnet motor, whose rotor does not consist of a winding fed by an electric current, but rather by a series of magnets with a constant magnetic field and a stator fed by a DC current. This design offers a quieter, more compact and higher power density motor than any available alternative (Alstom, 2013).

It is used in the AGV, which offers speeds of up to 360 km/hr (Railway Technology, 2012).

3.1.3.6 Maglev

An alternative to conventional HSR is *Maglev*, diminutive of magnetic levitation, which uses magnetic interactions to suspend and propel the train forward. It was first made commercially operational in 1984, at the Birmingham International Airport in the United Kingdom, but later closed due to maintenance issues and ongoing costs. China and Japan have expressed interest in the technology with China investing large amounts of capital into a Maglev designed to operate at 500 km/hr, but the technology has not developed much further. Although it offers greater speeds, the cost and technological risks, including construction, maintenance and practicality, are too great and were not considered in the Phase 2 study, nor my design (AECOM, 2013).

3.1.3.7 Design Choice

Any of these motors could potentially be used for the Australian HSR as they have been implemented in a variety of trains all capable of accelerating the train to high speeds. The functional requirement which must be satisfied is that the linear G-forces must not exceed 0.5G.

The Shinkansen N700, which offers the highest acceleration rate of all Shinkansen trains, accelerates up to 2.6 km/hr/s, or equivalently, 0.074G (Everything Explained, 2016). Since this high speed train, which offers a comparatively high acceleration rate, is well below the functional requirement, the motor choice will satisfy the requirement irrespective of motor type. Given that the asynchronous motor is more widely established than the competing permanent magnet motor, it was selected for the design in this study.

3.1.3.8 Deceleration

The functional requirement relating to G-forces must also be satisfied when decelerating or braking. Braking rates differ from system to system; however, it is highly improbable that 0.5G would be exceeded by a high speed train as this is equivalent to a train going from 300 km/hr to 0 km/hr in under 17 seconds; such a high deceleration rate would overcome adhesion of the wheels and would result in the carriage sliding, rather than slowing to rest. Hence, the functional requirement is satisfied regardless of the brakes used (Loumie & Junbauer, 2005; Costache, 2012).

There are a variety of braking mechanisms utilised in high speed trains, which all involve a variety of design details. The Phase 2 Study specifies that regenerative brakes are assumed because they offer energy efficiency improvements, hence they will be used in the design outlined in this study (AECOM, 2013). Regenerative braking involves sending the captured kinetic energy back to the power source by reversing the terminals on the traction motor, consequently reducing the power demand by up to 20% (Woodford, 2015). Regenerative braking is compatible with asynchronous motors, so this does not conflict with the previous motor specification (Electrical4U, 2016).

3.1.4 Track/Train Specifications

3.1.4.1 Track Type

There are two primary track types implemented in high speed rail, namely ballast or slab track. Ballast is the more traditional track structure, consisting of rails and sleepers above and below ballast, usually in the form of crushed stone. Ballasted track is relatively quick and cheap to install; however, due to its nature, the track will move under load, which necessitates ongoing maintenance to restore the line and level and, potentially, ballast replacement. Ballast has been used for high speed rail; however, slab track is typically preferred. Slab track consists of rails directly connected to concrete slabs, rather than to sleepers in ballast. The rigid concrete slabs provide greater stability and little maintenance, with a higher upfront capital cost. Slab tracks have a design life of at least 60 years, compared to the 15-year design life ballast offers, and can be more easily designed to meet noise and vibration requirements by balancing acoustic performance and rail stability (RailSystem, 2015). Ballast and slab tracks are displayed in *Figures 7 and 8*, respectively. The Phase 2 study specifies that slab track will be used for the Australian HSR, hence it will be used in this study (AECOM, 2013).

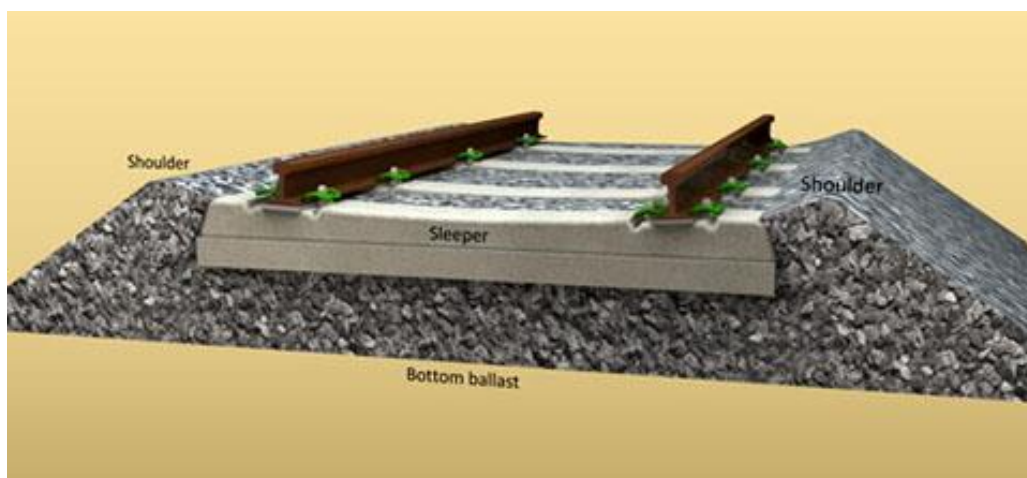


Figure 7: Ballast Track (RailSystem, 2015)

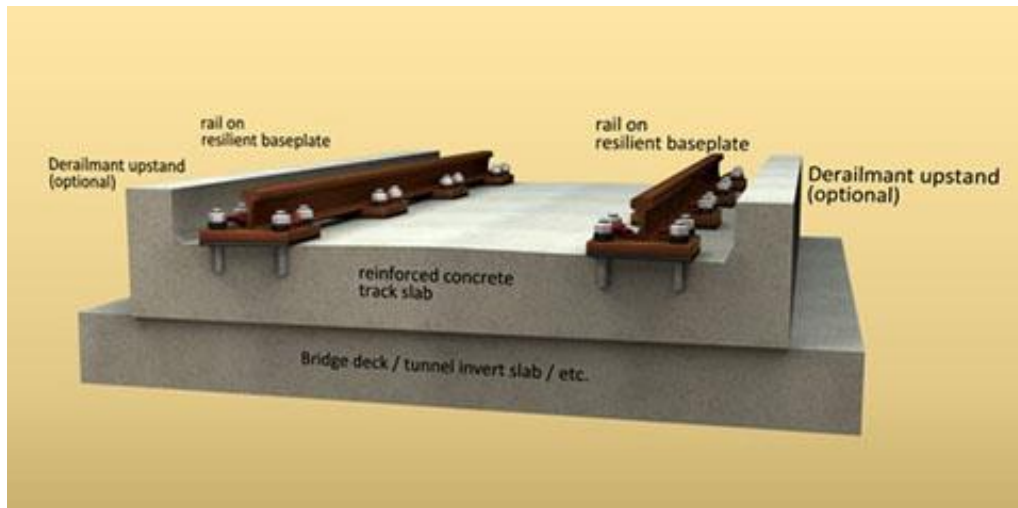


Figure 8: Slab Track (RailSystem, 2015)

3.1.4.2 Track Gauge

Track gauge is the spacing of rails on the railway line, measured between the inner faces of the rails. All rolling stock on the line must have the same track gauge. The international standard track gauge is 1435 mm and it is specified in the Phase 2 study that the standard will be used to enable procurement of standard rolling stock (AECOM, 2013; Farlex, 2011). Using non-standard track gauge introduces unnecessary risk and uncertainty in the design, hence, the standard gauge will be used in my design.

3.1.4.3 Rolling Stock

Internationally, there is a multitude of train sets (a set of railroad carriages), or rolling stock, which could be acquired and implemented in Australia. Rather than discuss the numerous options, I will address the criteria that the train must satisfy and then select an existing train model which most strictly satisfies these requirements. The Phase 2 study calls for a train 200 metres in length (with the option of 300 metres as the line develops), with electrical regenerative braking and a maximum operating speed of 350 km/hr. There are a variety of other specifications for the rolling stock, but they are fairly generic and cover comfort, accessibility, convenience, reliability and security, all of which were deemed out of scope of this design as they do not directly affect the train's performance, as described in *Section 1.6*. Additionally, the train must use an asynchronous motor for propulsion, as designated in *Section 3.1.3*, operate on slab track (*Section 3.1.4.1*) and be powered by two 25kV 50Hz autotransformers (*Section 3.1.2*).

After assessing the variety of options, it was decided that the Chinese CRH3C, or alternatively the Velaro CN, will be used in this design. The train is a slight modification of the Velaro 3, a member of the Siemens Velaro high speed train family which is used in Germany, Spain, China, Russia and Turkey. Aside from satisfying all of the criteria outlined above, a Chinese train was chosen because China has quickly become the most established high speed rail nation in the world, evidencing the strength of their product and their ability to construct economical, effective rail lines (Everything Explained, 2016).

Table 10 details the relevant specifications for the CRH3C. Figure 9 displays a photograph of the CRH3C train in Beijing.

Table 10: CRH3C Design Specifications (Gazette, 2007)

Variable	Specification
Max Operational Speed (km/hr)	350
Length (m)	200
Height (mm)	3,265
Width (mm)	3,890
Track Type	Slab
Track Gauge (mm)	1435 (Standard Gauge)
Brakes	Regenerative
Motor Type	Asynchronous
Transmission	AC-DC-AC
Power Supply	2 × 25kV 50 Hz



Figure 9: CRH3C train travelling in Beijing (Suhang, 2009)

3.1.4.4 Train Geometry

The train geometry can affect a variety of factors, including but not limited to: noise generation, weight, accessibility, speed, vibration, drag forces and cost. The geometry of the CRH3C is designated in *Table 10* as 3,265mm in height and 3,890mm in width. There is no evident reason to adjust this geometry for implementation in Australia, hence it will be used in my design.

3.1.4.5 Pass-by Noise

These various design components, from the design matrix, lead to determining of the system's pass-by noise range. It is difficult to predict the noise generated by a high speed train, even with the design specified, as there are a number of variables, including that there are three contributing noise types, namely rolling, equipment and aerodynamic noise. Aerodynamic noise dominates at speeds above 300 km/hr (Cowan, 2016), but even so, estimating this noise by simulation is highly uncertain and potentially meaningless, hence, literature values regarding typical HSR performance will be used to determine the system's pass-by noise range.

The California High-Speed Train study found that the noise generated by trains at 350 km/hr at a distance of 25 metres was approximately 84 dBA, as seen in *Figure 10*. The Phase 2 Study, on the contrary, found that at an equivalent speed and distance the pass-by noise peaks at

approximately 99 dBA, as seen in *Figure 11*. The significant discrepancy between these two values evidences the difficulty in estimating noise generation without experimental results. Noting that both of these evaluations were conducted without a specific rolling stock designated, the model is incomplete. There are no experimental pass-by noise values for the CRH3C readily available. Allowing an additional 10% uncertainty in the values provided in the California HST study and the Phase 2 Study, the system range of the pass-by noise is given by 76 to 109 dBA. This is a substantial uncertainty range, but unfortunately, without more information regarding CRH3C noise generation, the range cannot be viably reduced.

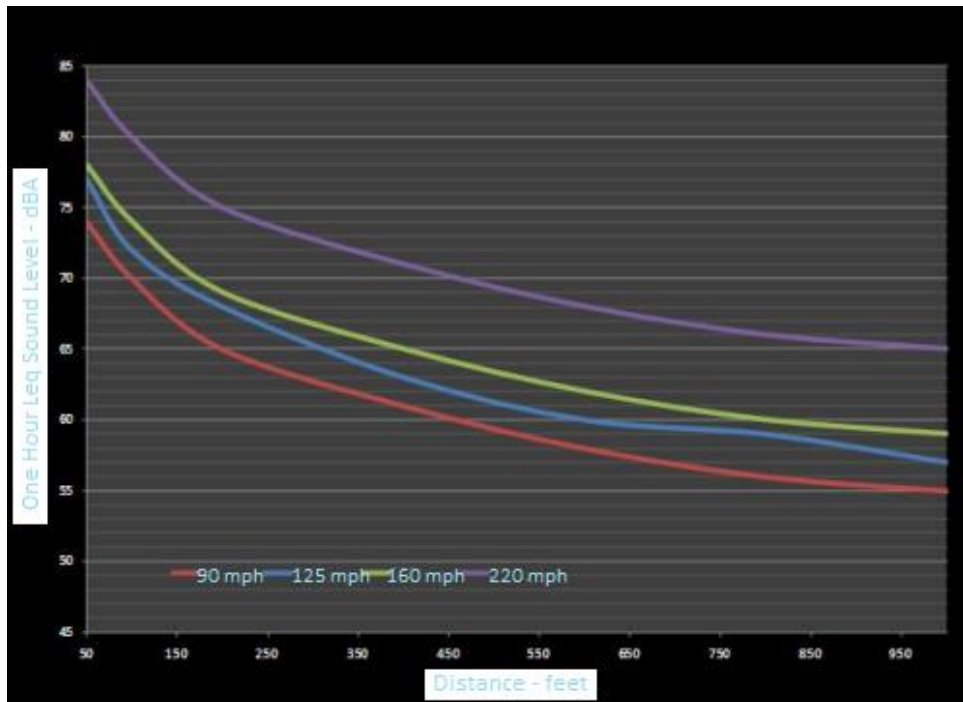


Figure 10: Outdoor HST Noise Levels (dBA) vs. Distance (Wolf, 2010)

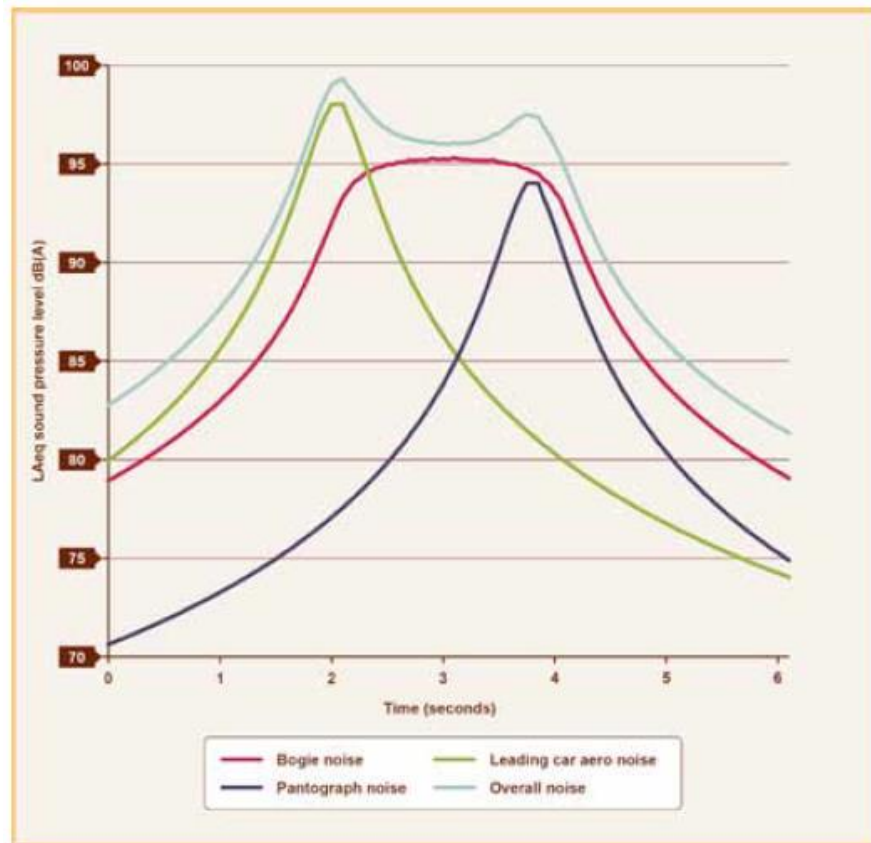


Figure 11: Noise levels for a high-speed train operating at 350kph (AECOM, 2013)

3.1.5 Carriage Design

Carriage design is a broad category with considerations including suspension, insulation, seating configuration, wheels, airflow and an assortment of other comfort and reliability factors. In this study, the only carriage design specifications that will be addressed are those that directly affect a functional requirement. From the design matrix, the affected functional requirements are “Vibrations”, “Cabin noise” and “Trip frequency”. Each of these functional requirements will be addressed along with the relevant design parameter to determine the system range of the design parameters and allow calculation of the information content in *Chapter 4*.

3.1.5.1 On-board Vibrations

The functional requirement necessitates that the *Illness Rating* of passengers is kept below 1, where 1 indicates that the passenger feels slightly unwell. Motion sickness is more commonly experienced in tilting trains or along routes with a high degree of curvature due to the induced rolling motion (Cheung & Nakashima, 2006). The CRH3C is not a tilting train and the route is relatively straight, hence, it is less likely that the passengers will experience motion sickness. The amount of motion-sickness on non-tilting trains varies significantly between studies. A study on the Japanese rail network reported that 18% of passengers experienced motion sickness (Suzuki, Shiroto, Tanka, Tesuka, & Takai, 2000), whilst others postulate that motion sickness cases in modern HSR are rare (Moskvitch, 2014). This discrepancy is most probably a result of the difference in track and train types; however, it also indicates that motion sickness rate predictions are difficult and highly uncertain.

There is a large amount of available literature regarding ground-borne vibrations and their propagation throughout the track surroundings; however, the functional requirement constrained the vibrations experienced by passengers, not those experienced in the surrounding

areas, hence, information regarding on-board vibrations is required and is less readily available. Therefore, the impact of the suspension and the seat design on the experienced vibrations cannot be easily determined without further investigation. Determining the motion sickness dose value is similarly quite difficult without experimental results recording vertical acceleration frequency. However, by using the same carriage design as currently used in the CRH3C, which has no published reports of excessive passenger discomfort, it can be concluded that the CRH3C performs within typical high speed train system ranges. From the literature, the percentage of passengers who experience motion sickness can be as high as 18%. If eighty-two percent of passengers measure between 0 and 1, nine percent between 1 and 2 and nine percent between 2 and 3, the mean *Illness Rating* will be 1.27. Arbitrarily setting the lower limit as zero, as it is plausible that no passengers will experience discomfort, the system range for the *Illness Rating* is between 0 and 1.27.

3.1.5.2 Cabin Noise

The cabin noise requirement is dependent on active noise control, a design parameter addressed later; however, the noise without active control, reduced by passive means, such as carriage insulation, can be predicted. This predicted noise can then be used as a basis for the cabin noise before active control is implemented. Similar to the vibrations, the experienced cabin noise is difficult to predict and typical high speed train noise range will be assumed for the CRH3C. *Figure 12* shows that the average interior noise levels of a rolling train has an A-weighted sound level of approximately 85 dBA. *Table 11* displays the interior noise specifications for different high speed vehicles travelling on an open field and in a tunnel, where some external noise is reflected back towards the carriage. *Figure 13* shows the A-weighted frequency of the cabin noise with increasing train velocity on both slab and ballast track; with slab track producing more noise and reaching an upper limit of around 80 dBA at 300 km/hr.

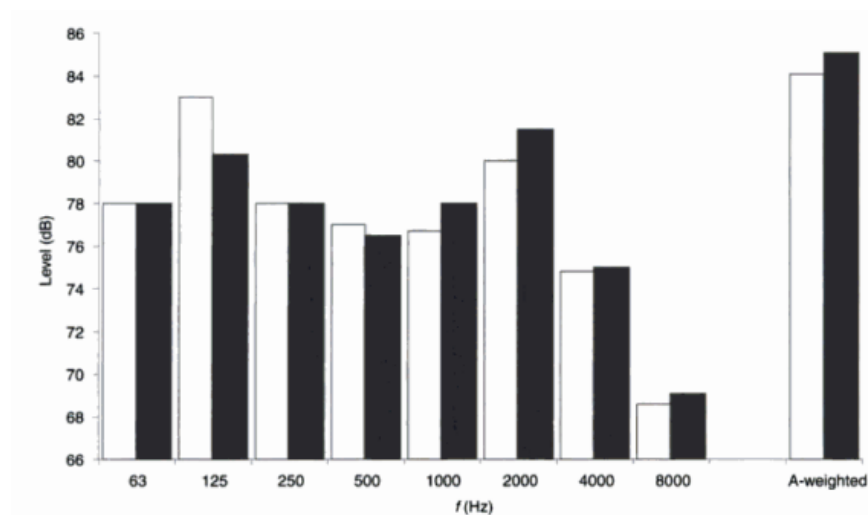


Figure 12: Train interior noise levels whilst rolling (white bars) and braking (dark bars) (Krylov, 2001)

Table 11: Interior noise specification for high-speed vehicles (Cho, Lee, Kim, & Ho, 2004)

Vehicle	Max. Speed (km/hr)	Noise Level [dBA]	
		Open Field	Tunnel
<i>KTX</i>	300	66	73
<i>TGV</i>	300	66	71
<i>Shinkansen</i>	240	69	4
<i>ICE</i>	250	65~68	70-73

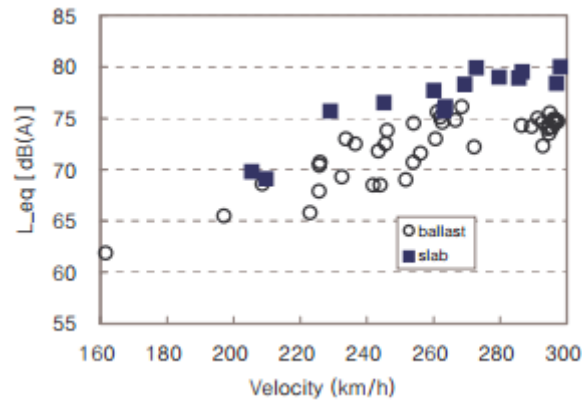


Figure 13: Interior noise of the passengers' compartment inside tunnels with ballasted and slab track (Cho, Lee, Kim, & Ho, 2004)

These literature values together show an interior noise range of approximately 65 to 85 dBA. Allowing an arbitrary 5% deviation from the upper and lower bounds due to the uncertainty in the CRH3C performance, the system range for the cabin noise without active noise control is 61.8 to 89.3 dBA.

3.1.5.3 Seating Capacity

The CRH3C is an eight-car trainset with seating capacity described in *Table 12*.

Table 12: Seating Capacity of the CRH3C (Gazette, 2007)

Car	1	2	3	4	5	6	7	8
Capacity	73	87	87	50	56	87	87	73

The total capacity of the CRH3C is 600 seats (Gazette, 2007).

3.1.6 Route Breakdown

The route defined in the HSR will be used in this study; however, the speed through each segment will be defined under the design parameter "route breakdown". The route breakdown is essential in determining the average speeds between each respective station along the Sydney-Canberra-Melbourne journey. Stopping at intermediate stations was ignored because the primary purpose was to estimate the system range for the duration of an express trip from Sydney to Melbourne, stopping only at Canberra. The trip duration affects the daily capacity of the HSR, hence, route breakdown is a design parameter mapped to the daily capacity functional requirement. It is also mapped to the interior noise functional requirement because carriage noise is greater in tunnels and, therefore, the requirement is dependent on an aspect of the route.

Appendix 3 of the HSR Phase 2 study contained detailed maps, showing terrain, track curvature, track nature (i.e. whether the section is in a tunnel, bridge or open field) and a variety of other factors which allowed approximation of the average speed between each station (AECOM, 2013). The maximum operational speed of the train is designed at 350 km/hr, hence, this was set as the maximum average speed for open sections of track. The maximum speed in tunnels is 250 km/hr, designated in the Phase 2 Study, therefore, the maximum average speed along the urban access corridors was given as 230 km/hr to allow for deceleration and stopping at the station. The lower limits were arbitrarily set as 50 km/hr less than the maximum average speeds to provide a sufficiently large system range, given that the train will have to decelerate to navigate track curvature, inclinations and tunnels throughout each route segment.

The results of this investigation are displayed in *Table 13* and a more detailed analysis of the route breakdown can be found in *Appendix 1.4*.

Table 13: Trip duration estimates between capital cities

From	To	Distance (km)	Lower trip duration (hrs)	Upper trip duration (hrs)
Sydney Central	Canberra Civic	314.8 (283)	0.979	1.168
Passenger Change			0.083	0.083
Canberra	Melbourne Southern Cross	687.0 (651)	2.045	2.412
TOTAL TRIP (SYD-CANB-MELB)		1001.8 (934)	3.024	3.581

Note: The distance is the sum of each route section between the capital city stations and the distance in brackets is the distance specified in the body of the Phase 2 report. The discrepancy is discussed in *Appendix 1.4*.

From *Table 13*, the system range for the trip duration from Sydney to Melbourne, with a 5-minute stopover in Canberra, is 3.024 to 3.581 hours, or equivalently, 181.4 to 214.9 minutes.

3.1.7 Active Noise Control

Active noise control (ANC) uses reference microphones to measure unwanted sound and calculate the required signal to cancel the noise. Speakers then reproduce the sound 180° out of phase with the incoming sound. An error microphone measures the resultant noise and the system adjusts accordingly (Ross & Zaouk, 2010). This process is depicted in *Figure 14*.

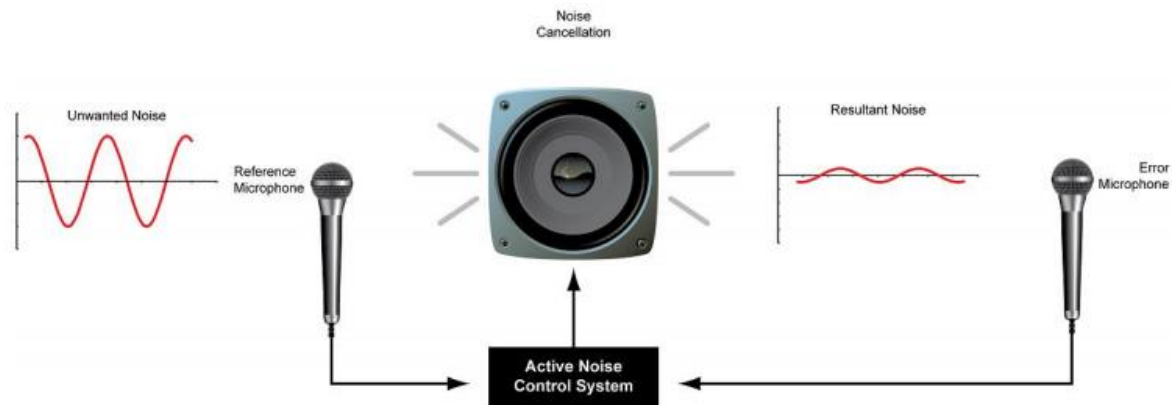


Figure 14: Active Noise Control (ANC) configuration (Ross & Zaouk, 2010)

Experimental results of active noise cancellation in a locomotive cab are shown in *Figure 15*. Using this figure, Ross and Zaouk (2010) conclude that ANC should reduce the detected sound by roughly 7 dB for most frequencies.

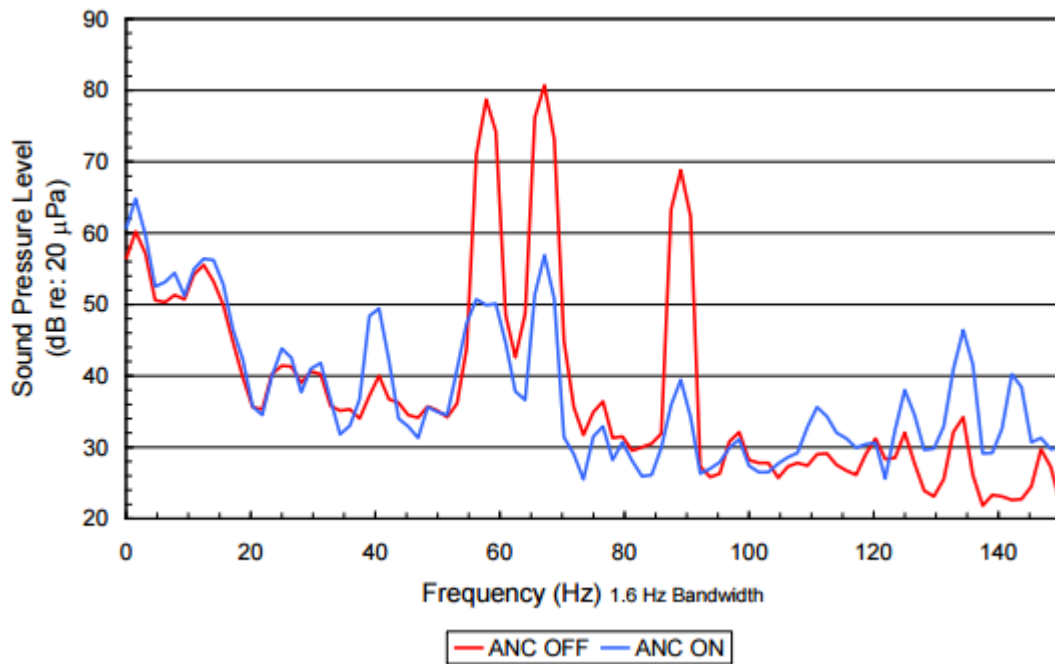


Figure 15: Active Noise Cancellation performance in a locomotive cab (Ross & Zaouk, 2010)

SNCF, who operate the French National Railway, report noise reduction of 3 to 4 dBA using ANC in their high speed electric carriages (Ross & Zaouk, 2010). Hence, from the cabin noise predictions in *Section 3.1.5* of 61.8 to 89.3 dBA, assuming a minimum reduction of 3 dBA on the upper limit and a maximum reduction of 7 dBA on the lower limit, by implementing ANC into our design, the system range for interior cabin noise is 54.8 to 86.3 dBA.

3.1.8 Station Design

Station design encompasses a variety of factors, including ticketing, security, seating, lavatories, food services, etc. However, for my design, the station design parameter is merely acting as a check for station plausibility (i.e. can the stations realistically manage the expected trip frequency). The functional requirement states that 53,200 commuters will use the HSR per day in each direction; therefore, with a train capacity of 600 passengers (*Section 3.1.5*), there will need to be roughly 89 trains per day to satisfy this requirement. Over an 18-hour operational day, this equates to a train leaving every 12 minutes.

Typical deceleration rates for high speed trains are around 0.5 m/s^2 , which is about half of the “full-service brakes” but accounts for track irregularities and poor conditions (Connor P. , 2011). If the train is travelling at its maximum operational speed of 350 km/hr, it therefore only requires just over 3 minutes to come to a halt; thus, the twelve-minute train spacing is not a safety hazard.

The parameter for station design is that it is adequately efficient to allow for disembarking and boarding passengers, as well as cleaning, within twelve minutes. A twelve-minute stopover efficiency is satisfied, with most high speed trains stopping for typically very short periods (Interrail, 2016); consequently, the system range for passenger capacity is greater than 53,200 per day per direction.

Each station must also have at least two tracks for travel in either direction, with capital city stations likely requiring 4 sets of tracks, as there would be express and regional journeys;

however, this is out of scope as the main criterion that this parameter needs to satisfy is that the system is physically capable of transporting the expected demand.

3.1.9 Summary of HSR Design

3.1.9.1 Design Summary

The proposed High Speed Rail system uses a Chinese CRH3C train design, along a standard gauge, slab track. The train utilises an asynchronous motor to achieve a maximum operational speed of 350 km/hr. The train is powered by $2 \times 25\text{kV}$ 50Hz transformers, with regenerative braking to improve energy efficiency. The train can house 600 passengers and the entire system can allow for over 53,200 passengers per day. Active noise control systems are implemented to reduce the passengers' sound exposure.

The expected duration of an express High Speed Rail journey from Sydney to Melbourne, with a 5-minute stopover in Canberra, is between 181.4 and 214.9 minutes.

Table 14 displays the predicted system range of each functional requirement.

Table 14: HSR System Ranges

Functional Requirement	System Range
Power	Power available $> 200\text{ kW}$
G-Forces	$F_G < 0.5G$
External Noise	76 – 109 dBA
Vibrations	$0 < IR < 1.27$
Duration	$181.4 < T_{\text{SYD-MELB}} < 214.9$ (minutes)
On-board Noise	54.8 - 86.3 dBA
Passengers per day	53200+

3.1.9.2 Design Review

Designing the HSR system was relatively straightforward because the Phase 2 Study provided a strong basis for the majority of design decisions. A train set was not specified in the Phase 2 study, so one of my major design tasks was to evaluate a host of train designs and choose one which satisfied the relevant design parameters. A Chinese train, CRH3C, was found to meet all essential requirements, however, there was less literature available regarding vibration and noise generation than European or American trains. As a result, there was significant uncertainty in the noise and vibration estimations and a number of assumptions were made which relied on my engineering judgement. To ensure my analysis and specifications were logical, I explained my thought process to my supervisor, my engineering peers and other non-technical colleagues.

Ultimately, the design is well-constrained and the system ranges seem sensible. An important aspect of my design process was defining the functional requirements and ensuring that the design was decoupled (i.e. equivalent number of design parameters and functional requirements). This process was straightforward for the HSR system; however, I wanted the functional requirements of the Hyperloop to use similar features, such as Power, G-forces and Vibrations, to ensure validity of the comparison. This presented some challenges in the Hyperloop design that are explored in Section 3.2.

3.2 Hyperloop Design Parameters

3.2.1 Overview

In the case of the Hyperloop, the functional requirements defined in *Section 2.5*, can be mapped by the following design parameters:

$$\begin{bmatrix} \text{Power} \\ G - \text{Forces} \\ \text{Capacity} \\ \text{External Noise} \\ \text{Vibrations} \\ \text{Pressure} \\ \text{Duration} \\ \text{On - board Noise} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & X & X & X & X & 0 & 0 & 0 \\ 0 & X & X & X & X & X & 0 & 0 \\ 0 & X & X & X & X & 0 & X & 0 \\ 0 & X & X & X & X & 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{Power Supply} \\ \text{Acceleration Mechanism} \\ \text{Capsule Design} \\ \text{Tube Specifications} \\ \text{Levitation Method} \\ \text{Air System} \\ \text{Route Breakdown} \\ \text{Active Noise Control} \end{bmatrix}$$

The design matrix, A, is lower triangular, which represents a decoupled design.

These design parameters incorporate a variety of physical components of the system, which are described throughout this chapter. To clarify how each design parameter is relevant to the mapped functional requirements, each parameter is discussed briefly below.

Power Supply:

- The power supply maps solely to the power functional requirement, as it is the only factor needed to meet the power requirement.

Acceleration Mechanism:

- This parameter defines how the capsule will reach maximum speed, as well as how it will decelerate. Consequently, it influences the G-forces requirement, as well as any other speed dependent requirements.

Capsule Design:

- Describes both the internal and external design of the capsule and therefore affects the capacity, the noise and vibrations generated during travel and also limits the operational speed of the capsule, due to aerodynamic considerations.

Tube Specifications:

- Describes the dimensions of the tube, as well as the primary materials. It therefore maps to the noise generated and limits the operational speed, due to aerodynamic considerations in conjunction with the capsule design.

Levitation:

- There are various potential methods for elevating the capsule from the tube surface; this parameter will specify a design type. The form of levitation will affect the experienced on-board vibrations and also limit the maximum operational speed of the capsule.
- This design parameter limits the maximum possible speed of the capsule and consequently affects the external noise requirement, thus coupling the design. To avoid this issue, the maximum speed will be determined by the capsule and tube parameters, which are limited by aerodynamic considerations, and the levitation method will be selected to satisfy this speed. For clarity, the levitation will not limit the maximum speed, but rather, will be selected based on a pre-determined speed constraint.

Air System:

- The pressure in the capsule needs to be maintained at atmospheric conditions; as such, a compression system needs to be incorporated into the capsule. The pressure is maintained through an air-circulation system, which is dependent on the capsule and tube design.

Route Breakdown:

- This parameter helps describe the duration of the travel.

Active Noise Control:

- This parameter is used to satisfy the capsule noise functional requirement and maps exclusively to this requirement.

As each design component is addressed, in descending order of the DP matrix, a more comprehensive understanding of what each design parameter encompasses will be evident. As the Hyperloop is in its infancy, a significant amount of information is not available regarding Hyperloop design. Hence, the Alpha study design components will be selected if there is limited literature and no design flaws are apparent.

SpaceX is hosting a “Hyperloop Pod Competition” which involves an international conglomerate of teams to design and build a Hyperloop capsule. Each team which progressed to the build phase of the competition, thirty-five teams in total, were contacted and any available information they could provide was analysed and considered in my design. Additionally, publically available information from the two start-up American Hyperloop companies, *Hyperloop One* and *Hyperloop Transportation Technologies* was also analysed and considered alongside the competition entrants’ designs. The Hyperloop companies employ highly qualified engineers, whereas the competition entrants are typically university students, hence the designs specified by the companies held more merit. Ultimately, my engineering judgement was used to make final design decisions based on the recommendations from the available collection of designs, with an emphasis on the robustness and viability of the design.

3.2.2 Power Supply

As discussed in *Section 2.5.9*, each Hyperloop capsule requires 535 kW of power. This will require a power source in the form of batteries, a grid connection or an independent power station feeding into the Hyperloop line. Musk et al.’s (2013) Alpha study suggested the use of lithium-ion batteries recharged at each station (Musk, 2013). Using batteries ensures the Hyperloop is self-sufficient and will also reduce the carbon related transport emissions, so they will be used in my design. A grid or independent power station connection is more reliable but would also pose its own problems regarding installation and high power demand. Additionally, a solar-battery power supply will ensure consistency of ticket prices, as there will be no dependence on the fluctuating oil market (Investopedia, 2015).

Appendix 1.3 computes the required battery assembly required. It was found that 26 Tesla Powerwall batteries, rated at 6.4 kWh, are required to provide 535 kW of power (Tesla, 2016). There are alternative battery options; however given that Musk et al.’s (2013) study suggests the use of Tesla batteries, the power estimations made in the study are based on the use of this type of battery in order to alleviate some required investigation.

3.2.3 Acceleration Mechanism

There are three primary methods proposed for generating thrust to propel the capsule forward, namely, motorised wheels, magnetic propulsion or compression of incoming air. These methods are discussed in detail below.

3.2.3.1 Motorised Wheels

This method requires the capsule to be elevated by wheels, which has not been specified in this stage of the design. The levitation design, see *Section 3.2.6*, will consider the specified propulsion mechanism and the capsule and tube specifications. At this stage, the acceleration mechanism will be specified independently of any other design specifications, as per the axiomatic matrix in *Section 3.2.1*.

This is a straightforward acceleration mechanism and relies on several sets of wheels running along the base of the capsule, which are powered by on-board electric motors. The advantage of this method is that it is a well-established propulsion technique, used in automobiles, trains and planes before take-off and after landing. This method has been proposed by a minority of Hyperloop design groups, but of the three options requires the least engineering and technology development (Cheetah Project, 2016).

Pneumatic, or air-filled, tires are the preferred option as they could potentially absorb imperfections along the tube surface and provide good traction during acceleration and braking. The alternative is steel wheels, as used in high speed rail, which have a lower coefficient of friction, are less resilient to tube imperfections than pneumatic tires and are not proven at the high speeds of the Hyperloop. Due to the continuous traction of the wheels, the capsule is limited to 0.3G during acceleration and 0.1G when braking, which is below the functional requirement limit of 0.5G (Cheetah Project, 2016).

Wheels are an unpopular design choice because they could potentially limit the maximum speed of the capsule, which is the main motivation of the Hyperloop. The current land speed record for a wheeled vehicle is Andy Green's jet powered Thrust SSC, which travelled at 1,228 km/hr along a salt track (Guinness World Records, 2015). However, the Hyperloop capsule needs to consistently travel at these extreme speeds without rapid deterioration of the wheels, which is unproven at this stage.

3.2.3.2 Magnetic Propulsion

Magnetic propulsion would utilise the same technology that is currently implemented in Maglev trains in Japan and China. The major advantage of this system is that it simultaneously provides levitation, by magnetic repulsion, and propulsion by changing polarity of the electromagnets situated along the tube. The changing polarity will cause the on-board electromagnetics to 'chase' the current through the tube and the speed of the capsule can be controlled by the frequency of the alternating current (The Venus Project, 2016). This interaction is demonstrated in *Figure 16*.

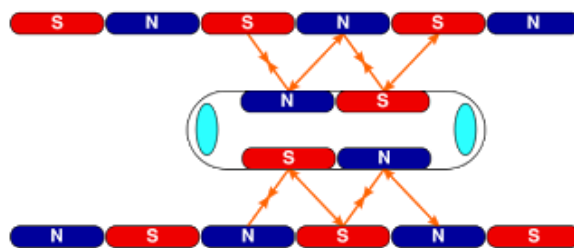


Figure 16: Electromagnetic System providing both levitation and propulsion (The Venus Project, 2016)

The acceleration rate can be controlled by adjusting the frequency of the alternating current; hence, the functional requirement that the capsule does not accelerate above 0.5G, can be satisfied by process adjustment.

Hyperloop One, a US start-up company, after investigating the potential acceleration mechanisms, has begun development of a magnetic propulsion system, indicating that this could be the most feasible option. *Hyperloop One* developers suggest that only 5% of the track needs magnetic propulsion. Due to the low pressure environment, the capsule can travel for roughly 100 miles without applying any other energy to maintain speed (Russon, 2016). Maglev is a proven concept, with a track in China capable of speeds of up to 500 km/hr (AECOM, 2013). The primary speed limitation for this mechanism is the aerodynamic drag; however, in the low pressure environment of the tube, the significantly reduced drag could allow speeds up to 1200 km/hr (Musk, 2013).

The major inhibitor to this technology is the substantial cost required in lining hundreds of kilometres of tubing with the magnetic apparatus. Although propulsion is only required for 5% of the track, levitation will be required throughout the entire journey. Previous Maglev ventures have failed due to the ongoing costs and maintenance required on the track (AECOM, 2013).

3.2.3.4 Compressive Thrust

The third propulsion method operates in a similar way to an airplane. Incoming air travels through a front-facing compressor, to a rear nozzle which expands the air and generates thrust, as per *Figure 17* (Makers UPV Team, 2016). Unlike the two alternative acceleration methods, this method does not have an inherent levitation mechanism and will require either magnetic levitation, air skis or wheels (see *Section 3.2.6*).

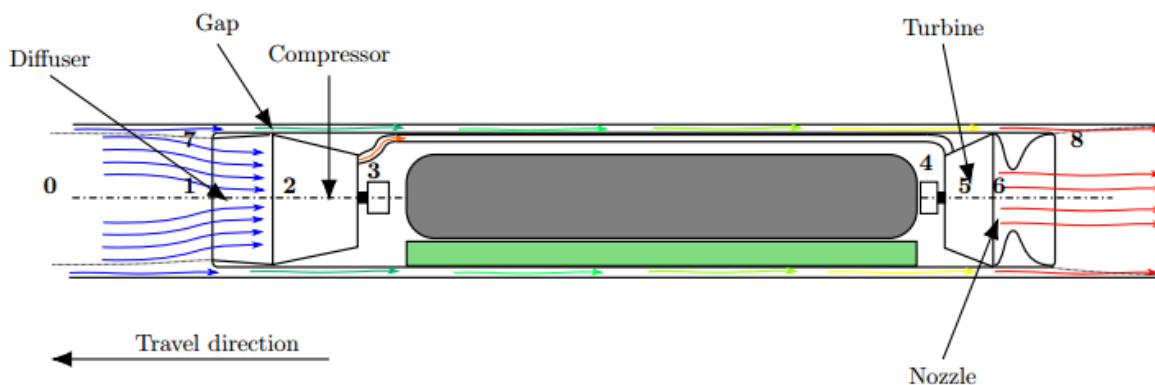


Figure 17: Flow process schematic (Makers UPV Team, 2016)

This design was proposed by a Hyperloop pod design team which won an award for ‘Best Propulsion Design’ and was also proposed in the *Alpha* study as a means to generate thrust to mitigate the small amounts of aerodynamic drag (TAMU, 2016). A compressor will be essential in any Hyperloop design to ensure that the flow is not choked between the capsule and the tube walls, which would cause a build-up of air mass and significantly increase drag (Musk, 2013). Thus, using the compressor to serve multi-purposes could reduce costs and design complexity.

3.2.3.5 Propulsion Specification

After careful deliberation and investigation of design types there are two potential propulsion combinations that could be implemented for an Australian Hyperloop.

The first design would operate like an aircraft; initially the capsule would accelerate using electric-motor wheels. Once a threshold speed has been reached, the compressor activates and simultaneously the levitation system will be progressively activated as the speed increases. The key feature of this design is that if magnetic propulsion or compression are not found to be economically or technically feasible, the design can be adjusted and the powered wheels used for the entire journey duration. This would likely mean a reduced maximum speed, due to the wheel limitations, however, it is a good design contingency. Another difficulty with modelling the turbine is that a larger compression and throttling stage will be required, consequently increasing the power demand of the capsule. The power demand is difficult to estimate without simulations and would alter the power supply functional requirement, which only accounted for compression to primarily generate minor thrust to overcome aerodynamic drag.

The second design would use magnetic propulsion for the start and end of each journey to reach cruising speed, after which it would rely on compression to generate thrust and mitigate the minor aerodynamic drag. This design is more simplistic than the first design as it does not involve retracting wheels, which will likely be difficult to implement, but it utilises Maglev propulsion technology which is more expensive than the electric-powered wheels.

The second design is more robust as there is no change in levitation method throughout the journey, which could cause mechanical failure and would require significant development and cost to achieve technical maturity. Therefore, my design will use the second design which uses magnetic propulsion for the primary thrust stage and air compression to overcome drag throughout the larger part of the journey. The magnetic propulsion system can be adjusted accordingly to ensure that the passengers do not experience G-forces greater than 0.5G and the functional requirement will be satisfied.

3.2.3.6 Braking Specification

Deceleration of the capsule will work in the reverse manner of the acceleration. The compression stage will be deactivated and the gradually increasing drag will cause the capsule to slow down, after which magnetic interactions will cause the capsule to brake, thus acting as the primary form of deceleration. The G-forces functional requirement will be satisfied as the two deceleration stages can be adjusted to ensure that the passengers do not experience linear forces greater than 0.5G.

3.2.4 Capsule Design

3.2.4.1 Capsule Dimensions

The capsule must be designed to satisfy the capacity functional requirement which necessitates a capacity of 27 passengers. A symmetrical design will make for an even number of seats, so a capacity of 28 will be designed for, for simplicity. Modelling the cabin dimensional requirements from commercial aircraft standards and typical layouts, the constraints outlined in *Table 15* need to be met for the Hyperloop capsule (SAAB, 2016; Quigley, Southall, Freer, Moody, & Porter, 2001; CBS News, 2009).

Table 15: Hyperloop Capsule Dimension Constraints (SAAB, 2016; Quigley, Southall, Freer, Moody, & Porter, 2001; CBS News, 2009)

Dimension	Distance (mm)
Minimum distance between a seat and another fixed structure, or seat in front.	178
Seat Width	440
Aisle Width	400
Internal height of cabin	1900
Distance from bottom of chair to floor	320

Auto Inventor was used to design a capsule with these constraints and subsequently determine all essential dimensions of the capsule, including external diameter and length. *Figures 18* and *19* show the proposed capsule design. There are a variety of essential features missing, including all propulsion, levitation and internal instrumentation, doors and lavatories. However, this design is intended to show a fundamental, high-level design, to satisfy the capacity functional requirement and determine the frontal area to more accurately predict flow behaviour.

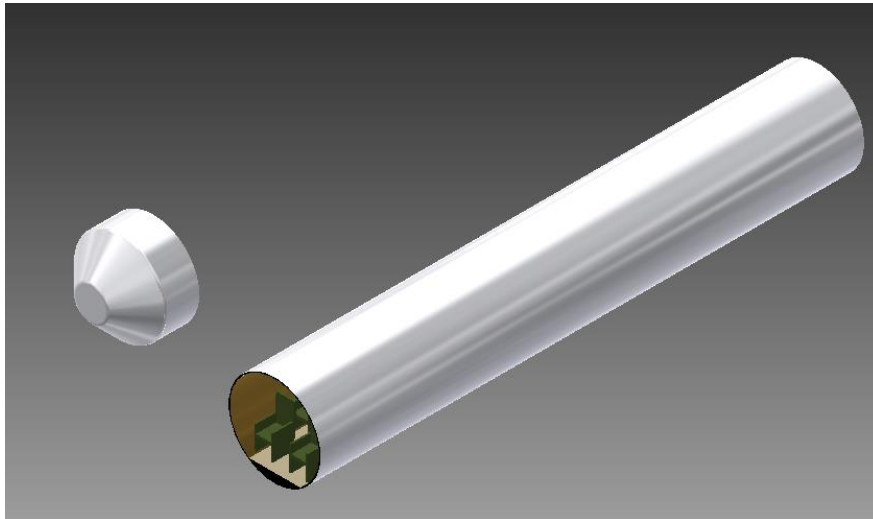


Figure 18: Hyperloop Capsule (Realistic)

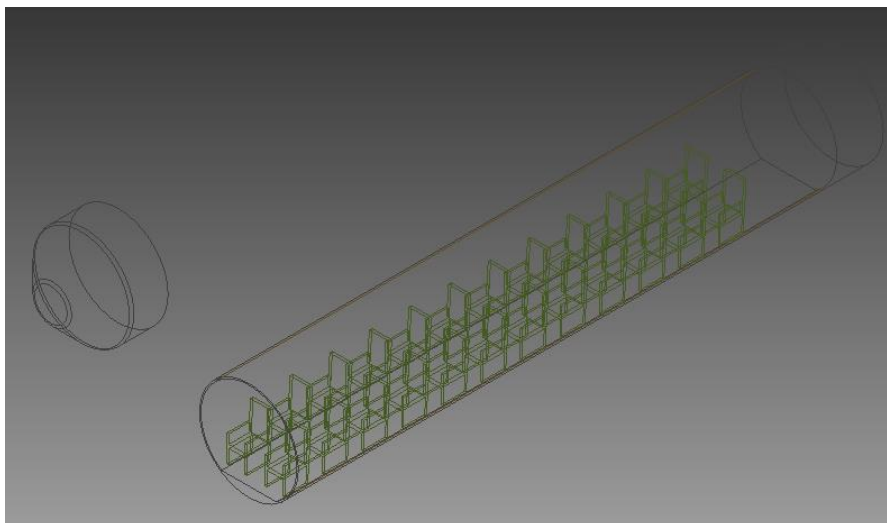


Figure 19: Hyperloop Capsule (Wireline)

Behind the seats there is an “empty” area that could house a lavatory and other essential amenities. An additional section beyond this has also been included in the design to account for the turbine. The lengths allowed for additional components may be inaccurate as they were based on engineering judgement; however, a minor change in the capsule length should not significantly affect the flow characteristics and therefore this estimation is sufficient.

The nose cone is included in these design drawings for completeness of the outer shell; however, CFD analysis will be required to determine the optimal nose cone shape and dimensions.

Figures 20 and 21 display a front and side cross-section of the capsule design, respectively.

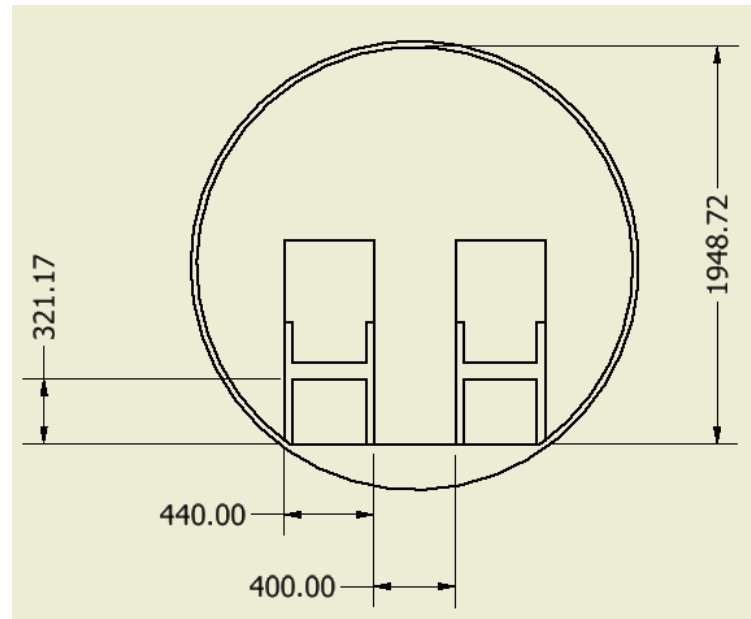


Figure 20: Hyperloop Capsule (Front cross-section)

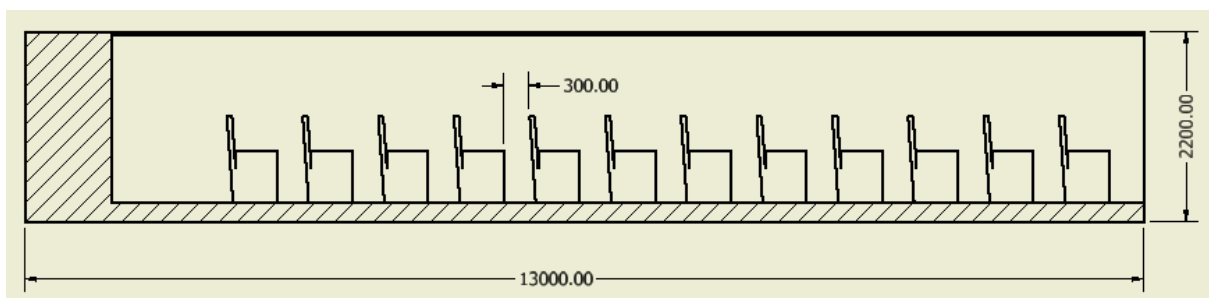


Figure 21: Hyperloop Capsule (Side cross-section)

From *Figure 20* and *21*, the minimum constraints outlined in *Table 15* are satisfied and the essential capsule dimensions could be determined. The diameter of the capsule is 2.2 metres and the length is roughly 13 metres. The thickness of the capsule walls was arbitrarily chosen as this does not significantly affect the key dimensions and will be determined through more refined design and analysis. This is the minimum capsule size to provide a capacity of 28 passengers.

3.2.4.2 Capsule Materials

An aluminium alloy will be used on the outer walls of the capsule, as well as thermal insulation to protect against the potentially high temperatures generated by the high speed flow regime. An aluminium alloy is suggested as the primary material for the capsule as it is strong, light and

commonly used in aircraft (Smithsonian National Air and Space Museum, 2016). Aluminium loses strength when exposed to high temperatures; however, a Hyperloop developer found, using CFD analysis, that the temperatures around the pod are not high enough to require special materials (Makers UPV Team, 2016). Aluminium also offers highly effective sound reflectivity which will be discussed in more detail in *Section 3.2.5.3*.

3.2.5 Tube Specifications

3.2.5.1 Tube Dimensions

The tube will be maintained at around 100Pa, as specified in Musk et al.'s (2013) Alpha study. As the capsule passes through the tube a large volume of air will be displaced, potentially causing choked flow and inhibiting the transit of the capsule. The Alpha study specifies two different capsule designs, a passenger-only capsule and a passenger-plus-vehicle capsule. The passenger-plus-vehicle capsule has a similar frontal area to my capsule design, of roughly 4m². For a capsule with this frontal area, a tube cross-sectional area of 8.55m², equivalent to a diameter of 3.3 metres, is required to prevent choked flow (Musk, 2013). This gives a capsule/tube area ratio of 45% and a diameter ratio of 68%.

Chin et al. (2015) conducted an independent flow analysis of the Hyperloop tube and determined that the tube diameter has to be roughly twice the original specified diameter to prevent choking the flow. Therefore, taking their findings, which offer a far more detailed analysis than Musk et al.'s (2013) design, the tube must have a diameter of approximately 6.6 metres, equivalent to a cross-sectional area of 34.2m² (Chin, Jones, Gray, & Berton, 2015). It is recommended that independent modelling is completed to validate Chin et al.'s model because the tube area will have a significant impact on the cost of the system. However, computational fluid dynamic modelling is out of scope of this study. The capsule/tube configuration is shown in *Figure 22*.

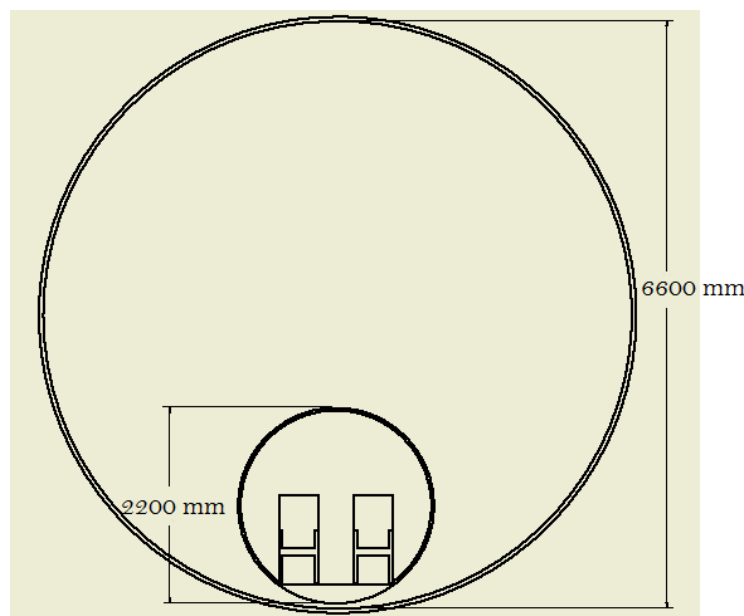


Figure 22: Capsule/Tube Configuration

3.2.5.2 Tube Materials

Musk et al.'s (2013) study specified a uniform thickness steel tube, reinforced with stringers, to keep cost to a minimum. One of the issues with a machined steel tube is that it will deform under its own weight, requiring the installation of expansion joints and potentially causing high maintenance costs and tube downtime (Hyperloop Transportation Technologies, 2016).

The cheapest feasible option is corrugated steel, which is less rigid than machined steel, so expansion joints are not required. The main issue with corrugated metals is that the finish accuracy is quite poor and as the capsule is levitating a minute distance above the tube surface, a smooth, consistent surface is important. The lower half would need to be faired with a concrete-like filler and a liner for the running surface, as per *Figure 23* (Hyperloop Transportation Technologies, 2016).

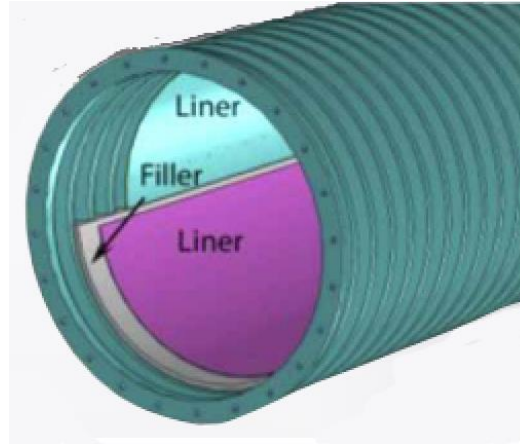


Figure 23: Corrugated Steel Tube (Hyperloop Transportation Technologies, 2016)

Fibreglass could potentially perform suitably and provide excellent accuracy for the curved sections using a computer-adjusted internal mould. Fibreglass is significantly more expensive than steel, but this would be offset by the reduced labour costs, by automating the construction of the tubes. It would not need expansion joints, but would need to be lined for surface accuracy, as per *Figure 24* (Hyperloop Transportation Technologies, 2016).



Figure 24: Fibreglass Tube (Hyperloop Transportation Technologies, 2016)

The machined steel specified in the Alpha study is chosen as the tube material due to the relative simplicity of construction and low cost of the material. Additionally, Australia has substantial steel resources and the use of machined steel to construct tubes would likely improve the ailing mineral sector (Kozioł & Wroe, 2016). This design component does not directly map to any functional requirements, but it is an important consideration in regards to cost and feasibility of construction.

A major technical challenge associated with the tubing is how to ensure that the entire length is airtight. Any ruptures or openings in the tube will result in a large pressure difference and a

shock wave will propagate along the route. This could cause catastrophic failure of the tube system, as per *Figure 25*.

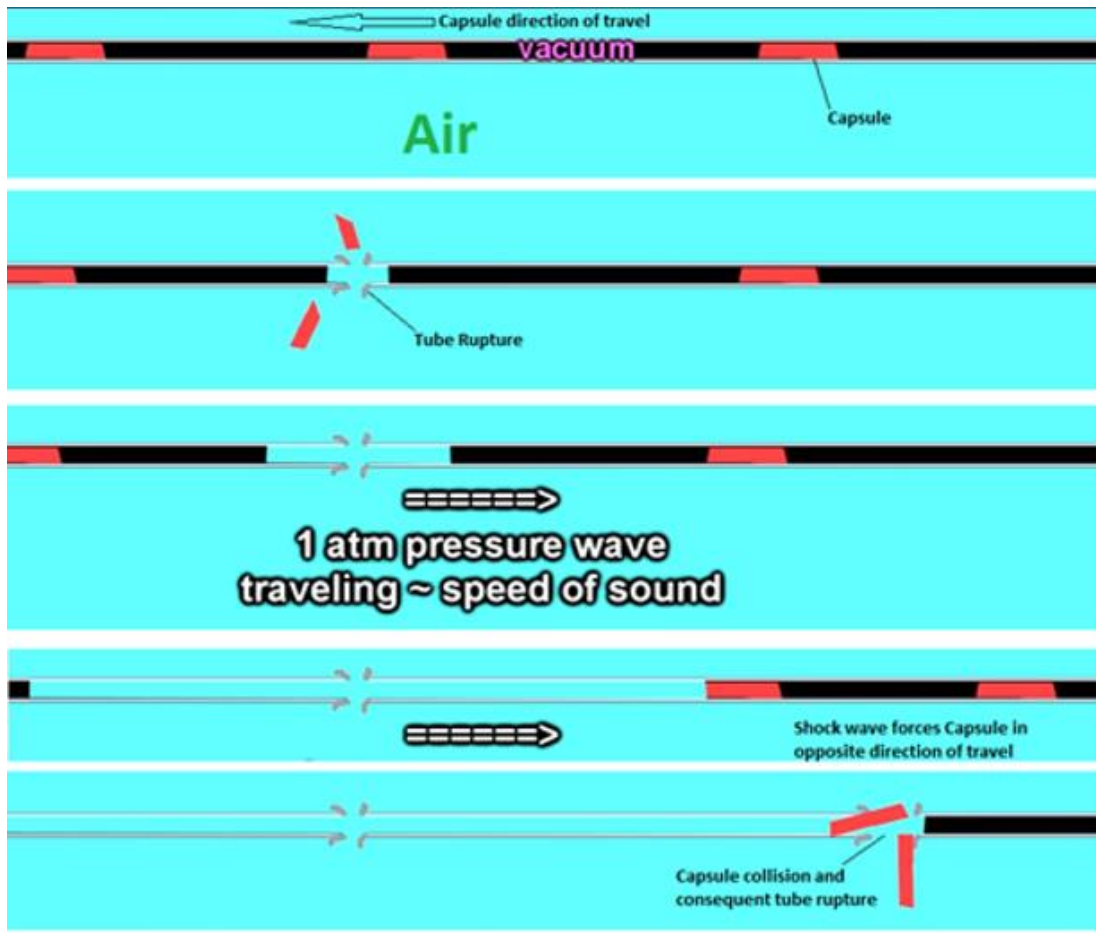


Figure 25: Tube Rupture (Thunderf00t, 2016)

If the tube segments are welded together, the temperature gradient between the top and bottom of the tube (due to heating from the sun) may cause buckling. Alternatively, Musk et al. (2013) suggest the use of expansion joints. However, the expansion joints will need to hold the vacuum in the tube during expansion, which is a technical development that has not been realised at the time of writing. The method of connecting the tube segments is one of the largest challenges associated with the Hyperloop and was considered out of scope in this design; however, it is essential that this component is considered during future development.

3.2.5.3 Noise Generation

With the propulsion method and capsule and tube dimensions specified, the external noise produced by the Hyperloop can now be evaluated and given a system range. Modelling and predicting the noise generation of the Hyperloop capsule at cruising speeds is very difficult, even with CFD analysis. The noise generated by a jet can be experimentally observed and by assuming the Hyperloop will produce a similar magnitude of sound, with plus/minus 25% deviation due to the different cross-sectional area, pressure and speed, the external noise can be estimated. A jet take-off produces around 150 dBA of sound (IAC Acoustics, 2016). This gives the Hyperloop a noise generation range of 112.5 to 187.5 dBA.

Sound absorption is the ability of a material to absorb, rather than reflect, sound waves. Typically, a building material's sound absorption properties are characterised by a noise reduction coefficient (NRC), which range between 0 and 1. A NRC of 0.4 means that 40% of

the incoming sound is absorbed and transmitted, whilst 60% is reflected back; see *Figure 26* (The American Institute of Architects, 2016).

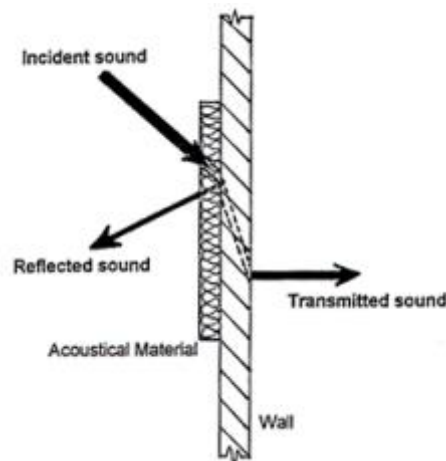


Figure 26: Sound Reflection/Transmission Diagram (Urban Acoustic, 2009)

The tube is composed of steel, which has a NRC of 0.1 (Urban Acoustic, 2009). Therefore, only 10% of the sound generated by the capsule is transmitted to the environment, which corresponds to a range of 11.25 to 18.75 dBA, thus satisfying the external noise functional requirement, which requires the noise range to be below 100 dBA.

However, 90% of the sound is reflected back, corresponding to a range of 101.3 to 168.8 dBA, toward the aluminium capsule, which has a NRC of 0.05 (Urban Acoustic, 2009). This low NRC value means that the sound transmitted into the capsule interior is only 5.1 to 8.4 dBA. This system range satisfies the capsule noise functional requirement, which requires the noise range to be below 85 dBA.

This sound could be reflected from the capsule back toward the tube and increase the external noise; however, the capsule is travelling at such high speeds that the noise will be produced at a different location and I envisage this effect to be negligible.

Unfortunately, this model is based on a significant assumption—that the Hyperloop produces sound in much the same way as a jet, which may be inaccurate due to different speeds and cross-sectional areas, in addition to vastly different external pressures. However, due to the reflectivity of the capsule and the tube, it is highly unlikely that the external noise functional requirement will not be satisfied.

3.2.6 Levitation Method

The levitation method describes the mechanism which will elevate the capsule from the tube surface. Three design types have been proposed by various developers, which are explored below.

3.2.6.1 Wheels

Wheels are the most conventional form of elevation and of the three options require the least development and cost because they are a well-established technology. However, as discussed in *Section 3.2.3*, wheels are limited at high speeds due to potential material damage. Further research would need to be conducted to determine the angle and assembly of the wheels, as well as whether pneumatic or steel would be more suited; however, in general the design is relatively straightforward.

3.2.6.2 Magnetic Lift

Magnetic lift utilises electromagnets to repel the capsule from the non-ferrous, metallic tube surface. Of the three options, this method has the highest associated construction and maintenance costs due to the long distance of magnetic infrastructure required. An alternative method has been proposed by some designers which uses a tube composed of a ferromagnetic material, whilst the capsule has in-built electromagnets, which attract the capsule to the upper surface of the tube. This method considerably reduces the construction and maintenance costs as the electromagnets are now attached to the capsule, not the entire length of the tube (Makers UPV Team, 2016). The issue with this design is that it has not been previously implemented and the levitation modules will need significant development to ensure there is no physical contact between the capsule and the tube when the capsule experiences disturbances. The advantage of the repulsion method is that, assuming no significant external forces, the capsule should not come into contact with the tube and the capsule should be stable (Kassim, Shaikh, Zainal, & Khairulanam, 2008). *Figure 27* demonstrates the basic principles of this mechanism.

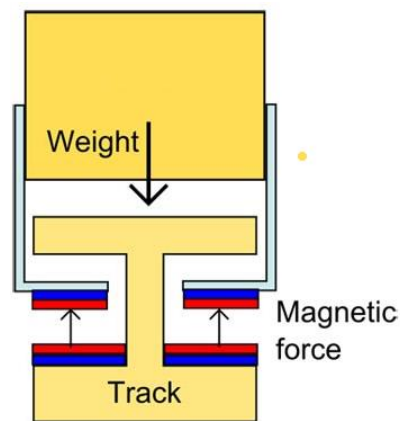


Figure 27: Simplistic Diagram demonstrating Magnetic Levitation (Science Buddies, 2015)

3.2.6.3 Air Bearings

Air bearings were proposed in the initial Hyperloop design from Musk et al.'s (2013) Alpha study. The gap height between the capsule ski and the tube wall can be maintained at high speeds, as any reduction in the gap height produces large restoring pressures which keep the capsule elevated, as shown in *Figure 28*. The capsule skis are then integrated into an independent mechanical suspension to ensure a comfortable journey for the passengers (Musk, 2013).

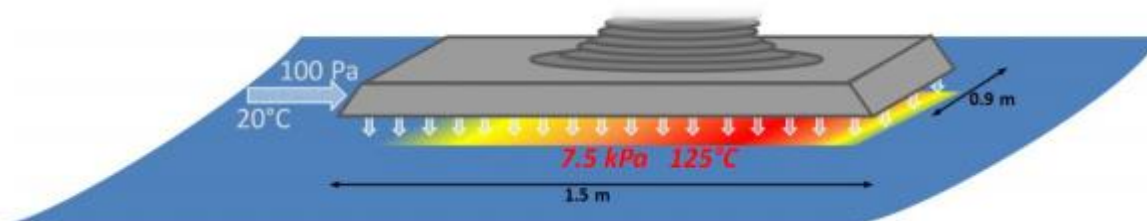


Figure 28: Air-bearing skis schematic (Musk, 2013)

The primary advantage of this design is that it significantly reduces tube construction costs as no levitation infrastructure, such as electromagnets, are required. Air bearings also have natural stability, low friction and a long lifetime, with significantly less maintenance than magnetic levitation (Dodson, 2013). Additionally, the compressed air can be generated from the existing compressor primarily used to generate thrust to mitigate drag forces, thus reducing the need for

additional components which will be required by the wheel or magnetic levitation method (Musk, 2013).

This design requires wheels when travelling at speeds below 160 km/hr as the dynamic pressures and aerodynamic flow are insufficient to maintain capsule elevation (Musk, 2013). This design has been highly criticised by engineers as it relies on immature technology that will require significant research and development before becoming viable (Dodson, 2013). Consequently, most developers have avoided the use of air skis due to the unpredictability in the forces and disturbances acting on the capsule (Makers UPV Team, 2016).

3.2.6.4 Levitation Specification

Elon Musk, in contrast to his original design, has suggested that wheels should be used in the first commercial Hyperloop to “limit the number of miracles in series” (Cheetah Project, 2016), implying that magnetic levitation and air skis, which are not well-established technologies, may cause issues in the development phase and potentially inhibit the construction of the Hyperloop. However, using wheels would inhibit the speed of the Hyperloop and, unless the speed of the Hyperloop is significantly greater than the High Speed Rail, then it is not worthwhile investing in the development of the technology. Air-bearing skis were not chosen in my design as there is insufficient experimental validation of the technology to endorse their use in such a large infrastructure technology. Hence, for my design, I will use magnetic levitation, which is a reliable form of levitation that should allow speeds of up to 1200 km/hr. Magnetic levitation can be easily implemented with the chosen acceleration mechanism, which is a combination of magnetic propulsion and turbines to maintain maximum speed (see *Section 3.2.3*).

Estimating the vibrations experienced by the passengers inside the capsule is difficult and highly uncertain. An investigation into Maglev stability found that there is limited available experimental data; however, mitigation techniques such as electrodynamic primary suspension damping and mechanical secondary suspension can be used to ensure a high level of ride comfort and safety (Cai, Chen, Mulcahy, & Rote, 1993). The Maglev train considered in Cai’s study is not subject to the external flow of the tube or speeds of up to 1200 km/hr, so additional mitigation may be required.

A study into motion sickness experienced during short-haul flights over a range of commercial airline flights, which typically travel at around 900 km/hr, found that 8.9% of passengers reported vomiting or nausea and 16.2% reported illness (Turner, Griffin, & Holland, 2000). Equating these degrees of sickness to an *Illness Rating* of between 2 and 3, and 1 and 2 respectively, an average *Illness Rating* of 1.34 can be interpreted. Due to the different shape and speed of the Hyperloop, we assume that the *Illness Rating* varies up to 25% lower or higher than the aircraft *Illness Rating* mean. Consequently, we obtain an expected range of 1.01 to 1.68. Arbitrarily setting the lower limit as zero, as it is plausible that no passengers will experience discomfort, the system range for the *Illness Rating* is between 0 and 1.68.

3.2.7 Air System

The pressure functional requirement specifies that the capsule must have a consistent, non-fluctuating pressure of between 75 and 101.25kPa. After the passengers have boarded, the capsule will be sealed before entering the depressurised tube. The capsule, if properly sealed, will retain its atmospheric pressure; however, an air circulation system will need to be included in the capsule, similar to a commercial aircraft. Utilising aircraft air-circulation principles, a small part of the compressed air, used to provide capsule thrust, is rerouted to a heat exchanger which cools the high temperature air. The compressed air is then mixed with previously used,

recirculated capsule air, cooled again and fed through expansion valves to the capsule interior (Lufthansa Technik, n.d.).

This design relies on a compressor; however, as one has been included in the acceleration mechanism design, a small part of this compressed air can be used and there is no need for additional compression. The power demand functional requirement allowed for some compressed air being used for air-skis which have been excluded from this design; hence, the air that was to be stored for air-ski levitation can be used in this air system. Thus maintaining independence of functional requirements.

To ensure that the capsule pressure does not steadily increase, a computer-controlled outflow valve monitors the capsule pressure and temperature and maintains a comfortable level by releasing capsule air outside when required. This ensures that the pressure does not fluctuate throughout the trip and ensures the comfort of the passengers (Lufthansa Technik, n.d.).

This technology has been implemented successfully in modern aircraft consistently for many years and is therefore reliable. The system range of the capsule pressure is difficult to estimate, but as it can be designed to suit the client's needs, it will be set to the design range of 75 to 101.25kPa.

3.2.8 Route Breakdown

The route defined in the HSR will be used for both transportation systems in this study; however, the speed between each segment will be defined under the design parameter "Route Breakdown". The same process for determining fast and slow regions was used in the Hyperloop "Route Breakdown" as was used in the HSR "Route Breakdown". However, the Hyperloop can travel at the same speed through tunnels or open field as the tube specifications will remain constant.

The maximum operational speed of the Hyperloop is designed at 1200 km/hr due to flow choking at higher speeds; hence, this was set as the maximum average speed for non-urban sections of the track. The capsule will travel at much lower speeds through the urban access corridors during acceleration and deceleration; hence, the maximum average speed in these sections was arbitrarily set as 600 km/hr. The lower limits were arbitrarily set at 300 km/hr less than the maximum average speeds to provide a sufficiently large system range, given that the Hyperloop will have to decelerate to navigate track curvature and inclinations throughout each segment, as well as the inherent uncertainty in the Hyperloop's ability to achieve speeds of 1200 km/hr.

The results of this investigation are displayed in *Table 16* and a more detailed analysis of the route breakdown can be found in *Appendix 1.4*.

Table 16: Trip duration estimates between capital cities (Hyperloop)

From	To	Distance (km)	Lower trip duration (hrs)	Upper trip duration (hrs)
Sydney Central	Canberra Civic	314.8 (283)	0.307	0.467
Passenger Change			0.083	0.083
Canberra	Melbourne Southern Cross	687.0 (651)	0.618	0.886
TOTAL TRIP (SYD-CANB-MELB)		1001.8 (934)	0.925	1.354

From *Table 16*, the system range for the trip duration from Sydney to Melbourne, with a 5-minute stopover in Canberra, is 0.925 to 1.354 hours, or equivalently, 55.5 to 81.2 minutes.

3.2.9 Active Noise Control

It was determined in *Section 3.2.5.3* that the passengers on board the Hyperloop will be subject to 5.1 to 8.4 dBA which satisfies the capsule noise functional requirement. However, should the on-board compression generate sound throughout the capsule, which is significantly more difficult to model, some noise control mitigation may be necessary. The noise generated by compressors can range between 70 and 90 dBA, which in addition to the reflected external noise would give a range of roughly 75.1 to 98.4 dBA (FHWA, 2015).

Implementing the same active noise control systems used for the HSR design, in *Section 3.1.7*, the noise can be reduced by 3 to 7 dBA. Should the noise cause discomfort for the passengers, noise-cancelling headphones could also be distributed among the passengers which can reduce incoming noise by roughly 13 dBA (Baur & Zalewski, 2008). However, noise cancelling headphones will not be included in the design of the capsule, as they are a mitigation procedure, not a design factor. Hence, applying the maximum and minimum noise reduction potential of ANC, the system range will be 68.1 to 95.4 dBA.

3.2.10 Summary of Hyperloop Design

3.2.10.1 Design Summary

In the proposed Hyperloop design, a capsule will levitate above the tube surface using *Maglev* principles and accelerate using magnetic propulsion. Once cruising speed of 1200 km/hr has been achieved, a compressor at the front of the capsule will compress incoming air, which will be expanded at the rear of the capsule generating thrust to mitigate the minor drag resistances generated by the flow regime. The capsule and tube both have circular cross-sections with a capsule/tube area ratio of 45% and a diameter ratio of 68%. The capsule's outer shell will be composed of an aluminium alloy, surrounding thermal insulation, and the tube will be constructed using machined steel. The capsule's on-board power requirements will be satisfied by an ensemble of 26 *Tesla* battery packs. Active noise control systems will be implemented on board to minimise passenger exposure to high noise levels and the air flow system implemented on conventional airplanes will be used to recirculate passenger air and maintain capsule pressure.

The expected duration of an express Hyperloop journey from Sydney to Melbourne, with a 5-minute stopover in Canberra, is between 55.5 and 81.2 minutes.

Table 17 displays the predicted system range of each functional requirement.

Table 17: Hyperloop System Ranges

Functional Requirement	System Range
Power	Power available > 535 kW
G-Forces	$F_G < 0.5G$
Capacity	Capsule Capacity = 28
External Noise	11.25 - 18.75 dBA
Vibrations	$0 < IR < 1.68$
Pressure	$75 \text{ kPa} < P < 101.25 \text{ kPa}$
Duration	$55.5 < T_{\text{SYD-MELB}} < 81.2 \text{ (minutes)}$
On-board Noise	68.1 - 95.4 dBA

3.2.10.2 Design Review

The design of the Hyperloop posed a number of challenges. The primary difficulty was the lack of reliable information and research. In recent years, Hyperloop has been heavily researched by university groups, industries and independent researchers; however, most of these parties have their own agenda, consequently producing an obvious bias in their findings. For instance, the use of wheels as a form of levitation was strongly criticised by the majority of researchers due to their inability to perform at high speeds. But teams or researchers in favour of the wheel design would state the wheels are suitable because a wheeled vehicle has travelled at speeds of up to 1228 km/hr. The land speed record was achieved in a radically different environment and the speed was not maintained for the duration that the Hyperloop capsule would require, nor was it subject to repeat journeys; hence, the wheels' ability to reach this speed is not sufficient evidence that they will maintain their performance over repeat Hyperloop journeys. The occurrence of potentially skewed literature was a recurring issue, so I thoroughly evaluated both the source of the information, the potential bias/es of the author/s, and their approach to the study, before making design decisions.

I was conscious of my own bias when making design decisions from literature recommendations, as I am ultimately in favour of innovative design and cost reduction. For instance, I was in favour of air bearing skis, because no magnetic levitation infrastructure is required, which would alleviate the need for expensive magnetic infrastructure. However, the concept is unproven and it is highly unlikely that the Australian government would support unproven, potentially dangerous, technology. I took note of my bias and decided to use the magnetic option as it is a more reliable design choice.

A number of assumptions needed to be made throughout the design, specifically regarding vibration and noise generation, which relied heavily on my engineering judgement. To mitigate the effect of an individual point of view and potential bias I checked all major design concepts with my supervisor, my engineering peers and other non-technical colleagues to ensure I wasn't overlooking obvious flaws. This collaboration was very rewarding and allowed me to expose technical issues with my design, as well as improve my verbal and written communication ability.

The use of axiomatic design also created a number of challenges due to the inflexibility of the design and functional requirements. A key factor of axiomatic design is that when the number of FRs is not equal to the number of DPs, the design can be either coupled or redundant, which complicates the determination of the design's information content. To prevent this complexity, I was careful in defining functional requirements and their design parameters to ensure the design was decoupled and the subsequent information content evaluation was straightforward. In doing so, I had to work around a number of design issues.

An example of this is the power functional requirement. A functional requirement outlines a design range which one's design parameters need to meet; however, the power required is dependent on a number of different design parameters including acceleration mechanism, levitation and the capsule design. Hence, although the functional requirement is solely satisfied by the power supplied, the design range is potentially dependent on other design parameters. To resolve this problem, I ensured that my design aligned with the initial assumptions used to define the Power Required FR. If the power required by the design exceeded the FR design range, I would have amended the design range accordingly; fortunately, my design was not radically different to the Musk et al.'s (2013) design and I was able to use the FR design range, without amendments.

Additionally, a number of design components were not included in the design of the Hyperloop, such as an external energy source to power the Maglev system, the assembly of the tubes, pylon construction and station design. They were omitted due to difficulties in creating a decoupled axiomatic matrix which incorporated these parameters, as well as limited available literature.

I am satisfied with the state of the design and believe that the design I have outlined is reliable and lower risk than the majority of the alternatives. I evaluated a host of designs, many of which were not cited or included in my evaluations because they were either not relevant or had been covered by an existing literature source. I would like to acknowledge *Hyperloop One*, *Hyperloop Transportation Technologies* and the SpaceX Hyperloop competition entrants, specifically those who either provided me directly with information, or who have made their designs and reports publicly available: *rLoop*, *Badgerloop*, *VicHyper*, *WARR*, *Cheetah*, *UPV*, *Delft* and *MIT Hyperloop Team*.

4 Information Content

4.1 Overview

Axiom 2 states that the best design is the one which minimises the information content. An information content of zero implies that the design is assured to meet the functional requirements of the system. A value greater than zero indicates the amount of extra information that is required before the design is guaranteed to meet the functional requirements (Suh, 2001).

The information content is a function of the probability of design success such that

$$I_{sys} = -\log_2 P_{sys} \quad (1)$$

P_{sys} is the probability that all m functional requirements are satisfied. Hence, if the FRs are independent, then

$$P_m = \prod_{i=1}^m P_i$$

Thus, it follows that

$$I_{sys} = \sum_{i=1}^m I_i = -\sum_{i=1}^m \log_2 P_i \quad (2)$$

To estimate the probability of a parameter's success, we must evaluate the system and design ranges. A functional requirement's system range can be normally or uniformly distributed depending on the design parameter, as per *Figures 29 and 30*. The area of the overlap between design and system ranges can give the probability of design success, which leads to determination of the information content.

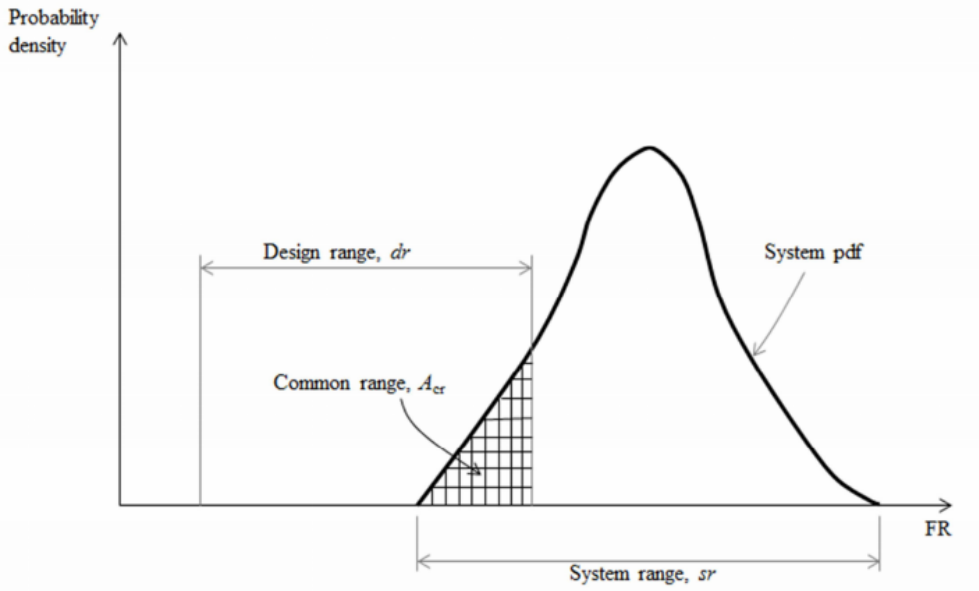


Figure 29: Normally Distributed System Range (Gurgenci, 2016)

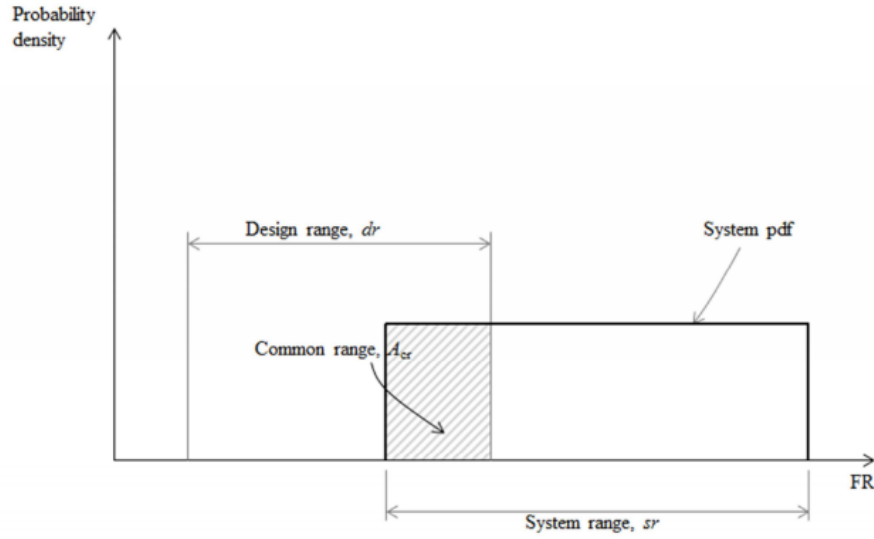


Figure 30: Uniformly Distributed System Range (Gurgenci, 2016)

For a uniform distribution, all possible values have equal probability; hence, the probability, P_i , is equivalent to the area of the common range. Hence, the information content can be determined by Equation 3

$$I_i = -\log_2 A_{cr} \quad (3)$$

where A_{cr} is the area of the common range.

For a normal distribution, the probability is weighted based on different values. A property of normal distributions is that 99.7% of the data lies within three standard deviations of the mean. Hence, I will assume the upper and lower bounds of the system range are three standard deviations above and below the mean, respectively. With the mean, μ , and the standard deviation, σ , the z-score can be calculated using Equation 4

$$Z = \frac{X - \mu}{\sigma} \quad (4)$$

where X will be the values corresponding to the common range. The z-score allows us to determine the probability of a particular range occurring within a normal distribution. For instance, the probability of obtaining a value with a z-score between -1 and 1, is 68%, as per Figure 31. Table 35, in Appendix 1.6, provides more accurate probability values for a larger range of z-scores.

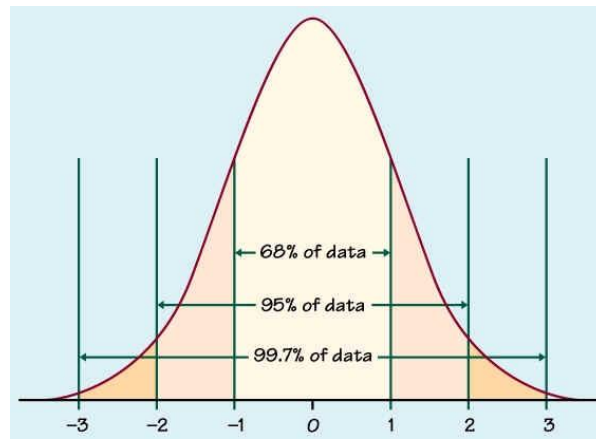


Figure 31: Z-Scores and Probability Distribution (Lake Tahoe Community College, 2008)

I assume that some of my parameters will vary according to a normal distribution and two z-scores will be determined for each functional requirement, corresponding to the lower and upper bounds of the common range. The probability of obtaining less than each Z-score can then be evaluated using *Table 35*. The difference between these probabilities gives the probability that the design will satisfy the functional requirement (equivalent to the area of the common range), consequently allowing determination of the information content.

4.2 High Speed Rail Information Content

4.2.1 Overview

Table 18 displays the design and system ranges for the HSR system.

Table 18: Design and System Ranges (HSR)

Functional Requirement	Design Range	System Range
Power	Power available > 200 kW	Power available > 200 kW
G-Forces	$F_G < 0.5G$	$F_G < 0.5G$
External Noise	External Noise < 100 dBA	76 – 109 dBA
Vibrations	$IR < 1$	$0 < IR < 1.3$
Duration	$T_{\text{SYD-CANB-MELB}} < 199 \text{ mins}$	$181 < T_{\text{SYD-MELB}} < 215 \text{ mins}$
Cabin Noise	Cabin Noise < 85 dBA	55 – 86 dBA
Passengers per day	53200	53200+

The functional requirements *Power*, *G-Forces* and *Passengers per day* all have a system range completely bound by the corresponding design range and therefore have information contents of zero because they can be controlled precisely during manufacture and operation.

Duration, *External Noise* and *Cabin Noise* system ranges were all predicted by average literature values that accounted for an arbitrary amount of uncertainty. Hence, the design parameters are most likely to perform around the means of the ranges, and normal distributions are most suitable for these functional requirements.

The vibration model is challenging to predict, and applying a normal distribution is not suitable because there is no value that is more likely than any other; hence, a uniform distribution will be applied.

4.2.2 External Noise

The design and normalised system range for the *External Noise* functional requirement are displayed in *Figure 32*.

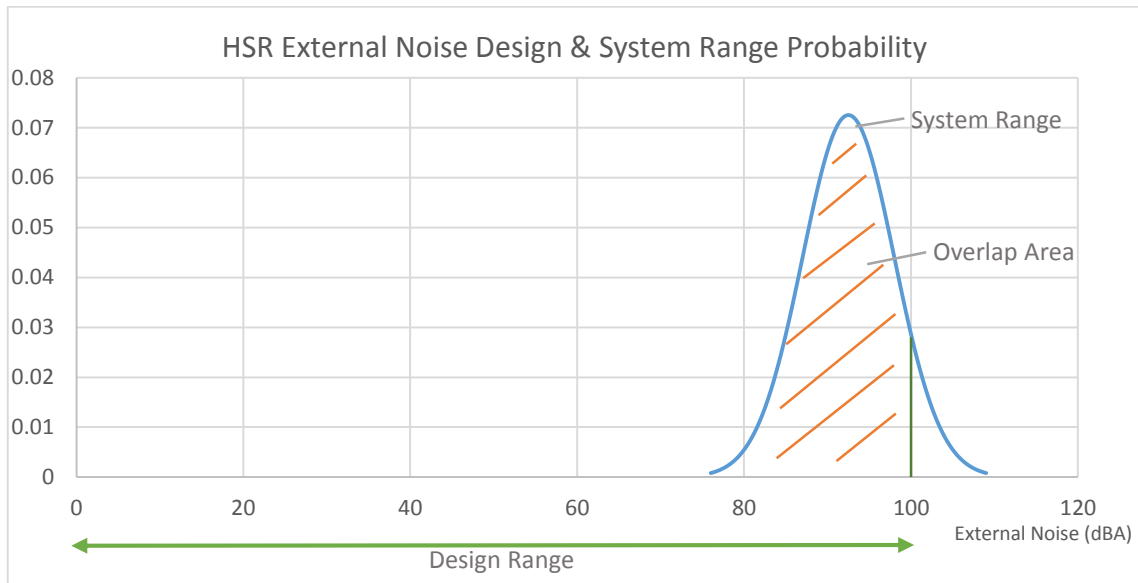


Figure 32: Probability of Design Success (HSR External Noise)

An evaluation of the z-scores was completed and is described in *Appendix 1.6*. From this evaluation, it was determined that there is approximately a 91% probability that the *External Noise* functional requirement will be satisfied. By applying *Equation 1*, this equates to an Information Content of 0.13.

4.2.3 Cabin Noise

The design and normalised system range for the *Cabin Noise* functional requirement are displayed in *Figure 33*.

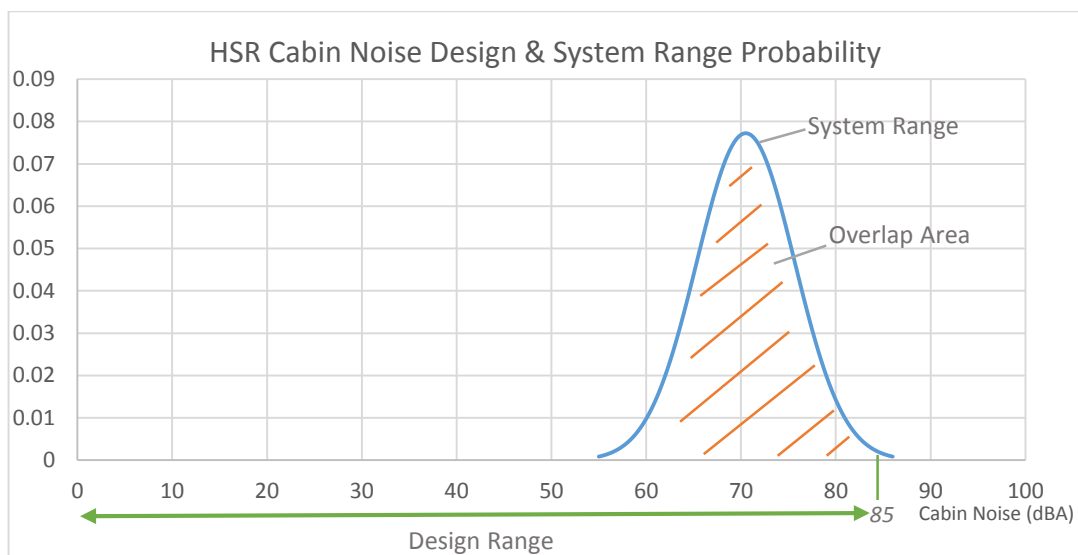


Figure 33: Probability of Design Success (HSR Cabin Noise)

An evaluation of the z-scores was completed and is described in *Appendix 1.6*. From this evaluation, it was determined that there is approximately a 99% chance the *Cabin Noise* functional requirement will be satisfied. By applying *Equation 1*, this equates to an Information Content of 0.01.

4.2.4 Duration

The design and normalised system range for the *Duration* functional requirement are displayed in Figure 34.

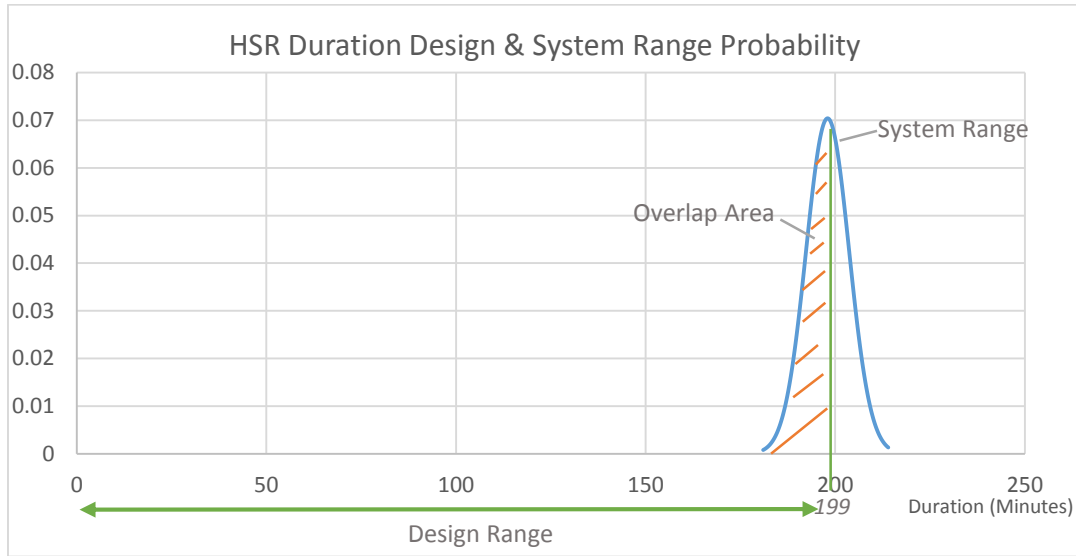


Figure 34: Probability of Design Success (HSR Duration)

An evaluation of the z-scores was completed and is described in Appendix 1.6. From this evaluation, it was determined that there is approximately a 57% probability that the *Duration* functional requirement will be satisfied. By applying Equation 1, this equates to an Information Content of 0.81.

4.2.5 Vibrations

The design and uniform system range for the *Vibrations* functional requirement are displayed in Figure 35.

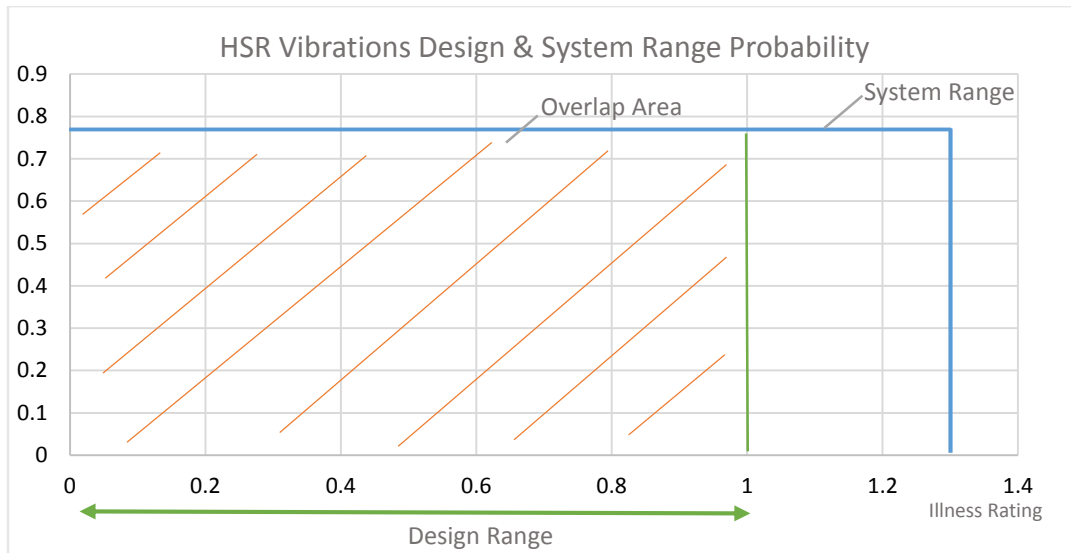


Figure 35: Probability of Design Success (HSR Vibrations)

The common range is from 0 to 1, whilst the system range is 0 to 1.3. Hence, the probability of the system range satisfying the functional requirement is

$$P_{Vibrations} = A_{cr} = \Delta x \times \Delta y$$

$$P_{Vibrations} = (1 - 0) \times (0.7692 - 0)$$

$$P_{vibrations} = 0.7692$$

Therefore, there is approximately a 77% probability that the external noise functional requirement will be satisfied. By applying *Equation 3*, this equates to an Information Content of 0.38.

4.2.6 Total HSR Information Content

Table 19 displays a summary of the HSR information content values.

Table 19: HSR Information Content Breakdown

Functional Requirement	Information Content
Power	0
G-Forces	0
External Noise	0.13
Vibrations	0.38
Duration	0.81
Cabin Noise	0.01
Passengers per day	0
TOTAL	1.33

The functional requirements are independent, hence *Equation 2* is valid and the total information content of the HSR system is 1.33.

4.3 Hyperloop Information Content

4.3.1 Overview

Table 20 displays the design and system ranges for the Hyperloop system.

Table 20: Design and System Ranges (Hyperloop)

Functional Requirement	Design Range	System Range
Power	Power available > 535 kW	Power available > 535 kW
G-Forces	$F_G < 0.5G$	$F_G < 0.5G$
Capacity	Capsule Capacity > 27 people	Capsule Capacity = 28
External Noise	External Noise < 100 dBA	11 – 19 dBA
Vibrations	$IR < 1$	$0 < IR < 1.7$
Pressure	$75 \text{ kPa} < P < 101 \text{ kPa}$	$75 \text{ kPa} < P < 101 \text{ kPa}$
Duration	$T_{\text{SYD-MELB}} < 65 \text{ minutes}$	$56 < T_{\text{SYD-MELB}} < 81 \text{ mins}$
Capsule Noise	Capsule Noise < 85 dBA	68 – 95 dBA

The functional requirements *Power*, *Pressure*, *G-Forces*, *External Noise* and *Capacity* all have a system range completely bound by the corresponding design range and therefore have information contents of zero.

Duration and *Capsule Noise* system ranges were both predicted by average literature values that accounted for an arbitrary amount of uncertainty. Hence, the design parameters are most likely to perform around the means of the ranges, and normal distributions are most suitable for these functional requirements.

The vibration model is challenging to predict and applying a normal distribution is not suitable because there is no value that is more likely than any other; hence, a uniform distribution will be applied.

4.3.2 Capsule Noise

The design and normalised system range for the *Capsule Noise* functional requirement are displayed in *Figure 36*.

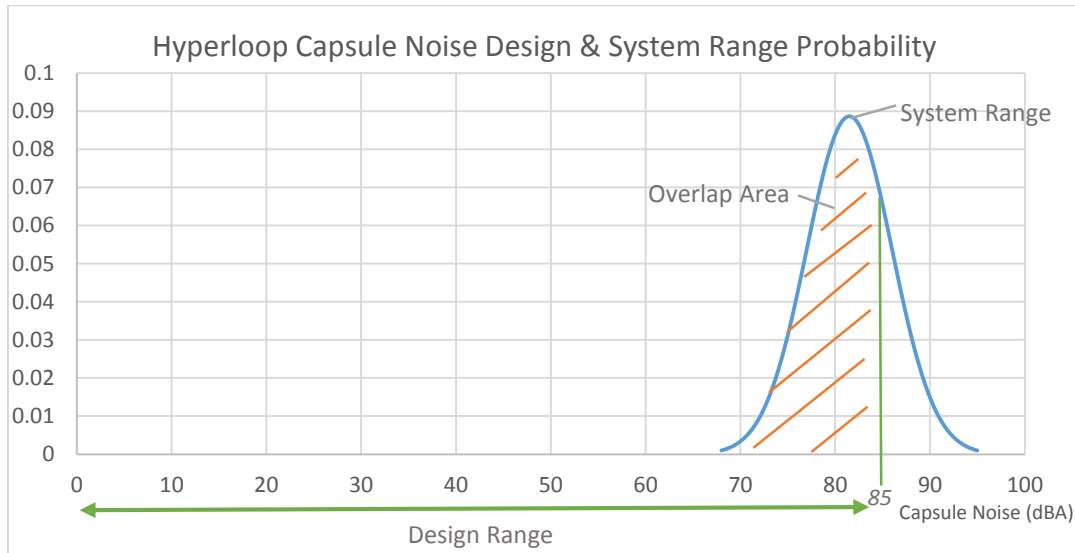


Figure 36: Probability of Design Success (Hyperloop Capsule Noise)

An evaluation of the z-scores was completed and is described in *Appendix 1.6*. From this evaluation, it was determined that there is approximately a 78% chance that the *Capsule Noise* functional requirement will be satisfied. By applying *Equation 1*, this equates to an Information Content of 0.36.

4.3.3 Duration

The design and normalised system range for the *Duration* functional requirement are displayed in *Figure 37*.

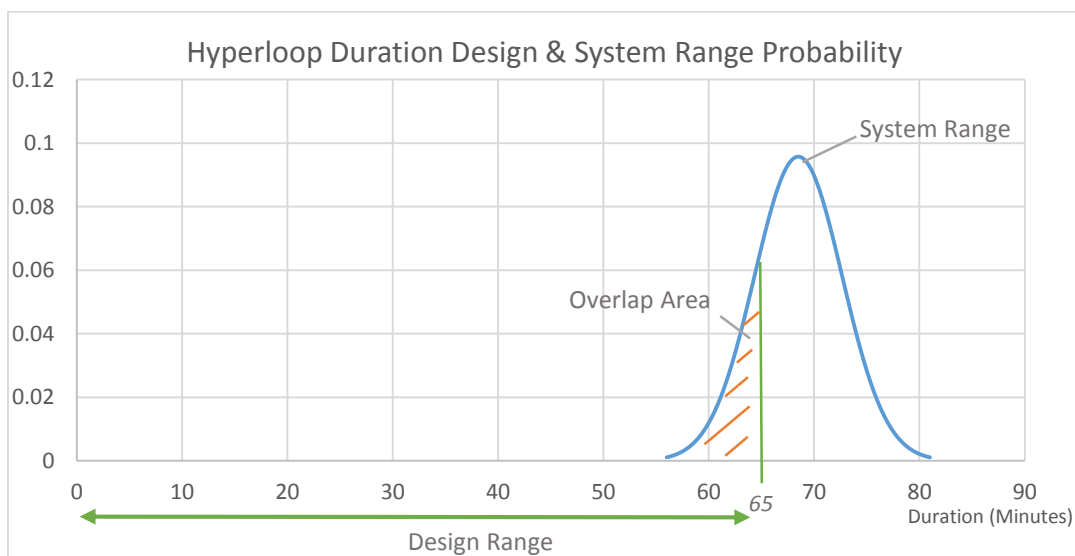


Figure 37: Probability of Design Success (Hyperloop Capsule Noise)

An evaluation of the z-scores was completed and is described in *Appendix 1.6*. From this evaluation, it was determined that there is approximately a 13% chance that the *Duration* functional requirement will be satisfied. By applying *Equation 1*, this equates to an Information Content of 2.99.

4.3.4 Vibrations

The design and uniform system range for the *Vibrations* functional requirement are displayed in *Figure 38*.

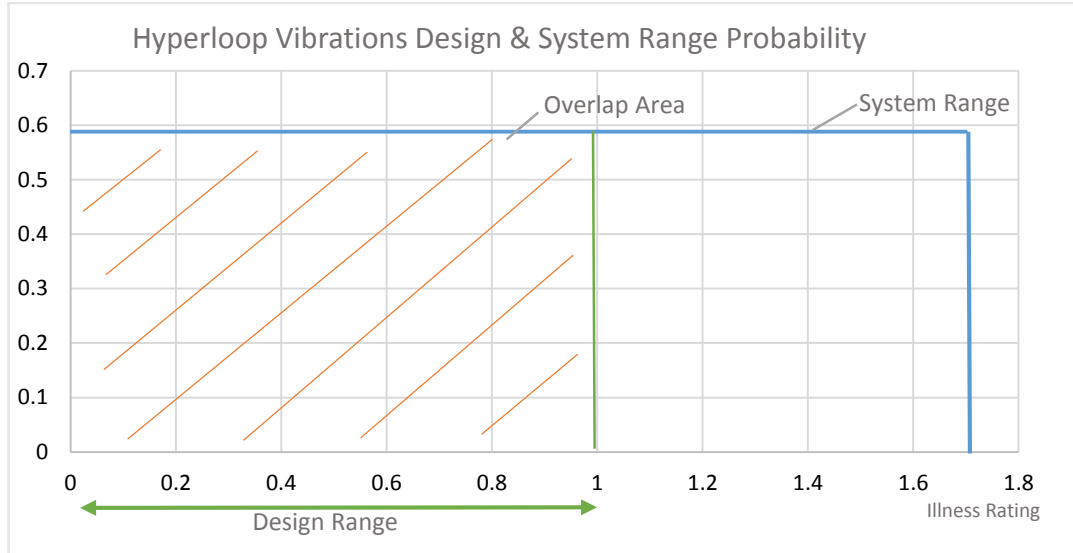


Figure 38: Probability of Design Success (Hyperloop Vibrations)

The common range is from 0 to 1, whilst the system range is 0 to 1.7. Hence, the probability of the system range satisfying the functional requirement is:

$$\begin{aligned}
 P_{Vibrations} &= A_{cr} = \Delta x \times \Delta y \\
 P_{Vibrations} &= (1 - 0) \times (0.5882 - 0) \\
 P_{vibrations} &= 0.5882
 \end{aligned}$$

Therefore, there is roughly a 59% probability that the *Vibrations* functional requirement will be satisfied. By applying *Equation 3*, this equates to an Information Content of 0.77.

4.3.5 Total HSR Information Content

Table 21 displays a summary of the Hyperloop information content values.

Table 21: Hyperloop Information Content Breakdown

Functional Requirement	Information Content
Power	0
G-Forces	0
Capacity	0
External Noise	0
Vibrations	0.77
Pressure	0
Duration	2.99
Capsule Noise	0.36
TOTAL	4.12

The functional requirements are independent, hence *Equation 2* is valid and the total information content of the Hyperloop system is 4.12.

4.4 Summary

The High Speed Rail system has an information content of 1.33 and the Hyperloop system has an information content of 4.12. Therefore, by the principle of axiomatic design, which stipulates that the design that minimises the information content is the better design, High Speed Rail is the preferred design option.

This was the expected result as the Hyperloop is a design in its infancy with a high degree of uncertainty in the majority of its components. As such, significantly more information regarding the Hyperloop is essential before the system is preferred to High Speed Rail.

The information content evaluation relied solely on the functional requirements and relevant design parameters, but neglected a number of design aspects which will need to be accounted for if either system is developed. For this reason, because the Hyperloop is an immature design and has a number of unknown elements, it will likely have a significantly higher actual information content. For instance, maintaining Hyperloop's low tube pressure was not included as a functional requirement because it was a critical design feature that most functional requirements depended on. It was not included because it created dependence between functional requirements, consequently violating Axiom 1. The construction and pressure and thermal loading of the Hyperloop was also not accounted for and the design of both systems relied on consistent performance which did not account for the frequency of maintenance or likelihood of mechanical failure. More information is required in these areas; it is exceedingly difficult, however, to model and account for these unknowns using axiomatic design.

It is important to note that the HSR design did not have an information content of zero, which indicates that additional information to that found in the Phase 2 Report is necessary before the HSR system can be installed in Australia. Both systems have a degree of uncertainty, and development of the designs will be needed before construction can commence.

Axiomatic design was initially proposed for this study because it provides a quantitative value that effectively defines the uncertainty in each design. By quantifying the uncertainty in each design, the design with less associated risk can be chosen as this is the design that has a greater likelihood of success. The issue with implementing axiomatic design in this particular study is that the systems have significantly different operating conditions. For instance, the maximum operational speed and expected journey time of each design is considerably different. An information content analysis does not account for the different outputs of the design and therefore is only applicable when the functional requirements and design ranges of both systems are equivalent. In this study, I attempted to keep the functional requirements consistent for both designs; however, due to the inherent differences in the systems, some disparity was unavoidable. As a result, relying entirely on a comparison of information contents is not sufficient for design selection. For rigorous design assessment, the cost and performance of both systems need to also be considered.

5 Cost Analysis

5.1 High Speed Rail Cost Analysis

There are a variety of infrastructure and non-infrastructure capital costs associated with the development and construction of a High Speed Rail system. All costs throughout this study are given in Australian Dollars (AUD).

5.1.1 Permanent Way

Permanent way encapsulates the track and its associated components, such as rail-crossings and turnouts where the tracks intersect. The Phase 2 study established a cost for the slab track per kilometre and cross-checked the estimations with international standards, determining that the cost per kilometre of a dual, slab track is \$3.55M. The frequency and position of turnouts and crossings was not determined in the Phase 2 study, nor my study, so an allowance for their cost was applied on a linear basis along the route, specified as \$200K per kilometre. As such, the total cost of the permanent way is \$3.5 billion.

5.1.2 Tunnels

The construction of tunnels is one of the main contributors to the expense of the HSR system because it involves a variety of key processes, including, but not limited to: earthworks, excavation, drainage and waterproofing, ventilation and track installation. The Phase 2 study specified a construction rate of roughly \$180M per kilometre of twin bore tunnel, which includes a \$20M (per kilometre) safety redundancy for unaccounted for factors. 51.3 km of the total route between Sydney, Canberra and Melbourne is in-tunnel, which equates to a total tunnel construction cost of \$9.2 billion.

5.1.3 Structures

The Phase 2 study considered sixteen different structure (bridges/viaducts) types for the alignment, whose selections was based on the local terrain, geology, flood susceptibility and the requirement of grade separations when other rail lines or roads need to pass over the HSR route. In order to simplify the cost processing, a singular unit rate of \$110M per kilometre was assumed for the structure cost rate. This equated to a cost estimate of \$5.6 billion for the Sydney-Canberra-Melbourne section. No uncertainty range will be specified here as (a) it would be arbitrary and (b) it will be covered by the total cost uncertainty, discussed in *Section 5.1.12*.

5.1.4 Earthworks

The term earthworks describes the processes and activities involved in excavating, moving and ground forming of cuttings and embankments. There are a variety of different earthwork types, including hauling mass, borrowing, dumping, filling and cutting, which each have different associated costs. The quantity and type of earthworks involved in the HSR installation was determined using the alignment software implemented by AECOM. From these values, they estimated \$7 billion of earthworks would be required for the Sydney-Canberra-Melbourne route.

5.1.5 Civil Works

Civil works covers an extensive number of different processes, which will be involved throughout the construction of the railway, including, but not limited to: fencing, construction of retaining and noise attenuation walls, slope stabilising, utility relocation, site clearance, drainage and landscaping. Similar to earthworks, it is difficult and potentially inaccurate to

assume a cost per kilometre for civil works, so the total cost specified in the Phase 2 study, of \$3.6 billion, will be used for my analysis.

5.1.6 Signalling & Communication

Table 22 details the costs associated with signalling for the HSR system.

Table 22: Capital costs associated with signalling systems

Signalling Element	Unit Rate (\$)	Unit of measurement	Characteristic
Track crossover	6,000,000	Each	Frequency every 20km
Station crossover	12,000,000	Each	At each station
Fixed balises	2,000	Per route km	Entire length
Control centre	35,000,000	Each	Two total

For clarity, a balise is an electronic beacon between the rails which is required as part of an Automatic Train Protection (ATP) system (Connor, Schmid, & Watson, 2016); and the control centre is a secure compound which includes signalling control, electrical and mechanical equipment.

Table 23 details the costs associated with communications for the HSR system.

Table 23: Capital costs associated with communication systems

Communication Element	Unit Rate (AUD)	Unit of measurement	Characteristic
Control centre – comm. Equipment	10,000,000	Each	Equipment only
Train operations data	100,000	Per train set	Included in rolling stock unit price
Train Wi-Fi	300,000	Per train set	Included in rolling stock unit price
Cable route	125,000	Per route km	Excludes tunnelled sections
Radio tower	800,000	Each	Every 6.5-12 kms
Base station (in tunnels)	500,000	Each	Every 500 m

The Phase 2 study specifies a cost of \$0.4 billion and 0.5 billion for the signalling and communications systems, respectively. This equates to a total cost of \$0.9 billion.

5.1.7 Power

Power is distinguished between two components, namely transmission and distribution. Transmission refers to the infrastructure required to receive power from the National Electricity Market (NEM) and to convert it to an appropriate power level for the HSR traction supply. Power distribution refers to the infrastructure associated with providing power to the HSR train sets, which includes overhead line electrification, traction power substations and autotransformers. In the Phase 2 study, the cost of the transmission and distribution systems was determined to be \$0.3 billion and \$2.4 billion, respectively. This equates to a cost of \$2.7 billion.

5.1.8 Stations

Along with the development and construction of stations, there are also a variety of car parks, stabling facilities and infrastructure and maintenance depots, which all contribute to the capital cost of the HSR system. The Phase 2 report goes into detail regarding the costs associated with each of these facilities; however, the detail is not essential for this study, so it will be omitted. The Phase 2 study specifies a cost of \$4 billion for the stations and facilities for the Sydney-Canberra-Melbourne alignment.

5.1.9 Land Acquisition

To develop, construct and operate the proposed HSR network, a large quantity of land will need to be acquired, both temporarily and permanently. Land needs to be acquired for a variety of purposes, including corridor reservation and preservation, stations, depots, facilities, power substations and tunnel ventilation, and to offset encroachment onto environmentally sensitive land or land within national parks. Similar to the station cost analysis, the Phase 2 study provides significant detail regarding the derivation of a cost estimate; however, for our purposes, this detail is not necessary. The Phase 2 study specifies a cost of \$1.9 billion for land acquisition.

5.1.10 Rolling Stock

The acquisition of the train sets is a non-infrastructure capital cost. The Phase 2 study directly sourced the cost estimations for HSR train sets from suppliers in Europe and Asia, determining that 300 metre train sets will cost \$70M each. This equates to a cost of approximately \$3.5 billion for the rolling stock required to service the Sydney-Canberra-Melbourne alignment in 2065. Although my design specifies the CRH3C train type, there is limited data available regarding the cost of stock supply of this train type, so the Phase 2 study cost estimation will be assumed for my system.

5.1.11 Development

There are development costs associated with the different stages of HSR installation; namely: pre-phase and preliminaries, planning, design and procurement; and construction and commissioning. Client development costs vary significantly between countries and systems, reflective of the difference in length and complexity of HSR systems, as well as the country's employment and wage structures, and their legal, legislative and political frameworks. Hence, the development costs associated with a number of European HSR lines were evaluated and it was predicted that the Sydney-Canberra-Melbourne alignment would require \$4.8 billion to cover the development costs.

5.1.12 Cost Summary

Table 24 summarises the infrastructure and non-infrastructure capital costs associated with the HSR system.

Table 24: HSR Cost Summary

Cost Category	Cost (Billion AUD)
Permanent Way	3.5
Tunnels	9.2
Structures	5.6
Earthworks	7
General Civil Works	3.6
Signalling & Communication	0.9
Power	2.7
Stations & Facilities	4
Land Acquisition	1.9
Rolling Stock	3.5
Client Development	4.8
TOTAL	46.7

AECOM's Phase 2 study allowed a high sensitivity range from -10% to +30% for their cost predictions (AECOM, 2013). As the values for my cost prediction were sourced from the Phase 2 study, I can assume that the sensitivity range is equivalent. Therefore, the cost range for my HSR system is \$42 billion to \$60.7 billion.

5.2 Hyperloop Cost Analysis

The Hyperloop capital costs will have contributions from the same categories as the HSR system, with relevant adjustments to the cost based on system design.

5.2.1 Tube/Pylon Route

Unlike the HSR, which has a "Permanent Way" associated cost, the Hyperloop will have a cost for the construction and assembly of the steel tubes and pylons. Machined steel was specified as the tube material, with roughly 20 mm thickness. Medium carbon steel used in Australia costs roughly \$1300 per tonne, as of 2012 (AZOM, 2012). Assuming a uniform thickness of 20 mm and a density of 7870 kg/m³, the cost per kilometre of the machined steel tube is \$1.05M. Applying a scaling factor of '3' to account for the cost of machining and installing the steel tubes, the cost per metre is roughly \$6350. Given a total route length of 1002 km, this equates to a total tube cost of \$6.4 billion.

The other major cost associated with the tubes is the magnetic levitation running throughout the entire route length and the short stretches of propulsion before and after each station. The cost of Maglev train systems typically ranges between \$35 and \$40M per kilometre; however, this includes the cost of the track, the rolling stock and a variety of other costs (Monorails Australia, 2016). It is difficult to determine how much the magnetic levitation and propulsion will cost when incorporated into the tube. The Alpha study suggests that the cost of the propulsion stator is \$35M per kilometre (Musk, 2013). Due to the low drag environment of the tube, only a small stretch of propulsion is required, whereas levitation is required throughout the whole length of the tube. Assuming that the propulsion costs significantly more than basic magnetic levitation, I will estimate that the cost per kilometre of the magnetic system is roughly \$15M per kilometre. This equates to a total cost of \$15 billion. This is a highly sensitive value

that was based primarily on engineering judgement, and will need to be developed further in the future.

Given that there is no available cost alternative for the concrete pylons, the cost of \$126,500 per pylon and 30 metre spacing, outlined in the Alpha study, will be used. This equates to a total pylon cost of \$4.2 billion. Thus, the route, assuming the cost of expansion joints is relatively negligible, will cost approximately \$22.4 billion (Musk, 2013).

5.2.2 Tunnels

Due to flow considerations, the HSR tunnels need to be significantly larger than the train cross-sectional area, typically around 8 metre diameter (Thompson, 2011); however, the Hyperloop tunnels only need to house the Hyperloop tubing, roughly 6.6 metre diameter. It was therefore assumed that the Hyperloop tunnelling will cost 15% less than the HSR. Thus, the cost per kilometre of tunnelling is \$153M. Assuming an equivalent tunnelling distance of 51.3 kilometres, this equates to \$7.8 billion (AECOM, 2013).

5.2.3 Structures

Due to the pylons supporting and elevating the tube, no bridges or viaducts are necessary for the Hyperloop route; hence, I assume there is no associated structures cost in addition to the pylons.

5.2.4 Earthworks

The earthworks associated with the Hyperloop would likely be different to those associated with the HSR system; however, with no additional resources to determine the cost difference, I will assume they are equivalent. Therefore, there are \$7 billion of earthworks required for the Hyperloop route. This will likely be an over-estimation of the cost because the pylons should reduce the amount of earthworks, but it would be largely guesswork to determine the degree of cost reduction.

5.2.5 Civil Works

The civil works associated with the Hyperloop may be different to those associated with the HSR system; however, with no additional resources to determine the cost difference, I will assume they are equivalent. Accordingly, the cost of Hyperloop civil works will be \$3.6 billion.

5.2.6 Signalling & Communication

The signalling and communication systems in the Hyperloop system will be different to those incorporated into the HSR system; however, given that signalling and communication systems are fairly standard, I will assume the cost is equivalent for both systems. Therefore, there will be \$0.9 billion associated with signalling and communication.

5.2.7 Power

Solar panels and battery storage are required to power the magnetic propulsion and levitation. The Alpha study suggests that the solar array and associated electronics will cost \$270M (Musk, 2013). Extrapolating this by distance to the Australian Hyperloop system, the expected solar array cost is \$480M. However, the power demand of my system is far greater than the Alpha study proposal because the magnetic levitation system will need to be powered for the entire tube length. Assuming the additional power sink will require approximately five times the power supply, this equates to a total cost of \$2.4 billion. This is a highly sensitive value that was based primarily on engineering judgement and will need to be developed further in the future.

5.2.8 Stations

The stations and facilities associated with the HSR system cost \$4 billion. The Hyperloop will need similar stations and facilities; however, there will likely need to be greater security due to the highly volatile, low pressure environment of the tube, and vacuum pumps will need to be installed at each station to allow capsule depressurisation. I assume a 25% increase in the cost of stations and facilities, such that the total cost will be \$5 billion. This is a highly sensitive value that was based primarily on engineering judgement and will need to be developed further in the future.

5.2.9 Land Acquisition

The land acquisition associated with the Hyperloop should be equivalent to the HSR system as the route is assumed to be identical. Hence, the cost of Hyperloop land acquisition will be \$1.9 billion.

5.2.10 Capsules

The Alpha study suggests that each capsule will cost \$1.15M, with the air bearing cost neglected. To accommodate the large volume of commuters expected to use the system, and assuming a capsule departs every 30 seconds, roughly 250 capsules are required to service the route. This equates to a total capsule cost of \$290M. The number of capsules was based on a rough estimation and will need further refinement in the future; however, the cost of the capsules is low relative to other components of the system.

5.2.11 Development

The HSR system requires \$4.8 billion for development. The Hyperloop is an untested, immature technology and will therefore require substantially more development. The cost of this development will likely be spread between a variety of companies attempting to develop the Hyperloop; however, the Australian Hyperloop will still need specific development, which I assume to be roughly four times the HSR system development. Hence, the Hyperloop will require \$20 billion for development. This is a highly sensitive value that was based primarily on engineering judgement and will need to be developed further in the future.

5.2.12 Cost Summary

Table 25 summarises the infrastructure and non-infrastructure capital costs associated with the Hyperloop system.

Table 25: Hyperloop Cost Summary

Cost Category	Cost (Billion AUD)
Tube/Pylon Route	25.6
Tunnels	7.8
Structures	-
Earthworks	7
General Civil Works	3.6
Signalling & Communication	0.9
Power	2.4
Stations & Facilities	5
Land Acquisition	1.9
Capsules	0.3
Client Development	20
TOTAL	74.5

There is a large degree of uncertainty in the Hyperloop cost estimation, particularly in the tube costs, earthworks, power supply, stations and development. Hence, I will apply a -30% to +50% uncertainty range on the cost. Therefore, the cost of the Hyperloop system should be between \$52.2 and \$111.8 billion.

One may argue that the uncertainty range should only be applied to the uncertain items in the Hyperloop budget and the rest should have the same uncertainty range as the HSR. However, this will not make a significant difference because the HSR-similar items add up to only \$12 billion, or 15% of the total cost estimate.

5.3 Financial Comparison

The capital costs associated with the HSR range from \$42 billion to \$60.7 billion. The capital costs associated with the Hyperloop range from \$52.2 billion to \$111.8 billion. A comparison of the upfront costs of each system is not sufficient to suggest a preferable system. The ongoing costs involved in running the system and the potential annual revenue of both systems must also be considered. The payback period and net present values (NPV) of the systems over a given timeline will provide a better comparative tool.

The total maintenance and operation cost of the HSR over a 50-year timeline is projected to be roughly \$96 billion for the Sydney-Canberra-Melbourne alignment (AECOM, 2013). Approximately 50% of this cost is associated with traction power supply; hence, as the Hyperloop is powered by solar arrays, its operational costs are substantially lower. Setting solar array maintenance cost to \$400 thousand per year (Vella, 2016) and assuming all other operational and maintenance costs are equivalent for both systems, the Hyperloop is projected to have a maintenance and operations cost of \$48 billion over a 50-year timeline. Assuming the maintenance and operations costs are consistent, this equates to a cost of \$1.9 billion per year for HSR and \$0.95 billion per year for the Hyperloop.

The HSR Phase 2 study suggests an average one-way ticket price of \$85 (AECOM, 2013), so this will be assumed as the ticket price for all HSR journeys, regardless of journey distance. Using the customer markets outlined in *Section 2.2*, the annual revenue of each service can then be estimated. The Hyperloop offers journey durations approximately one-third that of the time over the same distance taken by the HSR. Given the accessibility of the route it will also be faster than airplane flights, so it is anticipated that the ticket prices will be greater for the Hyperloop. In light of the greater performance, the Hyperloop ticket prices will be approximately 50% greater than HSR. This equates to an average ticket price of \$125. In practice, there would be a variety of ticket prices for both systems depending on the route duration and journey type; however, for a financial analysis, average ticket prices will suffice.

For the financial assessment, the following assumptions were made:

1. All capital expenditure costs occur before the operation of the transportation lines, such that the total cost of the system occurs in a lump sum payment in year zero
2. A discount rate of 4%, as suggested in the Phase 2 study (AECOM, 2013)
3. Consistent, annual maintenance and operation costs
4. No asset renewal
5. Expected passenger demand is met in the first year and is satisfied in all operational years
6. Static ticket prices, independent of journey type/duration or year.

Assumptions 3 and 4 result in consistent annual expenses and Assumptions 5 and 6 result in consistent annual revenue. The NPV and payback period are primarily being used as a relative, comparison tool, so these Assumptions are acceptable. *Table 26* provides a summary of the financial parameters.

Table 26: Financial Summary

System	High Speed Rail	Hyperloop
Initial Investment	46.7 billion AUD	74.5 billion AUD
Annual Revenue	1.65 billion AUD	2.65 billion AUD
Annual Expenses	1.90 billion AUD	0.99 billion AUD
Annual Net Profit	-0.25 billion AUD	1.69 billion AUD
Discount Rate	4%	4%

An implication of this analysis is that the HSR system is not predicted to generate positive cash flow in the 50-year timeline; however, the HSR system proposed by AECOM is predicted to generate annual profit after approximately thirty years (AECOM, 2013). The reason for this discrepancy is that my system does not incorporate the Brisbane-Sydney alignment which will provide significant, additional revenue. The Hyperloop annual revenue would also increase with the inclusion of the Brisbane-Sydney market, so the financial comparison remains valid.

It is worth noting that only one of the Japanese National Railways' eight Shinkansen high-speed routes (the Tokyo-Osaka line) generates enough revenue to cover the costs of operation and maintenance. Further, this line transports 140 million passengers per year, which represents far more passengers than the Australian line is envisaged to carry. Therefore, it is not surprising that the Australian HSR will not generate a net annual profit (The Economist, 2016).

For the purpose of a direct comparison, the future value of the systems was evaluated. This evaluation assumed that the value of money does not vary with time and the annual net profit is constant for the entire duration of the project.

Figure 39 displays the future values of the HSR and Hyperloop systems, respectively.

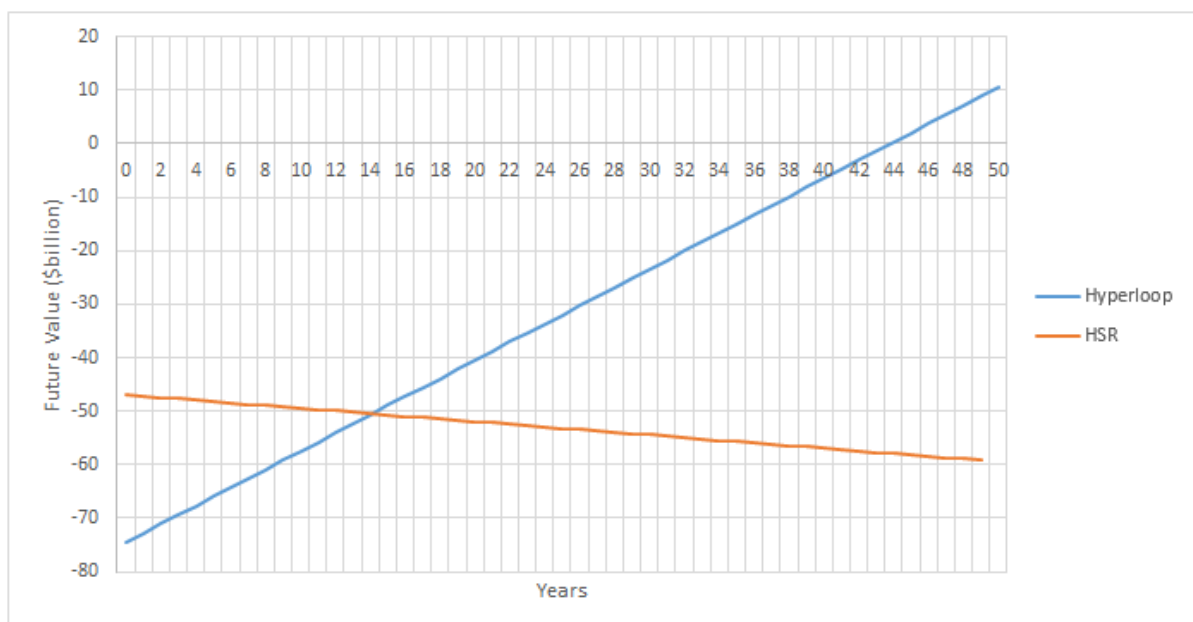


Figure 39: Future value of HSR and the Hyperloop

Applying the future value model, as per *Figure 39*, The Hyperloop project is predicted to pay back the initial investment in roughly 44 years, whereas it is predicted that the initial expenditure on the HSR project will never be recovered. The maintenance and operational cost of HSR exceeds the annual commuter revenue, so there is a net annual loss each year over this 50-year timeline. Hyperloop generates a net profit because of the lower maintenance and operational costs and the higher commuter volume and ticket prices.

Although payback period is a frequently used metric to gauge a project's success, it fails to account for the time value of money. Hence, for long-term investments, like these projects, there is a greater potential for inaccuracy over time and the payback period will not necessarily provide an accurate portrayal of project profitability. For this reason, it is important to consider the NPV of both projects with time. Money in the present is worth more than the same amount in the future because of inflation and the potential earnings that could be made using the money during the intervening time. The NPV accounts for the time value of money and is therefore a more accurate metric for determining a project's feasibility over a long timeline. If a project has a positive NPV during its lifetime then the project is profitable (Investopedia, 2016).

The NPV of HSR and the Hyperloop are displayed in *Figure 40*.

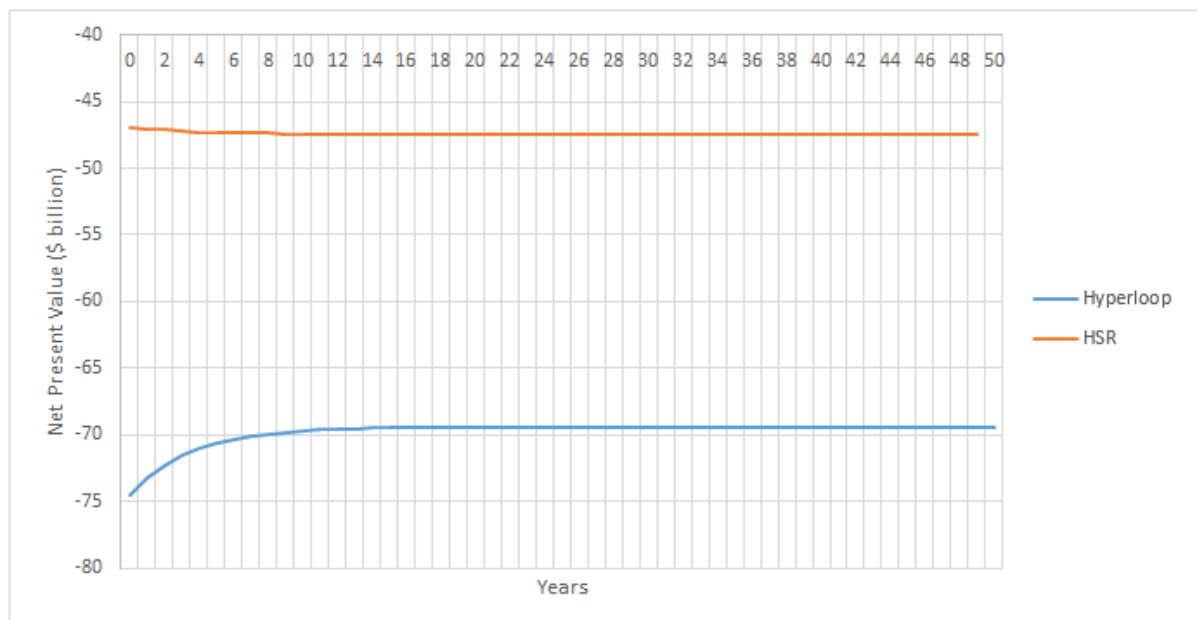


Figure 40: Net Present Value of HSR and the Hyperloop

The NPV of HSR plateaus around negative \$47.4 billion and the NPV of Hyperloop plateaus around negative \$69 billion. Although neither project is predicted to generate a net, lifetime profit, the NPV of the Hyperloop is substantially less than that of the HSR system and, therefore, from an investment point of view, the HSR is the preferable system.

The ticket price for the Hyperloop system was set rather arbitrarily, so a sensitivity analysis was conducted and the future value and net present value of the Hyperloop system is shown in *Figure 41* and *42* below. The same discount rate of 4% was used for every NPV model.

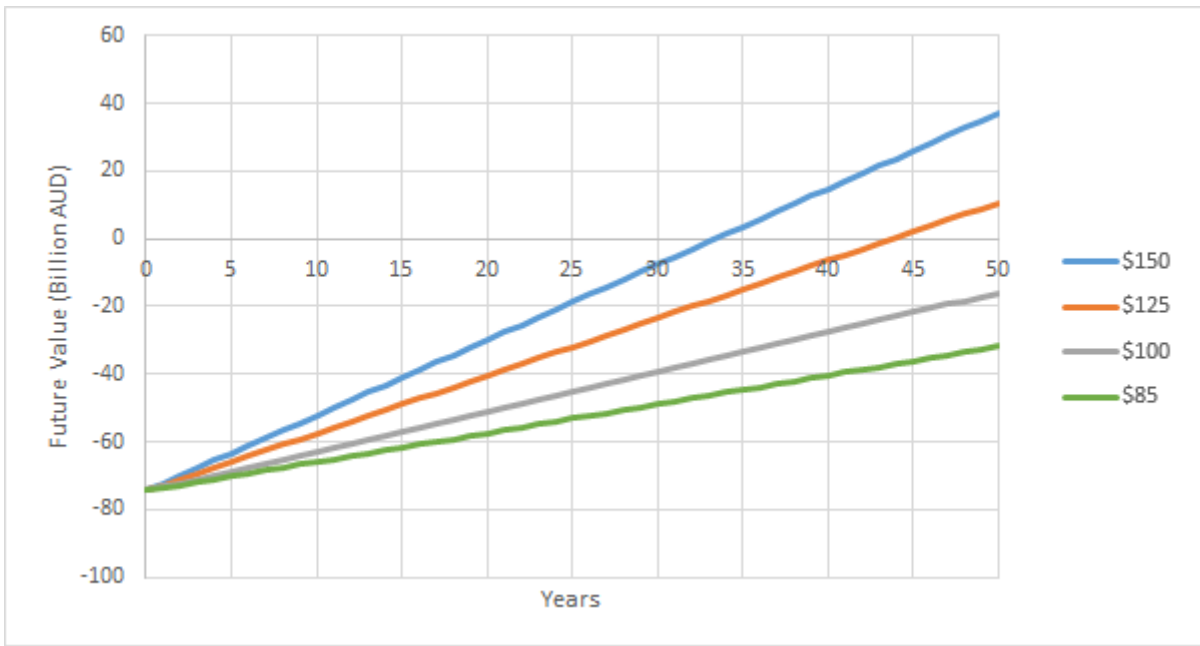


Figure 41: Hyperloop Future Value (Ticket Price Sensitivity)

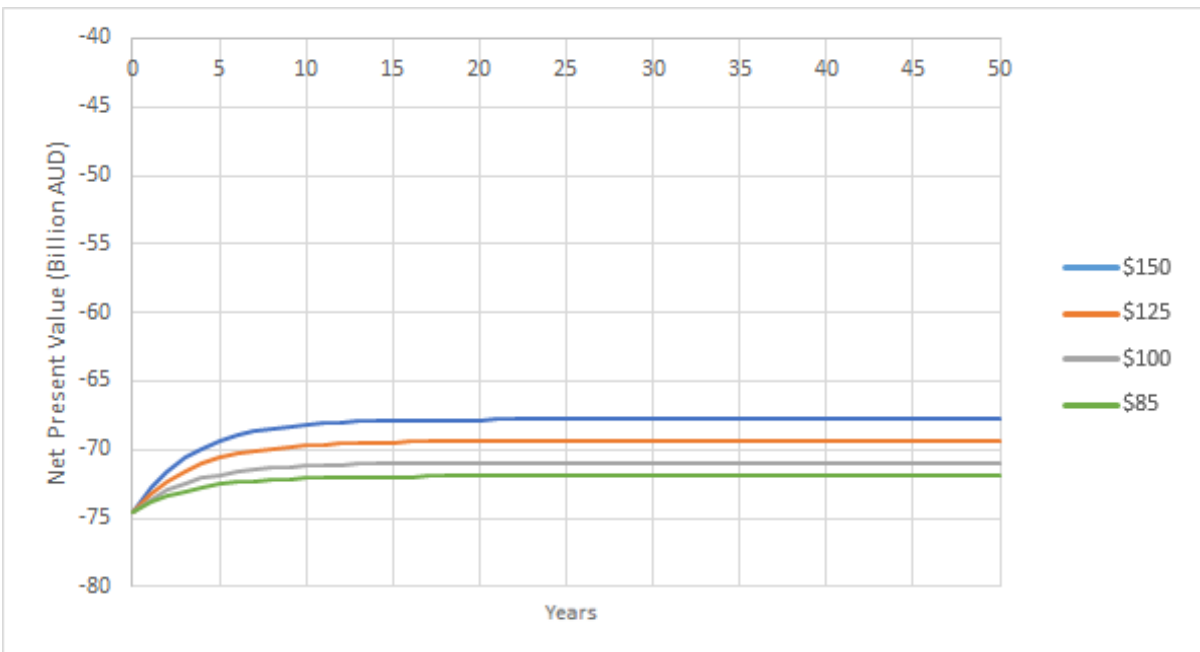


Figure 42: Hyperloop Net Present Value (Ticket Price Sensitivity)

Setting Hyperloop ticket prices to the same as the HSR, the Hyperloop will still make a net annual profit due to the lower operational costs. The ticket price has some effect on the NPV of the Hyperloop system; however, it is insufficient to overcome the significant NPV gap between the two systems and, based on this metric, the HSR system is still preferable.

It is important to reiterate that the NPV and payback periods determined in this study are not representative of the actual values of the projects, due to the extent and degree of the assumptions made throughout this analysis. There are a number of other financial factors that need to be considered in a large-scale transportation system's construction. For instance, current Australian Prime Minister, Malcolm Turnbull proposed that value capture could finance the HSR system (Karp, 2016). Value capture is a form of financing that recovers some of the value that public infrastructure generates for private landowners through land taxes or a levy on

developers of new properties. The two transportation systems would connect rural areas to urban access corridors, so there could be a substantial amount of value capture to help fund the HSR or Hyperloop. Considerations concerning value capture, and other sensitive forms of revenue, were beyond the scope of this study.

Although the financial analyses were not comprehensive, they serve as a useful comparative metric in this instance as the assumptions were consistent for both systems. A more thorough and detailed cost analysis is suggested for both of these systems to determine actual project profitability.

6 Conclusions and Recommendations

This study investigated the implementation of both High Speed Rail and the Hyperloop along the eastern coast of Australia, connecting Sydney, Canberra and Melbourne. Axiomatic design was utilised to design each system at a preliminary level and to quantify the relative uncertainty in each design, via an assessment of their respective information contents. All design choices were made on a basis of safety and reliability and therefore, any immature or under-developed alternatives were not selected in the final design. A cost analysis was conducted to determine the difference in cost of each system and to model the future and net present value of each project over a fifty-year timeline. The findings of this study suggest that HSR is the preferred design option due to less uncertainty in the design and lower capital costs.

The proposed High Speed Rail system uses a Chinese CRH3C train design, along a standard gauge, slab track. With an operational maximum speed of 350 km/hr, the expected duration of an express HSR journey from Sydney to Melbourne, with a 5-minute stopover in Canberra, is between 181 and 215 minutes. An evaluation of the design's ability to satisfy the functional requirements determined the information content of the HSR system to be 1.3. The financial assessment of the HSR subsystem costs estimated that the total capital cost associated with the HSR system is between 42 and 60.7 billion AUD. The system is not predicted to generate a net annual profit in the investigated fifty-year timeline, due to its high maintenance and operation costs.

In the proposed Hyperloop design, a capsule will levitate above a machined steel, tube surface using *Maglev* principles. It will accelerate using magnetic propulsion and, with an operational maximum speed of 1200 km/hr, the expected duration of an express HSR journey from Sydney to Melbourne, with a 5-minute stopover in Canberra, is between 55.5 and 81.2 minutes. An evaluation of the design's ability to satisfy the functional requirements determined the information content of the Hyperloop system to be 4.1. The financial assessment of the HSR subsystem costs estimated that the total capital cost associated with the HSR system is between 52.2 and 111.8 billion AUD. The system is predicted to generate a net annual profit; however, due to the sensitivity and inherent assumptions of the model, it is unclear whether the project will be profitable in the fifty-year timeline.

By the principle of axiomatic design, which stipulates that the design which minimises the information content is the better design, High Speed Rail is the preferred design option. Additionally, the HSR system is projected to cost roughly 20% less than the equivalent Hyperloop system in conservative models, and 45% less in non-conservative models, further validating HSR as the preferred design choice. The Hyperloop has lower maintenance and operation costs than HSR, however, the financial model is insufficient to make conclusions regarding the long-term profitability of the Hyperloop system.

The use of axiomatic design created a number of challenges due to the inflexibility of the design and functional requirements. As a result, there were some design elements that were omitted and others whose performance relied on a number of underlying assumptions. The limitations imposed by axiomatic design is primarily due to the inherent uncertainty in the Hyperloop and therefore, axiomatic design is not recommended for undeveloped technologies. Furthermore, for validity of the comparison, the functional requirements of both systems were kept similar; however, the vast differences between the designs and output performance resulted in the design parameters being highly manipulated to prevent coupling of the design matrix and dependence between functional requirements. It is recommended that a more thorough design of the

Hyperloop is investigated, including independent analysis of the flow behaviour, levitation mechanisms and propulsion systems. Axiomatic design is not recommended for this refined design due to the aforementioned limitations of the design method.

The cost analysis relied on a number of simplifying assumptions; however, by keeping the assumptions similar, the fractional difference between the two systems should be representative of the actual differences. All design choices were made on a basis of reliability and safety; hence, the cost of the overall Hyperloop system was roughly ten times larger than Musk et al.'s (2013) initial cost prediction of 6.6 billion AUD which relied on undeveloped or immature technology. The development of air-skis or wheels capable of withstanding repeated, supersonic journeys will alleviate the need for magnetic levitation, which will substantially reduce the cost of the system. However, basing designs and subsequent cost assessments on subsystems which do not commercially exist is highly indeterminate. The uncertainty range in the cost assessment could be reduced by a lengthier and more detailed analysis; therefore, a more comprehensive cost analysis is recommended as a future study.

Policy makers may find the results of this study sufficient to cease discussion of an Australian Hyperloop and continue with development of HSR. However, the conclusions of this study were based on a design uncertainty and cost metric, and neglected the difference in performance. Performance of the two systems was neglected because it would be arbitrarily defined by the added value of a shorter duration. The Hyperloop journey time is roughly one-third the HSR journey time. Is this performance increase worth investing twice as much? Three times as much? This is a question I pose to reiterate the arbitrary nature of investigating performance. This is a non-engineering aspect and requires surveys and political discussions; however, the reduction in trip duration is undoubtedly a major factor when comparing the systems.

The Hyperloop was proposed three years ago, in 2013. Since then, two US companies have formed and are competing to produce the world's first Hyperloop. They have had discussions with a number of European and Asian countries and are both constructing development tracks (Russon, 2016), which will serve to validate the vacuum model and experimentally validate some of the engineering subsystems outlined in Musk et al.'s (2013) study. Therefore, it is important to emphasize that although High Speed Rail seems like the better design choice at the time of writing, as shown in this report, this may not be the case in the coming years. Policy makers should continue to develop the Hyperloop and investigate its feasibility before committing themselves to a large-scale high speed rail project which may be archaic by the time it is operational. Australia has fallen behind the rest of the developed world on a number of technological breakthroughs in recent history (Eggleton, 2016). The Hyperloop may offer Australia the opportunity it needs to be at the forefront of a new technology and mode of transportation.

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Appendix

1.1 Induced Commuters

The HSR Phase 2 Study provided the number of commuters per year without the HSR in 2065, by extrapolating from current commuter numbers and the commuter numbers expected with the inclusion of the HSR. The increased numbers result from new commuters resulting from the improved transportation options. These commuter numbers are displayed in *Table 27* below.

Table 27: HSR Commuter Predictions (2065)

HSR	Sydney	Intermediate 1	Canberra	Intermediate 2	Melbourne
Sydney	X	45270	13690	5300	26950
Intermediate 1		4350	4880	350	3060
Canberra			X	2550	4890
Intermediate 2				X	84020
Melbourne					X
W/O HSR	Sydney	Intermediate 1	Canberra	Intermediate 2	Melbourne
Sydney	X	43420	11660	4460	20930
Intermediate 1		4300	4680	320	2130
Canberra			X	2240	4130
Intermediate 2				X	81660
Melbourne					X

From *Table 27* above, the percentage of induced commuters could be calculated for each section of the HSR route. By assumption 1, which proposes that the Hyperloop will induce a maximum of 10% more commuters than the HSR, percentage induced was also readily calculable. Both results are displayed in *Table 28* below.

Table 28: Induction comparison between HSR and Hyperloop

% Induced by HSR	Sydney	Intermediate 1	Canberra	Intermediate 2	Melbourne
Sydney	X	4%	17%	19%	29%
Intermediate 1		1%	4%	9%	44%
Canberra			X	14%	18%
Intermediate 2				X	3%
Melbourne					X
% Induced by Hyperloop (Max.)	Sydney	Intermediate 1	Canberra	Intermediate 2	Melbourne
Sydney	X	14%	27%	29%	39%
Intermediate 1		11%	14%	19%	54%
Canberra			X	24%	28%
Intermediate 2				X	13%
Melbourne					X

1.2 Hyperloop Demand

Table 29 below shows the upper predictions for the market share controlled by Hyperloop and the additional percentage of induced commuters predicted by 2065.

Table 29: Upper predictions for Hyperloop Demand

Station 1	Station 2	No. of 1000 Commuters per year (w/o HSR)	HSR Market Share [%]	Hyperloop Market Share	Induced Hyperloop (Max) [%]
Sydney	Intermediate 1	43.42	6	6+5 (11)	14
Sydney	Canberra	11.66	38	38+15 (43)	27
Sydney	Intermediate 2	4.46	43	43+15 (58)	29
Sydney	Melbourne	20.93	70	70+15 (85)	39
Intermediate 1	Intermediate 1	4.30	2	2+5 (7)	11
Intermediate 1	Canberra	4.68	10	10+5 (15)	14
Intermediate 1	Intermediate 2	0.32	28	28+15 (43)	19
Intermediate 1	Melbourne	2.13	76	76+15 (91)	54
Canberra	Intermediate 2	2.24	25	25+15 (40)	24
Canberra	Melbourne	4.13	56	56+15 (71)	28
Intermediate 2	Melbourne	81.66	6	6+5 (11)	13

The following equation was used to compute the number of Hyperloop commuters per year:

$$\begin{aligned} \text{Commuters} = & \text{No. of 1000 commuters per year} \times 1000 \times \left(1 + \frac{\text{Market Share}}{100}\right) \\ & \times \left(1 + \frac{\text{Induced}}{100}\right) \quad (1) \end{aligned}$$

Using the values provided in Table 29, the number of Hyperloop commuters per year was computed, using Equation 1, establishing the third column of Table 30. This subsequently provided the number of commuters boarding at each station per year, by the sum:

$$\text{Commuters boarding at station} = \sum_{\text{Station}} \frac{\text{Hyperloop Commuters}}{2} \quad (2)$$

The sum is divided by 2, because the Hyperloop Commuters variable accounts for both directions of travel. From Assumption 4, this is assumed to be twice the number of commuters boarding the station in a given direction. The results of this computation are displayed in Table 30 below. A similar sum is used to compute the number of passengers disembarking at a respective station each year.

Table 30: Predicted commuter demand per year by 2065 (Hyperloop)

Station 1	Station 2	Hyperloop Commuters per year [million]	Commuters Boarding at Station per year [million]*	Commuters disembarking at Station per year [million]*
Sydney	Intermediate 1	5.44	$(5.44+7.85+3.34+24.73)/2$ [20.68]	
Sydney	Canberra	7.85		
Sydney	Intermediate 2	3.34		
Sydney	Melbourne	24.73		
Intermediate 1	Intermediate 1	0.81	$(0.81+0.8+0.16+2.98)/2$ [2.38]	$5.44/2$ [2.72]
Intermediate 1	Canberra	0.80		
Intermediate 1	Intermediate 2	0.16		
Intermediate 1	Melbourne	2.98		
Canberra	Intermediate 2	1.11	$(1.11+3.75)/2$ [2.432]	$(7.85+0.8)/2$ [4.32]
Canberra	Melbourne	3.75		
Intermediate 2	Melbourne	10.15	$10.15/2$ [5.075]	$(3.34+0.16)/2$ [2.306]

Note the final two columns of *Table 30* are the second and third columns of *Table 5* in *Section 2.2.3*, indicating how these calculations lead into the body of the report.

1.3 Power Consumption

Table 31 below illustrates the power demands for the Hyperloop pod and was used to define the functional requirement relating to power for the Hyperloop.

Table 31: On-board Power Demand (requirements described in *Section 2.4.6*)

Sink	Power Required (kW)
Compressors	425
In-flight Entertainment	2.7
Miscellaneous	N/A
Sub-Total	427.7
Total (w. 25% allowance)	~535

1.4 Route Breakdown

1.4.1 High Speed Rail

Table 32 displays a variety of information extracted from the Phase 2 study used to determine and upper and lower bound for the trip duration between Sydney, Canberra and Melbourne. A variety of techniques and values are used which are covered under the following headings, describing its respective column's contents.

1.4.1.1 From/To

The intermittent stations, which are not stopped at during an express journey, were provided in the HSR Phase 2 Appendix 3, which discussed alternative routes and ultimately giving preference to a specific route and station location.

1.4.1.2 Distances

The distance between stations was available in the HSR Phase 2 Appendix 3 for the majority of the stations, excluding Sutton to Canberra Civic and Craigieburn to Melbourne Southern Cross, which are anticipated to use an urban access corridor not specified in the Phase 2 study. These two distances were estimated using *Google Maps* and evaluating the distance of train lines along the respective routes.

There is a spur in the route, depicted in *Figure 43*, which branches from Gunning, towards Sutton and Canberra, and returns along the same route. The specific distance from Goulbourn, the station before the spur when heading South from Sydney, to Gunning, was not provided; however, Gunning is roughly halfway between Goulbourn and Yass, hence, the distance between Goulbourn and Gunning and Gunning and Yass, was assumed equal to half of this distance, calculated as 37.2 kilometres.



Figure 43: Canberra Spur Alignment (Blue route preferred and assumed in this study) (AECOM, 2013)

The total distance of the route between both Sydney and Canberra and Canberra and Melbourne is greater than the distance specified by the Phase 2 study, with the anticipated distance indicated by brackets in *Table 32*. The discrepancies in the distances is potentially because the Phase 2 study neglected the urban access corridors connecting the outer-city stations to the central stations, or their distance estimates may have been lower. This detail was not finalised in the Phase 2 study as inner-city tunnelling requires in-depth council discussions; hence, it was assumed for the sake of this study.

1.4.1.3 Phase 2 Duration & Speed Interpretation

The distances specified between stations in the Phase 2 Appendix 3 was also provided with the expected duration of travel for most of the stations; those *greyed out* did not have duration estimates provided. From these known durations and distances, the speed assumed by the Phase 2 authors could easily be interpreted by the simple relation:

$$Seed [km/hr] = \frac{Distance [km]}{Duration [hr]} \quad (1)$$

1.4.1.4 Upper and Lower Average Speeds and Trip Durations

The average speed along a given section of the track was given an upper and lower bound, as discussed in *Section 3.1.6*, and the trip duration was then interpreted by rearranging equation 1:

$$Duration [hr] = \frac{Distance [km]}{Speed [km/hr]} \quad (2)$$

Table 32: Trip Duration Evaluation for the High Speed Rail (AECOM, 2013)

From	To	Distance (km)	Phase 2 Duration (hrs)	Phase 2 Speed Interpretation (km/hr)	Lower Average Speed (km/hr)	Upper Average Speed (km/hr)	Lower trip duration (hrs)	Upper trip duration (hrs)
Sydney Central	Casula	31.1			180	230	0.135	0.173
Casula	Douglas Park	39.7			300	350	0.113	0.132
Douglas Park	Bargo	33.1	0.094	350.6	300	350	0.095	0.110
Bargo	Yerrinbool	14.7	0.042	352.8	300	350	0.042	0.049
Yerrinbool	Hanging Rock	43.4	0.124	350.3	300	350	0.124	0.145
Hanging Rock	Goulbourn Airport	48.3	0.138	350.5	300	350	0.138	0.161
Goulbourn	Gunning	37.2	0.106	350.6	300	350	0.106	0.124
Gunning	Sutton	44.8	0.128	350.5	300	350	0.128	0.149
Sutton	Canberra Civic	22.5			180	230	0.098	0.125
Sydney Central	Canberra Civic	314.8 (283)	1.067				0.979	1.168
<i>Passenger Change</i>							0.083	0.083
Canberra	Sutton	22.5			180	230	0.098	0.125
Sutton	Gunning	44.8	0.128	350.5	300	350	0.128	0.149
Gunning	Yass	37.2	0.106	350.6	300	350	0.106	0.124
Yass	Wagga-Wagga	160.0	0.450	355.6	300	350	0.457	0.533
Wagga-Wagga	Albury-Wodonga	117.0	0.333	351.4	300	350	0.334	0.390
Albury-Wodonga	Wangaratta	61.0	0.174	350.8	300	350	0.174	0.203
Wangaratta	Seymour	148.3	0.424	350.0	300	350	0.424	0.494
Seymour	Craigieburn	63.7	0.182	350.2	300	350	0.182	0.212
Craigieburn	Melbourne Southern Cross	32.5			180	230	0.141	0.181
Canberra	Melbourne Southern Cross	687.0 (651)	2.167				2.045	2.412
TOTAL TRIP (SYD-CANB-MELB)		1001.8 (934)	3.317	302.0			3.024	3.581

1.4.2 Hyperloop

The HSR route breakdown forms the basis for the Hyperloop route breakdown. The same distances and section breakdown (urban access corridor/open field) was used. The lower and upper limits of the Hyperloop capsule were adjusted to account for the higher speeds the Hyperloop is capable of; however, the methodology is the same.

Table 33 displays the breakdown used to determine an upper and lower bound for the trip duration between Sydney, Canberra and Melbourne.

Table 33: Trip Duration Evaluation for the Hyperloop

From	To	Distance (km)	Lower Average Speed (km/hr)	Upper Average Speed (km/hr)	Lower trip duration (hrs)	Upper trip duration (hrs)
Sydney Central	Casula	31.1	300	600	0.052	0.104
Casula	Douglas Park	39.7	900	1200	0.033	0.044
Douglas Park	Bargo	33.1	900	1200	0.028	0.037
Bargo	Yerrinbool	14.7	900	1200	0.012	0.016
Yerrinbool	Hanging Rock	43.4	900	1200	0.036	0.048
Hanging Rock	Goulbourn Airport	48.3	900	1200	0.040	0.054
Goulbourn	Gunning	37.2	900	1200	0.031	0.041
Gunning	Sutton	44.8	900	1200	0.037	0.050
Sutton	Canberra Civic	22.5	300	600	0.038	0.075
Sydney Central	Canberra Civic	314.8			0.307	0.469
<i>Passenger Change</i>					0.083	0.083
Canberra	Sutton	22.5	300	600	0.038	0.075
Sutton	Gunning	44.8	900	1200	0.037	0.050
Gunning	Yass	37.2	900	1200	0.031	0.041
Yass	Wagga-Wagga	160.0	900	1200	0.133	0.178
Wagga-Wagga	Albury-Wodonga	117.0	900	1200	0.098	0.130
Albury-Wodonga	Wangaratta	61.0	900	1200	0.051	0.068
Wangaratta	Seymour	148.3	900	1200	0.124	0.165
Seymour	Craigieburn	63.7	900	1200	0.053	0.071
Craigieburn	Melbourne Southern Cross	32.5	300	600	0.054	0.108
Canberra	Melbourne Southern Cross	687.0			0.618	0.886
TOTAL TRIP (SYD-CANB-MELB)		1001.8			0.925	1.354

1.5 Battery Assembly

Musk et al.'s (2013) study estimated that to provide 325 kW of power, 1500 kg of Tesla batteries are required. This equates to roughly sixteen Tesla Powerwall batteries, where each battery weighs approximately 97 kg (Tesla, 2016). Hence, by evaluating these values in *Table 34* below, the number of batteries required to provide 535 kW of power can be computed.

Table 34: Battery Estimations

Power Required (kW)	Mass of Batteries (kg)	Number of Batteries
325	1500	16 (15.5)
535	2470	26 (25.5)

The blue and green cells represent the known and calculated values respectively, where the mass of the larger battery system was calculated by:

$$Mass (System 2) = Mass (System 1) \times \frac{Power (System 2)}{Power (System 1)}$$

1.6 Probability Evaluation

1.6.1 HSR Functional Requirements

1.6.1.1 External Noise

Firstly, the z-score values for the lower and upper overlap bounds, 76 and 100, need to be calculated. In this instance, the mean, μ , is 92.5 and the standard deviation, σ , is 5.5. With this information the z-scores can be determined using *Equation 4* and the probabilities can be interpreted using *Table 35*.

For X=76:

$$Z_{76} = -3$$

From the Z-score tables:

$$P_{76} = 0.0013$$

For X=100:

$$Z_{100} = 1.36$$

From the Z-score tables:

$$P_{100} = 0.9131$$

The probability of the system range falling within this range is the difference between the two probabilities, such that:

$$P_{External\ Noise} = P_{100} - P_{76}$$

$$P_{External\ Noise} = 0.9118$$

1.6.1.2 Cabin Noise

Firstly, the z-score values for the lower and upper overlap bounds, 55 and 85, need to be calculated. In this instance, the mean, μ , is 70.5 and the standard deviation, σ , is 5.2. With this

information the z-scores can be determined using *Equation 4* and the probabilities can be interpreted using *Table 35*.

For X=55:

$$Z_{55} = -3$$

From the Z-score tables:

$$P_{55} = 0.0013$$

For X=85:

$$Z_{85} = 2.81$$

From the Z-score tables:

$$P_{85} = 0.9975$$

The probability of the system range falling within this range is the difference between the two probabilities, such that:

$$P_{Cabin\ Noise} = P_{85} - P_{55}$$

$$P_{Cabin\ Noise} = 0.9962$$

1.6.1.3 Duration

Firstly, the z-score values for the lower and upper overlap bounds, 181 and 199, need to be calculated. In this instance, the mean of the system range, μ , is 198 and the standard deviation, σ , is 5.7. With this information the z-scores can be determined using *Equation 4* and the probabilities can be interpreted using *Table 35*.

For X=181:

$$Z_{181} = -3$$

From the Z-score tables:

$$P_{181} = 0.0013$$

For X=199:

$$Z_{199} = 0.18$$

From the Z-score tables:

$$P_{199} = 0.5714$$

The probability of the system range falling within this range is the difference between the two probabilities, such that:

$$P_{Duration} = P_{199} - P_{181}$$

$$P_{Duration} = 0.5701$$

1.6.2 Hyperloop Functional Requirements

1.6.2.1 Capsule Noise

Firstly, the z-score values for the lower and upper overlap bounds, 68 and 95, need to be calculated. In this instance, the mean, μ , is 81.5 and the standard deviation, σ , is 4.5. With this

information the z-scores can be determined using *Equation 4* and the probabilities can be interpreted using *Table 35*.

For X=68:

$$Z_{68} = -3$$

From the Z-score tables:

$$P_{68} = 0.0013$$

For X=95:

$$Z_{95} = 0.78$$

From the Z-score tables:

$$P_{95} = 0.7823$$

The probability of the system range falling within this range is the difference between the two probabilities, such that:

$$P_{Cabin\ Noise} = P_{95} - P_{68}$$

$$P_{Cabin\ Noise} = 0.7810$$

1.6.2.2 Duration

Firstly, the z-score values for the lower and upper overlap bounds, 56 and 65, need to be calculated. In this instance, the mean, μ , is 70.5 and the standard deviation, σ , is 5.2. With this information the z-scores can be determined using *Equation 4* and the probabilities can be interpreted using *Table 35*.

For X=56:

$$Z_{56} = -3$$

From the Z-score tables:

$$P_{56} = 0.0013$$

For X=65:

$$Z_{65} = -1.14$$

From the Z-score tables:

$$P_{65} = 0.1271$$

The probability of the system range falling within this range is the difference between the two probabilities, such that:

$$P_{Cabin\ Noise} = P_{65} - P_{56}$$

$$P_{Cabin\ Noise} = 0.1258$$

1.6.3 Z-Score Table

Table 35 displays z-scores and their relevant standard normal probabilities. The probability given is the area to the left of z.

Table 35a: Z-Score and Standard Normal Probabilities ($z < 0$)

<i>z</i>	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-3.4	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0002
-3.3	.0005	.0005	.0005	.0004	.0004	.0004	.0004	.0004	.0004	.0003
-3.2	.0007	.0007	.0006	.0006	.0006	.0006	.0006	.0005	.0005	.0005
-3.1	.0010	.0009	.0009	.0009	.0008	.0008	.0008	.0008	.0007	.0007
-3.0	.0013	.0013	.0013	.0012	.0012	.0011	.0011	.0011	.0010	.0010
-2.9	.0019	.0018	.0018	.0017	.0016	.0016	.0015	.0015	.0014	.0014
-2.8	.0026	.0025	.0024	.0023	.0023	.0022	.0021	.0021	.0020	.0019
-2.7	.0035	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0027	.0026
-2.6	.0047	.0045	.0044	.0043	.0041	.0040	.0039	.0038	.0037	.0036
-2.5	.0062	.0060	.0059	.0057	.0055	.0054	.0052	.0051	.0049	.0048
-2.4	.0082	.0080	.0078	.0075	.0073	.0071	.0069	.0068	.0066	.0064
-2.3	.0107	.0104	.0102	.0099	.0096	.0094	.0091	.0089	.0087	.0084
-2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
-2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
-2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
-1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0250	.0244	.0239	.0233
-1.8	.0359	.0351	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
-1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
-1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
-1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
-1.4	.0808	.0793	.0778	.0764	.0749	.0735	.0721	.0708	.0694	.0681
-1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
-1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
-1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
-1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
-0.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
-0.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
-0.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
-0.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
-0.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
-0.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
-0.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
-0.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
-0.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
-0.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641

Table 35b: Z-Score and Standard Normal Probabilities ($z > 0$)

<i>z</i>	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998