Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

Cost estimation for the Helsinki-Tallin fixed link connection.

Treball realitzat per:
Marc Arranz Compte

Dirigit per:
Gonzalo Ramos Schneider
Xiaoshu Lu-Tervola

Grau en:
Enginyeria Civil

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Departament d'Enginyeria Civil i Ambiental

TREBALL FINAL DE GRAU

Declaration

I declare that except where specific reference is made to the work of others, the content of this dissertation is original and has not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text. This dissertation contains less than 27.261 words including appendices, bibliography, footnotes, tables, equations and figures.

Marc Arranz Compte
May 2017

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Abstract

This thesis wants to evaluate the different kind of infrastructures for water crossings. We will find different construction methods, materials, and the advantages or disadvantages of each alternative are analized. We also will find the evaluation of the Helsinki-Tallin boundary conditions such as the geology, bathymetry, and ships' intensity, among others, for analizing the suitability of each infrastructure in the Gulf of Finland scenario.

We will try to quantify the cost of a underwater tunnel infrastructure: for achieving this purpose and due to the complexity of the tunnels cost estimation, a multiple linear regression has been choosen as the method to identify the influent parameters and obtain a cost estimation equation based on historical data.

The resulting equation for the cost per km estimation is:

$$\mathrm{Y} = -1086344086 + 180800{,}7 * \mathrm{Area} + 546046{,}1 * \mathrm{End}$$

After having studied the Helsinki-Tallin boundaries and once applied the cross section area of 195 m3 and Ending year at 2017, the cost per km for the Helsinki-Tallin tunnel link has been obtained, needing 4 bilion of euros for excavating the tunnel through their 80 km length.

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Chapter 1 - Introduction and Objectives

The water crossings infrastructures often give an optimal solution for achieving the minimum travel time and infrastructure length between two areas separated by water. As in these cases, the terrestrial travel time tends to be very long; the water crossings projects are a valuable alternative to be studied when the connection wants to be more effective.
Finland, country which is known for being located very close to Sweden and Estonia, and being surrounded by the Gulf of Finland and the Gulf of Bothnia, has difficulties for being interconnected with certain countries and therefore; a part of being the place where this thesis is developed; Finland was found as a suitable candidate for studying the cost and consequences of constructing a hypothetical water crossing fixed link.

In the actuality:

Nowadays, the connection between the Baltic and the Nordic countries are mainly done by ferry. The ferry is known for being a transport mean which does not require any infrastructure, a part of ports, for satisfying their services. Therefore, because it does not need big inversions, this service has been easily implemented around all the ports of the Baltic Sea. This is why different ferry operators are working there. For example companies such as Eckero Line, Viking Line, St. Peter Line, Finnlines, Stena Line, Scandlines, Tallink Silja Line, DFDS Seaways, Wasaline, Unity Line and TT Line, among others.

Figure 1: Map of the Baltic Sea Ferry routes – Font: http://www.st-petersburg-essentialguide.com

However, the ferries also have some disadvantages. On the one hand ferries depend on the weather and their services can't be always operative. On the other hand the ferries' velocities are slow compared to other transport means. As a result, attractive fixed link infrastructures have begun to be studied.

Fixed link proposal:

The fixed link connection was already studied by SWECO's company, the geological survey of Finland and the geological survey of Estonia before this thesis began. SWECO's company contributed with the prefeasibility study of the project [98] and the geological survey of Finland and Estonia characterized the project geology [6][99].
In the prefeasibility study, the infrastructure chosen for the Helsinki-Tallin connection is the underwater tunnel and the socio-economic analysis of the fixed link execution is done exhaustively. It also studies the projects' construction alternatives and makes costs estimation for the underwater tunnel solution. The objective of this tunnel is to reduce the travel time from around 1h 40 min to 30 min.

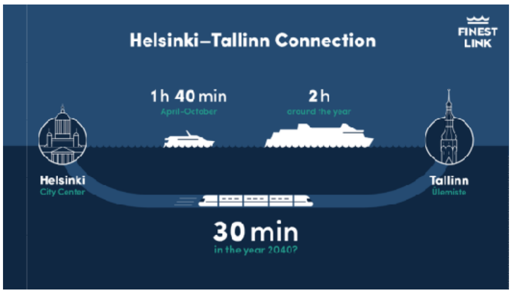


Figure 2: Underwater tunnel proposal between Helsinki and Tallinn. Font: Finest Link webpage

The goals of this thesis are to go deeper on the analysis of the infrastructures alternatives and their cost estimation. For doing so, the different infrastructures and their construction methods will have to be identified and their advantages and disadvantages will have to be studied.

The study of the project's bathymetry, geology, infrastructure length and maritime activity will be essential for defining which infrastructures are suitable to be constructed in the present project. It is clear that not all the infrastructures will be feasible, because each solution needs of certain requirements such as space, guarantee the security of the passengers, etc.

Finally, the cost prediction for the infrastructure that seems optimal will be quantified. It could be achieve with research of budgets from similar historical water crossing projects. In the case the historical costs per meter or cubic meter are not too disperse, the cost estimation will be done directly multiplying by the project length or volume. Otherwise, in the case that the cost prediction is more complex, statistical analysis such as regression models will be needed to predict the project cost according to different explanatory parameters.

Chapter 2 - State of the art

In this first chapter, all the types of water crossing infrastructures present at the moment and their respectively construction methods are exposed.

2.1 Type of infrastructures for water crossing and their different construction's methods.

The water crossings' projects infrastructures can be divided in three main categories, which difference remains on their spatial location respect of the water mass to be crossed. The projects facilities can be conducted under the water, through the water, or over the water and as a consequence are named as tunnels, submerged tunnels and bridges respectively.

As the media through these infrastructures passes are very different; such as soils, rocks, water and air; for each of the options the constructing methods are clearly different. In the following subsections the properties of tunnels, submerged tunnels and bridges are analyzed as well as their possible construction methods.

2.1.1 Tunnels

The tunnels' projects have been widely used in water crossing's projects around the world; it can be seen with the 94 projects studied in the analysis done in the chapter 4, section 1.

The tunnels have some advantages respect of the other kind of infraestructures, such as being more secure against external collisions and floods, not representing a visual impact,not representing an obstacle for maritime transports, or not increasing the rate of loss of marine spices.

However, some negative impacts are also generated, such as the production of vibrations; the need of storage and extraction of big quantities of soil or rocklike materials; the non optimal straight line path due to the geological conditions; and the risk of flooding, during and post the excavation process.

2.1.1.1 Construction methods implemented in the existing tunnels

The underground construction industry has been experiencing a strong procedures and technological development. The most used tunnels excavation methods are TBM, D&B and the Austrian method.

However, all these methods work efficiently, only under certain conditions. For that reason, different projects' properties have to be considered for being able to elect a lean construction methodology.

The most important parameters to be analyzed for determining which is the proper method to be usedare: the dimensions and shapes of the tunnels' cross sections, the geological properties of the projects and its surroundings, the final quality expected for the tunnels, the health and safety of the workers and the users, the time available and advance rates of the excavations, the flooding risks of the tunnels, and the environmental disturbance produced.

In the following paragraphs,the pros and cons of the TBM, D&B and Austrian methods will be commented in base to different publications done by the Norwegian's tunneling, geotechnical and rock mechanics societies[65]or railsystem enterprises. [73]

TBM Tunnels

Tunnel Buried Machine method consist of a rotating cutting wheel, located at the front end of a shield, which disaggregates ground materials by friction and makes it flow into a chamber for its posterior extraction. This chamber can be either pressurized (EPB shield) or not (Slurry TBM) and is connected with a system of hydraulic jacks. The hydraulic jacks, permit the movement of the TBM by pushing its hydraulic jacks against the preinstalled lining or rock surface. Therefore, once the TBM have excavated between 1.5 and 2 meters, the hydraulic jacks are retrieved and,if needed, a new ground support or pre-cast concrete tunnel ring is built using an erector. This erector, consist in a rotating system, which pick up different pre-cast elements and places them in their respectively position. Therefore, when a new ring is properly installed, the TBM's systems are elongated, the hydraulic jacks can act over the new lining or rock surface and a new excavation cycle can start once more.

New EPBS are very modern and can inject different types of products during the excavation. The correct mixture facilitates the material disintegration and flow, which helps to obtain quicker advance rates and less erosion in the cutting wheels. These cutting wheels can be replaced if the discs are too worn or if the geology change. In EPBS, a divers' team is required for this operation, as the chamber is pressurised for maintaining the stability of the excavation front.

For using TBM tunneling method, it is needed a big initial inversion as the machines are designed specifically for the project and cannot be used for other projects ones finished.
In addition, the TBM machines need of big turning radius in their trace, limiting the ability to turn around.

As a consequence, TBM method is only compatible for long water crossings which have the possibility to amortize the machinery cost. However, it reduce the number of temporary access (attack shafts) if the project is well laid out, it can also minimize the number of over breaks along the tunnel and do not require of very skilled labors, as the procedure can be learned quickly due to their cyclicality.

Drill and Blast Tunnels

Drill and Blast method is the mostly used for excavating through rocklike environments. The method permits the tunnel excavation in all kind of rocks and it is known for their low initial inversion cost and its quick excavation rates. The process consists in the repetition of a six steps sequences.

First of all, different blast holes are dilled in the rock; then, the explosives are inserted and loaded; the blast is detonated; the tunnel is ventilated; and the procedure is stopped until there is no dust in suspension. Then, the disaggregated materials are removed of the tunnel at the same time that the remaining imperfections are polished; the ground capacity is improved with support elements (Bolts) or concrete lining; ventilation facilities are elongated and once arrived to this point, the excavation cycle starts again.

The method has their pros and cons. The main disadvantage is that cannot be used in soft soils and therefore their flexibility is limited to areas without large soil properties changes. D&B, with absence of lining use, is more proper to tunnels flooding as unless constructing usually with impervious materials, cracks, karstification or failure zones; whichcreates an hydraulic gradient and can canalize big quantities of water to the excavation area.

The tunnels quality is reduced as over break is inevitable; furthermore, more noise and vibration are produced and there is a major probability of preexistent edifications damage. Their processes are cyclic but needs of skilled people due to the constant challenges appearing along the excavation.The method also generates a dangerous and unpleasant working environment and the risks of serious accidents from handling explosives is present. It is also needed more than one shaft for opening multiple headings.

However, despite of the fact that having some disadvantages, the method is widely used for different reasons such as it achieves the quickest advance rates; it is the method which do not require usually of pre-cast concrete elements and uses a minimal ground support (Bolts); it is the cheapest method for short tunnels with favorable geotechnical conditions due to its small inversions on machinery, which can be re-used for other projects.

Austrian method

The Austrian method is a procedure used in tunnels with large sections and soft soils conditions. The method is very manual and begins with the excavation of small galleries.Once each of the galleries is completed, their walls and gables are concreted and the subsequent new galleries are executed and interconnected. When all the galleries are connected, the vault of the resulting big gallery is also concreted. The section of the tunnel is finally completed when the remaining material between the galleries is removed totally.

Methods comparison

Between the three exposed tunneling methods, which is the proper one cannot be defined without knowing the projects' context, as they have advantages and differences in lot of different aspects.

While the main disadvantage of D&B method is that cannot be used in hard or soft soils as requires of a bigger resistance due to its explosion phase and its minimal ground support, the TBM can deal with both kind of materials.

Despite the fact that D&B method is the one that achieves the quickest advance rates in short-medium length tunnels and conducts to minimize the excavation costs due to its minimal ground support and small inversions on machinery, TBM minimize the over breaks and improve the tunnel quality.

Whereas D&B method has a lack of flexibility during excavation as it cannot be used in areas with large soil properties changes, it can be used for short lengths due to its machinery reuse capacity.

Despite the fact that D&B with its absence of lining is more proper to tunnels flooding as unless constructing with impervious materials as rocks are, crack can still be present and conduct big quantities of water to the excavation area.

Although it is clear that TBM presents also lot of advantages respect D&B, such as requiring less skilled labors due to its repetitive operations and easy training; eliminating all the temporary accesses if the project is well laid out; being naturally stable; being safer and more pleasant environment for workers than is D&B; reducing the noise and vibration; and eliminating the risk of serious accidents from handling explosives.

2.1.2 Immerse tunnels

2.1.2.1 Construction methods implemented in the existing immerse tunnels

The immerse tunnel independently of its constructive method, permit the fabrication in serie of long and easy transportable sections modules which optimize the result quality and provides to the procedure of more ciclicity. As these methods have not been widely used and suppose and extra challenge, should be notice that a large team of expertise would be needed when designing and building this type infrastructure.

Over the sea bottom

An example close to Finland of an infrastructure which rest over the sea bottom is the Fehmarnbelt project. It is the longest rail and road tunnel under sea (18 km), which is still underdevelopment in 2017, and will connect Denmark with Germany.

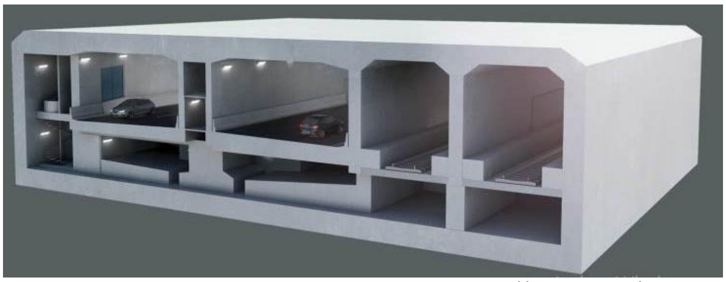


Figure 3: Image of the Fehrmanbelt section - Font: https://femern.com/en [37]

This method is very useful for crossing shallow water masses. Using this method and locating the tunnel in side a trench,creates an extra of safeness, which is achieved thanks to be protected by the surrounding soil/rock. However, the high cost and the long time required is one of the difficulties to dare with. These handicaps, which are product of the big amount of submerged work required, are summed to the environmental impact produced. As the sea bottom needs to be excavated, sediment spillage cannot be avoided.

Therefore, excavation techniques chosen have to try to minimize the spillage as is being done in Fehmarnbelt link project. Furthermore the downpipe for depositing the foundation’s materials are conducted by laser and echo sounding.

The immerse cut & cover/rest over the sea bed method, works with element modules which their buoyancy/weight ratios need to be less than 1 (Sinks).

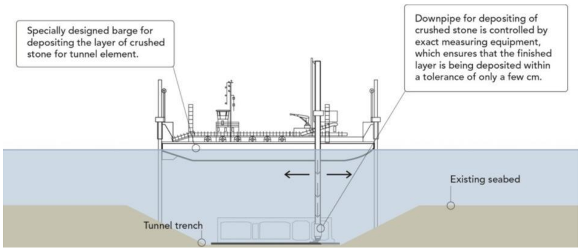


Figure 4–Fehrmanbelt's foundation preparation - Font: https://femern.com/en ; [37]

The procedure to be followed for immerse Cut & Cover tunnels construction consist of 5 steps:

1. Transport of the tunnel modules

The heavy tunnel elements are transported like a hollow ship hulls floating over the sea, attached by mean of winches and carried by mean of a tugboats' team.

Figure 5: Fehrmanbelt, transport of the tunnel elements - Font: https://femern.com/en [37]

2. Immersion of the modules

When the elements arrive to the place, they are suspended with pontoons, and the immersion of the pieces starts. The partial filling of the sections is done, with water and ballast, for making the elements heavy enough to allow the sinking of the elements by their own weight.For a controlled descent, the elements are guided by cable winches, GPS and echo sounding technology.

Figure 6: Fehrmanbelt, Immersion of the modules with pontoons.- Font: https://femern.com/en [37]

3. Assembling of the elements

When the tunnel elements has been placed in the tunnel trench and lined up, a hydraulic arm is used to haul the elements. Then, the rubber gasket touches the end of the previous element and a watertight chamber between the elements is created. When the water from the elements is removed and filled with air, a differential pressure is created, which generate a tremendous force that ensure the correct connection between the modules. Afterwards, the joints are concreted and the bulkheads can be removed, obtaining the final result.

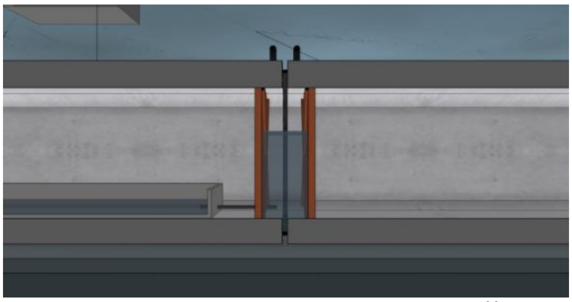


Figure 7: Fehrmanbelt, assembling the tunnel modules - Font: https://femern.com/en [37]

This method, do no contribute in shortening the distance of connections as the sea bottom used to be non-flat. Furthermore, in presence of mud and soft soil, it has to be removed as settlements would be produced.

The good point of the solutions is that in fairways, where the depth is less than 15 meters, it gives an extra of safety against ship collisions because the infrastructure is located inside a trench. Another advantage is that as it rest along all its guideline, the sections length can be as big as able to transport or construct, being an advantage when building very long tunnels.

Floating Immerse Tunnel

Another way to construct immerse tunnels is by mean of floating structures anchored to the sea bottom by mean of hinches, piers or by using pontoons. For doing so, it is important to set the Cross sections' dimension that able the buoyancy/weigh ratio to be small. This relation needs to be positive, for making the tunnel flotate, in the case of anchors and piers; and negative, for making the tunnel sink, in the case of pontoons. The small vertical forces, which are produced between the tunnel modules and the supports, permit the equilibrium to be reached. Furthermore, as water is moving around the structure, variable lateral forces are also present in the structure and therefore dynamic analysis need to be done for a proper structural analysis characterization.

The small vertical forces permit the uses of large spans. There are three kind of dangers that the structure is exposed to and which solutions or capacity needs to be studied. These are the exposition to a possible collision, motive due to the structure must be located deep enough for avoiding vessels collisions; the exposition against submarines collisions or the exposition to a fatal inundation of the tunnel sections,due to a massive water entrance or a possible occurrence of an explosion inside the tunnel.

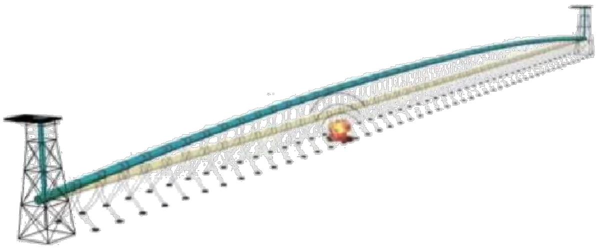


Figure 8: Hypothetical explosion of a SFT - Font: Global response of submerged floating tunnel against underwater explosion; [76]: pp 825-835

The floating immerse tunnels haven't still being used in practice, but the design concept have been considered when deciding deep water crossings infrastructures such as Norwegian fjords. The materials which can be used for immerse tunnel construction are defined in the chapter 2, section 2.

Furthermore, floating immerse tunnel method do not generates a big environmental impact as excavation of a trench is not needed. Submerged work is required, but lesser and more monotone than tunnels resting over the sea bottom as only foundations, usually shallow foundations, needs to be installed for anchoring the tunnel elements.

Should be note that unless they have not still being used, different projects of immerse tunnel are already planned to be constructed.

Figure 9: Aerial view of the conceptual Sognefjord SFT - Font: Development of a submerged floating tunnel concept for crossing the Sognefjord; [76]: pp 593-602

In these kinds of tunnels, if they are very long, vertical ventilation shafts are needed to guarantee the correct air quality inside the tube.

Floating immerses tunnels type of supports:

In the following pictures, it can be seen the floating immerse tunnels supports; it can be by mean of anchorages, piers and pontoons. The combination of different supports is also a possibility to be considered during the infrastructures' design.

The advantages and disadvantages about each of the supports will be state as follows:

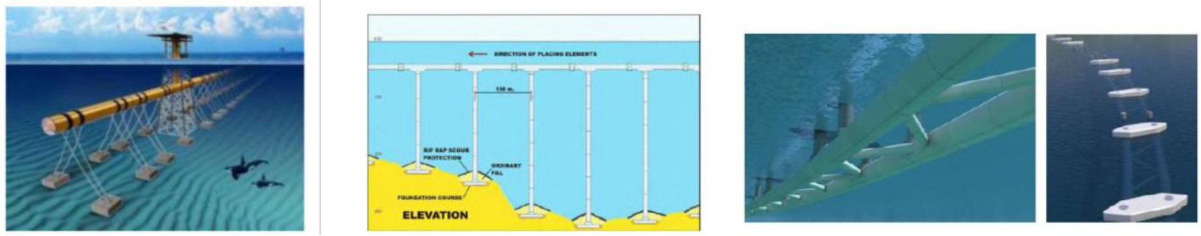


Figure 10, Figure 11, Figure 12– Support types for a SFT tunnel - Font: Strait crossing 2013; [76]

The anchors tend to be the cheapest and quicker solution, followed by the pontoons and finally the piers; depending on the quantity of subaquatic work, depth, and the piers resistence needed.

About what submarine navigation interference concerns, the pontoons are the best solution, followed by the anchors and finally by the piers. However, the piers are the only element with strength enough to resist a submarine collision if it is contemplated in the design and if its construction is properly laid out.

Despite pontoons do not interfer to submarines; they are an obstacle for ships, as possible ships collisions can suppose an irreparable damage for the infrastructure. On the other hand, anchors and piers are more protected against ship collisions. It should be notice, that in order to absorb vertical and lateral loads, anchors need to be in tension and with an inclined configuration.

2.1.3 Bridges

The use of bridges with long piers, have already being built. Therefore, they should be able to be implemented also in deep water crossings. These infrastructures, despite of the fact that are affecting the navigation of high vessels, would create a new surface profitable for other future projects as offshore oil stations, renewable energy plants, etc. Furthermore, the high ships navigation could be easily solved by the use of navigational channels with the creation of mobile spans along the tunnel trace.

The main problem is the number of piers to be executed; as the water's buoyancy do not act over the bridge spans, the vertical solicitations are bigger than would be in floating immerse tunnels and therefore the length of the spans needs to be shorter. Increasing the number of piers respect an Arquimedes' bridge (SFT).

These high piers would affect clearly the submarines. Then, the piers should be prepared against big collisions which makes them more expensive.In addition, the piers have to be attached to competent strata and therefore, undersea excavation is needed.

2.1.3.1 Construction methods implemented in the existing Bridges

For understanding the bridges typology a web page about the history of bridges was consulted and complemented with other web pages such as [76], [36] and [97].

Beam bridges [97]

The beam bridges are the simplest and oldest bridges' types. They consist on a stiff beam which is hold by one support in each of its ends. This supports used to be piers and the weight of the beam presses them down and can transmit also a bending moment.

The beams can have different cross sections and be solid or hollow. There are three main shapes of beams, such as double T sections, box beams, or L shaped beams.

The beams can be made of steel; reinforced concrete; or HPFC materials, see chapter 2 section 2. As steel behavior against tensions and compressions is good and they are very lightweight, they are very useful for building long bridge spans. However, due to its price and problems against corrosion, HPFC and reinforced concrete is also used. In RC, reinforced concrete, the concrete absorbs all the compressions while the wires absorb the tensions once the concrete has cracked against the existing tensions.The bridges can be composed by different piers, spans and be as long as needed by the addition of the comented previous elements.

Cantilever Bridges [33]

The Cantilever Bridges are composed by spans which are cantilevers. Their construction can be made by using balance cantilever method, which consists on start building different arms from two subsequent piers. The arms are constructed symmetrically by inserting and connecting different sections on each side of the pier for avoiding the bridge to resist large bending moments, as they are equilibratedand only vertical forces are applied over the piers. When half of the span is reach from one pier and its consecutive pier, both arms edgesare joined and the construction of the full span is reached.

Figure 13 – Balance Cantilever construction method - Font: http://www.bridgesofdublin.ie/bridge-building/types/cantilever; [33]

Arch Bridges

The arch bridges were already built by the Romans long time ago. Thanks to their arched shape, the arch bridges are able to convert all the external solicitations as an axial force of compression which is finally transmitted to the ground. The absence of bending moments and shear efforts makes materials as concrete works perfectly and be able to reach longer spans.

Suspension Bridges

Figure 14: Suspension Bridge – Font: https://media.cntraveler.com

The suspension bridges are bridges which have one or more towers. These towers are interconnected by suspender cables.The deck of the bridge is attached by anchors to the suspension cables. The vertical effort is therefore propagated to the cable and it is finally dissipated in the towers or tunnel ends.

Tied Arch Bridges

Figure 15: Arch Bridge – Font: https://secure.surveymonkey.com

The tied Arch method is a fusion of the suspension bridges and the arch bridges methodology. Unless they also use suspenders to transmit the vertical deck solicitations, like it is done in suspension bridges, in arch bridges there are not towers and the efforts are transformed as an axial effort. It is done by mean of two structures in arch shape located at each side of the bridge deck. This axial force runs through all the arch, until reaching the both structure ends; finally, the axial forces are transmitted as a vertical force to the terrain.

Cable stayed bridges

Figure 16: Cable Stayed Bridge – Font: http://global.kawada.jp/bridges/cablestayed.html

The cable stayed bridges uses towers as well as in the suspension bridges with the only difference that the deck is not suspended of a suspension cable. It is suspended with cables which are directly connected to the towers.

Floating bridges

As in very deep water crossings, the piers are very high;they have to be very thick to avoidthe buckling phenomena.For this reason, the piers are very expensive and other solutions, such as floating bridges, have started to be used. It can be seen for example in the Nordhorland Bridge, Norway.

Figure 17 – The Nordhordland floating Bridge - Font: The Nordhordland Bridge – Twenty years in service; [76]: pp 330-339

The floating bridges are not a recent discovery; the solution was already used for Romans and the army for provisional river crossings.Unless they are still not widely used, there are already twenty floating bridges around the world.

2.2 Type of materials which can be used for Submerged Floating Tunnels and water crossing infrastructures

Information about the possible materials which can be used in SFT tunnels makes reference mainly in the "Preliminary design and comparison of SFT tube with different high performance fiber concrete materials" present in the Strait Crossing document [76].

The SFT and bridges' piers, for water crossings, are submerged in a complex environment and their materials put forward a very high demand on water proofing, compressive strength, tensile strength, water resistance, durability, fire resistance, impact resistance, explosions, and protection against corrosion.

For that motive, and as ordinary concrete cannot meet the requirements. In this chapter other materials and its properties will be analyzed for their posterior implementation in SFT projects.

The list of materials which can be used in SFT are materials as steel; ordinary reinforced concrete (RC); high performance fiber concrete (HPFC's), such as fiber reinforced concrete (FRC), glass fiber reinforced concrete (GRC), polypropylene fiber reinforced concrete (PPFC), Steel fiber reinforced concrete (SRC), hybrid fiber reinforced concrete (S-PPFC)); and multilayered materials, also called Sandwich.

There are three main factors when choosing the materials to construct a marine structure, two of them are safety and sustainability, while the third is price based. The analysis of these materials properties is done in the following lines.

Steel

Steel materials have a very good behavior against tensile and compression efforts at the same time that has a lightweight. However, the corrosion is one of its main problems.

Different solutions to fight against corrosion have been studied and can be found in publications such as "New challenges for the fire safety in sft tunnels" from Strait Crossings journal. Nevertheless, in this thesis are only mentioned due to its complexity.

Sandwich

The sandwich consists of a multilayered material which makes profit of the characteristics of each material. The materials of the layers appointed from inside to the exterior used to be steel, concrete and finally aluminum. This combination is due to steel plate able to absorb the tensile efforts, the concrete layer improves the material stiffness and the external aluminum frame layer empowers the structure to corrosion resistance.

HPFC's

The high performance fiber concrete materials, abbreviated as HPFC's materials, have appear in the last decade and are widely used in water crossing projects because their good behavior against compression, their extent tension strength, their anti-impact resistance, their waterproofing and their durability.Can be seen that compared with reinforced concrete (RC), the HPFC's have higher tensile strength and crack resistance.

The properties of current HPFCs with different fiber and main mechanical parameters are listed in Table 1 extracted from "The preliminary design and comparison of SFT tube with different high performance fiber concrete materials.

Table 1. The properties of high performance fiber concrete with different fiber

Concrete material	Characteristics	Main mechanical parameters	Note
RC (C25)	—	f_{cd}=11.5Mpa, f_{td}=1.23Mpa, E_c=28.0Gpa,v=0.16	—
SRC	Advantage: higher compressive strength and tensile strength， good flexural and impact toughness properties，strong anti-explosion and anti-permeability Disadvantage: difficult to mix uniformly	f_{cd}=120Mpa, f_{td}=19.4Mpa, E_c=52.2Gpa,v=0.22	high cost, need to ensure that steel fiber bond strength with concrete construction technology requirement: steam curing can increase significantly quality and performance of SRC
GRC	tensile, bending, shear, impact resistance, fatigue resistance and fracture toughness are significantly improved compared with RC	f_{cd}=23.3Mpa, f_{td}=2.16Mpa, E_c=29.9Gpa,v=0.24	poor resistance to alkali, easy to embrittlement
PPFC	tensile strength, freeze-thaw resistance, anti-carbonation and fatigue resistance are all greatly improved, suitable for hydraulic structures	f_{cd}=20.5Mpa, f_{td}=2.20MPa, E_c=31.5Gpa,v=0.20	poor effect to late shrinkage cracks and temperature cracks
S-PPFC	mechanical properties (strength and toughness) are determined according to mixed quantity of different fibers	f_{cd}=55.0Mpa, f_{td}=7.2Mpa, E_c=32Gpa,v=0.20	avoid the negative effects of fiber mixing; mixing should be sufficiently and uniformly

Table 1: The properties of high performance fiber concrete with different fiber - Font: Preliminary design and comparison of SFT tubewith different high performance fiber concrete materials; [76]: pp760-767

After analyzing the properties of the different HPFC's materials, the modelization of a SFT calculated by ANSYS analysis in the same publication [76] and their conclusions are also comented remarked.

Practical case: Finite element analysis for each material

The structure to model had this geometry and properties:

1. The project was located in China.
2. Prototype model was presented 2007.
3. The SFT length is considered 100 meters, which are divided in five standar tubesmodules of 20 meters.
4. There was four cables, two vertical in two anchor foundations and two in the foundation of the middle inclined.
5. The both ends of the tunnel are considered embedded.

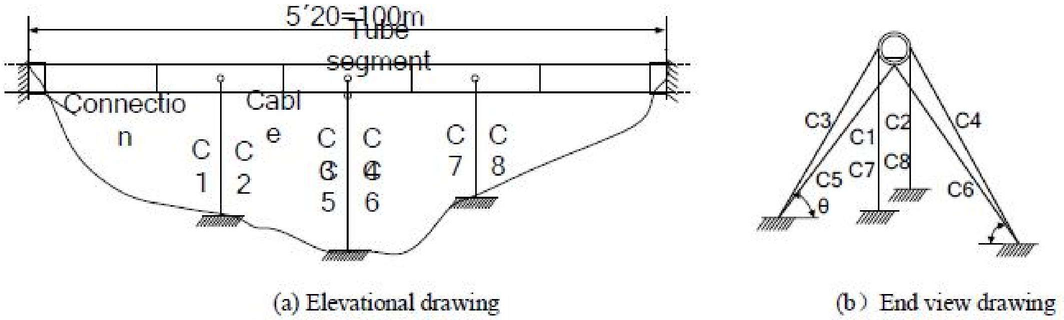


Figure 18– Drawins of the proposed SFT model configuration - Font: Preliminary design and comparison of SFT tube with different high performance fiber concrete materials; [76]: pp760-767

The internal stresses and displacements of the SFT are analyzed by using the general finite element method for each material. The considerations of the ANSYS analysis are:

1. Three degrees of freedom at each node.
2. The cable is simulated by element link180
3. The carriageway plate in tube segment is ignored.
4. The boundary condition of tube is simulated as hinge connection.
5. The model in all has 16086 nodes and 12008 elements.

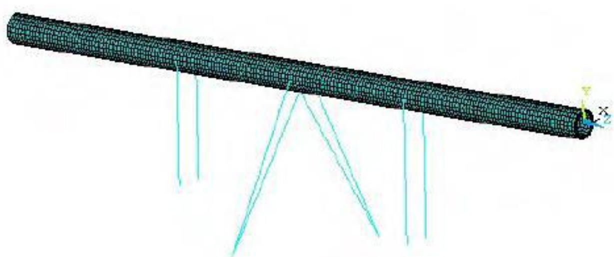


Figure 19 – Analysis of SFT by finite element method - Font: Preliminary design and comparison of SFT tube with different highperformance fiber concrete materials; [76]: pp760-767

The results obtained after the ANSYS results are extracted and summarized in table 2.

Table 3. Calculation results of SFT with different HPFC material

Material	Section type	Tube Shell thickness δ (m)	Maximum tensile stresses (Mpa)	Maximum compressive stresses (Mpa)	Estimation Cost (10^4RMB/m)
C. M.	sandwich	0.30	0.70	0.70	2.02
SRC	circle	0.10	2.76	2.76	1.25
GRC	circle	0.12	1.98	1.94	1.15
PPFC	circle	0.12	1.96	1.96	1.12
S-PPFC	circle	0.10	2.42	2.42	1.18

Table 2: The properties of high performance fiber concrete with different fiber
Font: Preliminary design and comparison of SFT tube with different high performance fiber concrete materials; [76]: pp760-767

Analysis of the findings

After studying the different materials properties and analysing the example given by Strait Crossings, some conclusions can be made.

First of all, SRC, GRC, PPFC and S-PPFC have a good -good tensile strength, crack resistance, impermeability and their prices are the cheapest. However, GRC is not good for maritime infrastructures for his poor resistance to alkali attacks. On the other hand, materials as PPFC are also not suitable for SFT for their poor effect to late shrinkage cracks and temperature cracks.

Though; if PPFC and SRC are combined,the S-PPFC materials , the advantages of both materials are obtained. It have a good properties, economy and are recommended for SFT construction. Therefore among all the HPFC materials, the best options for this the studied project conditions are SRC and S-PPFC.

About what Sandwich materials concerns, their price is almost the doble than HPFC's materials, being overspending and achieving a small tensile and compressive resistance.

The handicap of steel is mainly the problems with the corrosion and that their price is larger than HPFC materials.

Chapter 3 - Helsinki-Tallinn Connection

Research for obtaining information useful regarding the Helsinki and Tallinn connection was needed to understand the projects conditions, its viability, its social-economical impacts and the possible infraestructuresto be built.
Furthermore, knowing about the infrastructure context is basic for the definition of those parameters which will be used as input in the final cost prediction based on the stadistical analysis of historical data.

Along the next paragraphs, information about the actual travel time using ferries and the distance between the two cities is going to be described; information about actual commuting and cargo transporting activities are going to be exposed; and a prognostic of transport increment after the fixed link execution, made by SWECO will be included. The new connections opportunities also generated for the new scenario execution will be commented.

As mentioned in the abstract, socio-economic background is important for understanding the projects needs, dimensions and scope; the most relevant aspects and conclusions of the existent prefeasibility document will be mentioned but are not the main goal of the thesis study. For a deeper understanding, the original and complete study can be found online and is included in the bibliography.

Other aspects which are going to be covered by this chapter are the geological properties of the project area, the vessels and submarines activity in the zone, the sea water velocities, the shipping density and their circulation directions and information regarding the historic meteorological data.

Information used for deepening in the projects properties was obtained also from other sources such as the geological survey of Finland (GTK), the geological survey of Estonia (EGK), the nord stream gas project, and the Baltic Marine Enviroment Protection Comission.

3.1 Project description

A background about the project is needed for studying the alternatives to the fixed link connection. For that reason, some information such as the distance separation between Helsinki-Tallinn and the actual travel time; the actual maritime cargo and passengers transport; the opportunities generated thanks to the hypothetical fixed link; the bathymetrical and geological data about the gulf of Finland; the present services crossing the Gulf of Finland; the properties and accidents of the vessels crossing the Finland's gulf; the meteorological conditions of the region; the water properties of the sea water; and the social and economical justification of the project is going to be covered in this section.

3.1.1 Distance separation and travel time

The distance between both capitals is eighty kilometers and the actual ferries spends an average time of two hours to do whole the journey. As the ships do not have limitations for moving except by the sea bottom depthness, the travel is done in straight line.

In previous studies for the tunnel location, different tracks are considered (B1, B2, C, D, E). Thepoints of their tracks can be seen in the following mapextracted from the seabed study developed in the railway tunnel zone across the Gulf of Finland [2].

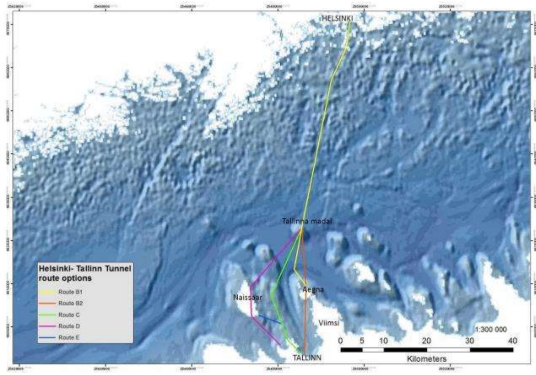


Figure 3. Seabed topography at the railway tunnel zone across the Gulf of Finland. (EMODnet Bathymetry Consortium (2016). EMODnet Digital Bathymetry (DTM). EMODnet Bathymetry).

Figure 20– Seabed topography at the railway tunnel zone across the Gulf of Finland. EMODnet Bathymetry Consortium (2016). EMODnet Digital Bathymetry (DTM). -Font: Acoustic-seismic survey along the proposed railway tunnel route options, between Helsinki and Tallinn. 19.8.-1.11.2016 [2]

The vertices of these line paths can be seen in the next table from the same report [2].

Table 1. Different route option coordinates (from S to N) in ETRS89- GK25FIN.

route B1*		route B2		route C		route D		route E**	
X	Y	X	Y	X	Y	X	Y	X	Y
25486388	6609595	25486123	6593493	25485247	6593918	25480487	6595777	25480942	6600504
25483728	6613261	25486388	6607054	25484265	6594918	25473857	6602429	25475465	6602740
25485462	6622857	25486388	6609595	25483318	6595856	25473772	6603266		
25492315	6657173	25485462	6622857	25482257	6596922	25473604	6609179		
25495777	6664626	25492315	6657173	25478407	6607315	25485462	6622857		
25496630	6670875	25495777	6664626	25485462	6622857	25492315	6657173		
		25496630	6670875	25492315	6657173	25495777	6664626		
				25495777	6664626	25496630	6670875		
				25496630	6670875				

*starts from North of Aegna Island.

**section between route option C and Naissaar (see fig. 1).

Table 3: Different route option coordinates (From S to N) in ETRS89-GK25FIN - Font: Acoustic-seismic survey along the proposed railway tunnel route options, between Helsinki and Tallinn. 19.8.-1.11.2016 [2]

It can be seen that because tunnels need ventilation shafts, the tracks considered pass through islands to make able the shafts to reach the surface without danger of collision. The location of these shafts in island also facilitates the excavation of the shafts.

3.1.2 Transportation

Cargo transport

The cargo transport, between Helsinki-Tallin, has been increasing along the time; reaching a maxiumum of around 90 million tons in 2013. The data used in the prefeasibility study is from http://www.ulkomaankaupanreitit.info/kuljetukset and used in the prefeasibility study to show the grow up of cargo transport in Helsinki.

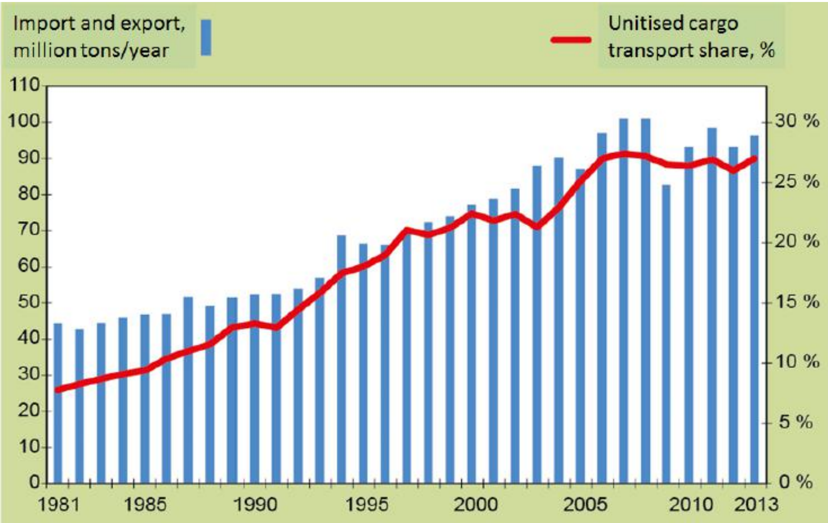


Figure 21: Import and export volumes in cargo transport between 1981-2013 - Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

Passengers transport

The number of passengers is also commented in the prefeasibility study as can be seen inthe following snapshot, showing a growing up on the commuting between both capitals.

Total passenger flow between Helsinki and Tallinn has in ten years grown from 5.5 million passengers to 8 million passengers a year. The yearly growth rate has been about 2.4%.

Figure 2.3 – Information regarding the passengers between Helsinki and Tallinn per year - Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

3.1.3 New opportunities - Rail Baltica connection

Furthermore, the Helsinki-Tallinn fixed link may be connected no only with Estonia, also with the Rail Baltica train line; which would connect Finland also with European countries such as Poland, Latvia, and Lithuania with the posterior extending to Russia and Belarus.

Furthermore, in order to facilitate the rails interconnection between different European countries, the need gauge needs to be 1435 mm (European gauge) for a quick transfer.

In the following figure, the Rail Baltica connection can be seen in yellow in the map extracted from the prefeasibility study and the future connections can be seen in red and dashed blue.

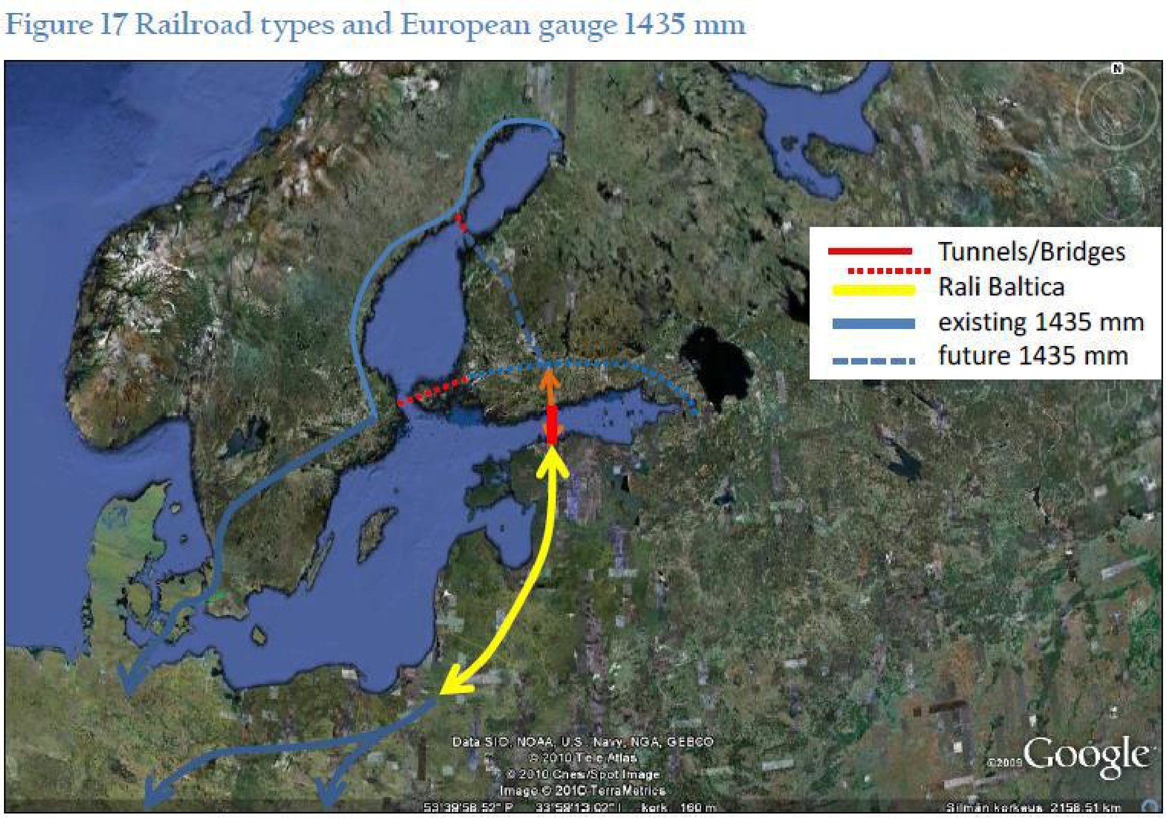


Figure 22: Fixed link connection with Rail Baltica - Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

Futhermore, a cross-section for the possible tunnel given in (4. Anttikoski, U. 2007 Are fixed transport connections across the Baltic Sea from Finland to Sweden and Estonia feasible? , 5 pp. Finnish Geotecnical Society, http://www.getunderground.fi/getfile.ashx?cid=72805&cc=3&refid=8) and the uncertainties about the finnish basement are revealed.

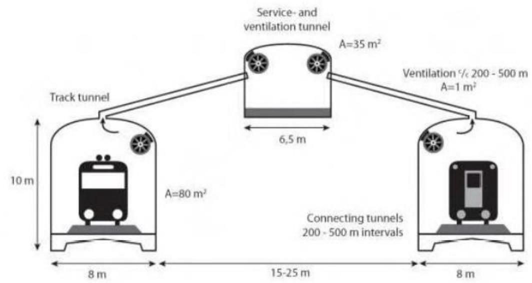


Figure 23– Submited cross-section of the rock tunnel under the sea - Font: http://www.getunderground.fi/getfile.ashx?cid=72805&cc=3&refid=8 and extracted from Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction [99]

3.1.4 Bathymetrical and Geological Data

The information found about the overall Gulf of Finland geology and bathymetry was quite limited. Different geological maps about the sea bottom materials was found, but were not very useful because they only provides information about the top surfaces. Not indicating any of the interesting mechanical properties of the different soils.

Bathymetry was found via online "http://www.emodnet.eu/bathymetry" and can also be found by buying nautical charts but are for paid.However, some information more specific about the Helsinki-Tallinn fixed link area, have been developed since the idea of the project was born and was reachable online or under EGK or GTK demand.

These information was include in three documents, one which contains a 3D geological model between Tallinn-Helsinki possible tunnel area, made by EGK under GTK solicitation; another with the soil and bedrock conditions to be expected along the connections; and finally one with the geological profiles of the tunnel tracks. The three documents are explained in the following lines.

3.1.4.1 Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction

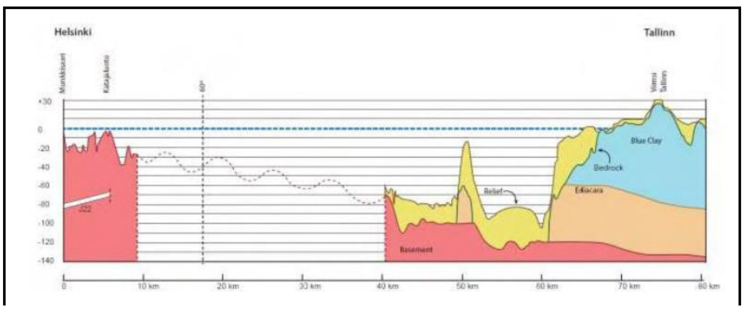


Figure 24–Font: Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction [99]
Cross-section through the Gulf of Finland from Helsinki, Munkkisaari to Tallin Vimsi according to the compiled 3D-model and data of Geotechnical Division of the City of Helsinki. J22 is the cleaned wastewater outlet tunnel, which was built in the 1980s and exteds from Viikinmäki wastewater treatment plant to the area south of Katajaluoto. The tunnel measures 17 km, of which 8 km are in the sea area.

The document includes a simplification of the whole gulf profile and the compilation of Physical-Mechanical properties of each material lay.

It can be seen that as the study was performed to know more information about possible soils/rocks where underground tunnels could be conducted, the information is very detailed in deep strata and less accurate for top layers, where can be concluded that are very weak (mud and clays).

For a major undersanding all the characteristics was summarized during the thesis development in the next table.

Table 1. Physical-mechanical properties of different formations along the Tallinn-Helsinki tunnel [8,9]. 1= volumetric weight, 2= compressive strength, 3= porosity, 4= P-wave velocity ca. 6000-6500 m/s, 5= thickness of formation.

		1	2	3	4	5
		G/Cm3	Mpa	%	m/2	m
Precambrian gneisses	A	2.65 - 2.75	110 - 240	0.1 - 0.2	6000 - 6300	
Rapakivi granites	B	2.65	100 - 200	0.1	6000 - 6500	
Weathered crystalline besement	C	2.0 - 2.6	1 - 100	1 - 20	2000 - 5000	1 - 20
Sandstones	D	2.0 - 2.8	1 - 25	10 - 20	2000 - 3000	n. 60
Siltstone	E	2.25 - 2.35	5 - 25	10- 15	2500 - 3500	1 - 2
Sandstones	F	2.1 - 2.2	1 - 5 Mpa	20 - 25	2500 - 3000	15
Blue clay	G	2.3 - 2.4	2 - 4 Mpa	8 - 10	2000 - 2500	45
Limestone	H	2.55 - 2.65	100 - 150	0.1 - 5.5	4000- 5500	20
Glauconite sandstone	I	1.95 - 2.1	1 - 20	1 - 10	2500 - 3000	2
Alum shale	J	1.9 - 2.0	40 - 50	1 - 10	3500 - 4000	3.5
Sandstones	K	2.1 - 2.8	1 - 40	1 - 20	2500 - 3500	3- 8
Quaternary loose sediments	L	1.5 - 2.2	<1	10 - 30	1500 - 2000	0 - 60
A= Rocks of Jägala complex, B= Naissaar and Neeme rapakivi, C= Weathered crystalline rocks, D= Ediacaran sandstones, E= Ediacaran siltstone, F= Cambrian quartzose sandstones of the Tiskre formation, G= Cambrian blue clay of the Lontova formation, H= Ordovician limestone, I= Ordovician glauconite sandstone of the Leetse formation, J= Ordovician alum shale of the Türisalu formation, K= Ordovician sandstones of the Kallavere and Ülgase formations, L= Quaternary deposits						

Table 4: Different Physical-mechanical properties of different formations along the Tallin-Helsinki tunnel. 1=volumetric weight, 2= compressive strength, 3=porosity, 4=P-wave velocity ca. 60000-6500 m/s, 5=thickness of formation. -Font: Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction [99]

To finish the report, a conclusion about which soils/rocks are suitable or not for the tunnel construction was reach and can be seen in the forth column of the next table.

Complex no.	Thickness m	Properties tbl. 1	Construction conditions	Tunnel km incl. 1.5 %	Formation
1	0 - 60	L	Very difficult	outside tunnel	Quaternary deposits;
2	20	H	Good	outside tunnel	Ordovician limestones;
3	10	J,I	Very challenging	outside tunnel	Lower-Ordovician alum shale and glauconitic sandstone
4	15 + 10	I,K	Very challenging	2	Lower-Cambrian and Lower-Ordovician sandstones;
5	60	G	Good	4	Blue clays (Lükati and upper part of Lontova formations);
6	60	D, E	Very challenging	4	Ediacaran silt- and sandstones (Kroodi formation);
7	15	C	Challenging	1	Weathered crust of basement
8	(km)	A, B	Very good	63	Precambrian basement metamorphic and igneous rocks

Table 5: TBM construction conditions through the different materials present in the Helsinki-Tallinn connection - Font: Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction [99]

The Summary table about the properties of the rocks was therefore created during the thesis redaction for a better understanding of the soil properties:

		Location		Min	Max	Extra
Quaternary deposits	Layers thickness	Burried valleys		10 cm	150 m	Name of some burried valleys: Merivälja, Ülemiste, Kopli and Harku buried valleys can be observed from east to west, and they extended tens of meters into the crystalline basement. They are filled with till and silt, sand and gravel deposits.
		Sea Bottom	General	20 m	60 m	from clays to gravels and tills
			Contemporary marine deposits (mud)	< 15 m		
			Post-glacial deposits (clays)	< 5 m		
			late-glacial (Baltic Ice Lake) deposits (varved clays)	< 20 m		
			Glacial deposits (till)	< 60 m		

		Material	Volumetric weigth	Compresive strength	Porosity	P-wave velocity	Water saturation
Quaternary deposits	Physical-mechanical properties	Sand	1,5 (sand) – 2,2 (till, clay) G/cm3	< 1 Mpa (Extremly weak rocks)	10 - 30%	1500 (mud, varied clay) – 2000 m/s (till).	The Quaternary sediments are water-saturated soft deposits
		Till , Clay					
		Mud, Varied clay					
		Till					

	Period	Material	Location	Thickness Min	Thickness Max	Volumetric weigth	Compressive strength	Porosity	P-wave velocity
Ordovician system	Middle-Ordovisian	Limestones	Baltic Klint limestone plateau in the southern part of the area	< 20 m		2,55–2,65 G/cm3	100–150 MPa (very hard rocks)	0,1–5,5 %;	4000–5500 m/s (Suuroja et al. 2010 a).

		Material	Formation	Thickness Min	Thickness Max	Volumetric weight	Compressive strength	Porosity	P-wave velocity
Ordovician system	Lower Ordovician	General	-	> 10 m		-	-	-	-
		Glauconite sandstone (TOP)	of the Leetse formation	2 m		1,95–2,10 G/cm3	1–20 Mpa	1–10 %	2500–3000 m/s (Suuroja et al. 2010 a).
		Alum shale (graptolite argillite) (MIDDLE)	of the Türisalu formation	3,5 m		1,9 – 2,0 G/cm3	40–50 Mpa	1–10 %	3500–4000 m/s (Suuroja et al. 2010 a)
		Quartzose sandstones with phosphatic brahiopod detritus (BOTTOM)	of the Kallavere and Ülgase formations	3 m	8 m	2,1–2,8 G/cm3	1–40 Mpa	1–20 %	2500–3500 m/s (Suuroja et al. 2010 a)

	Material	Thickness Min	Thickness Max	Volumetric weight	Compressive strength	Porosity	P-wave velocity
Cambrian system	General, siliciclastic rocks (clay-, silt- and sandstones).	100 m		-	-	-	-
	Blue clays of the Lükati formation Baltic Klint.	> 5 m (Ca. 60m)		2,10–2,20 G/cm3	1–5 Mpa	20–25%	2500–3000 m/s (Suuroja et al. 2010 a).
	Pure blue clay of the Lontova formation	45 m		2,30-2,40 G/cm3	2–4 Mpa	8–10%	2000–2500 m/s (Suuroja et al. 2010 a)

	Material		Thickness Min	Thickness Max	Volumetric weight	Compressive strength	Porosity	P-wave velocity
Edicaran system (used to be defined as Upper Vendian)	Weakly cemented sandstones, (red-brown-grey) clayey siltstones of the Kroodi formation.	General	Relatively thin (up to 1–2 m) layers, Reaching the 60 m		-	-	-	-
		Sandstones			2,0–2,3 G/cm3	1–25 Mpa	10–20 %	2000–3000 m/s
		Siltstones			2,25–2,35 G/cm3	5–25 Mpa	10–15 %	2500–3500 m/s

	Material	Thickness Min	Thickness Max	Volumetric weight	Compressive strength	Porosity	P-wave velocity
Precambrian crystaline basement	Rocks of Jägala complex	-		2,65-2,75 G/cm3	110–240 Mpa	0,1-0,2 %	6000-6300 m/s (Suuroja et al. 2010 a, b).
	Intrusive rocks (represented by the Naissaar and Neeme rapakivi massifs)	-		2,65 G/cm3	100–200 Mpa	0,10%	6000-6500 m/s (Suuroja et al. 2010 b)
	Weathered crystalline rocks	-		2,0–2,60 G/cm3	1–100 Mpa	1–20%	2000–5000 m/s (Suuroja et al. 2010 a, b).

Table 6: Summary of the geology – Own development.

3.1.4.2. 3D Model of the Estonian part and Geological data base for the possible Tallin-Helsinki tunnel area [6].

This document presents a simplification of the gulf of Finland geological profile as well as the Physical-Mechanical properties of each material layer. A 3D Map of the geology of the Estonia Area and Finland is done by mean of wave sounding and recompilation of other studies.

The (x,y,z) coordenates of a 3D model of the study area have been already compiled and are separated in two parts (Estonian and Finland). The information of the sea bottom model of the Tallinn side can be obtained by contacting Juha Korpi, from the Helsingin kaupunki institution.

About what the geological 3D model of the Finnish part concerns, it is only accessible under the Uudenmaanliitto, the Regional board of Uudenmaa, permission and their email of contact is “office@uudenmaanliitto.fi”.

3.2 Vessels properties and maritime activity

Properties about the density of shipping transit along the gulf of Finland, the main used channels, the vessels draughts and the number of accidents which took place during the lasts years is something to take into account when projecting a water crossing project as a Bridge or Immerse tunnel. Their spatial interaction can produce navigational changes or put the structure in danger for possible collisions motive for doing an accurate investigation.

All the data was extracted from the draft annual report on shipping accidents in the Baltic sea area in 2013; the report was performed for the Baltic Marine Environment Protection Commission and can be consulted online[101].

3.2.1 Shipping transit intensity by vessel type

The report include a map, Figure 24, with the main routes followed by ships and the boats. Their density is color scaled and makes easy to observe that the Gulf of Finland is one of the most transited, High shipping density. It is more transited than the Gulf of Bothnia, which is larger and wider. This means an extra challenge for bridges piles location.

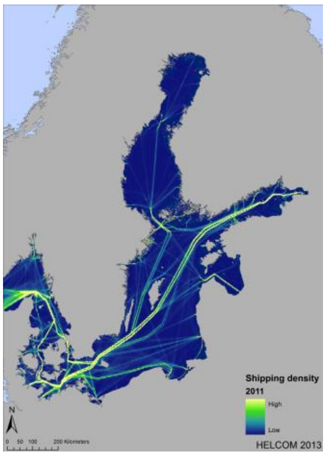


Figure 25: Monthly average density of shipping traffic during 2011, with the busiest routes highlighted in yellow.- Font: Annual report-Shipping accidents in the Baltic Sea in 2013. Riga [101]

Futhermore, another density indicator is the number of ships which crosses the13 conceptual AIS fixed lines along the baltic sea. AIS fixed lines. The location of the AIS lines can be seen in the figure 25 . Furthermore, the number of ships can be found separated by type or draught in table 7 and 8 respectively.

The comparison between the movement of ships through the gulf of Finland and the gulf of Bothnia conducts to the same conclusions. While in the Gulf of Finland, a total of 38.150

vessels crossed the Gulf of Finland AIS line; in the Gulf of Bothnia, the in-out flux of ships through theAland West and Aland East linesAIS lines was 15.830 vessels. Therefore, the flow of ships was 58,5% more in our project area than in the Swedish sea.
The Bothnia's gulf traffic distribution through the lines was 7,86% passengers ships; 67,1%Cargo; 10,82% Tanker; 9,92% other types; and 4,23% unknown vessels.
In the Finland'sGulf, it was 13,79% ; 52,7% ; 18,65% ; 10,4% ; and 4,41% respectively.

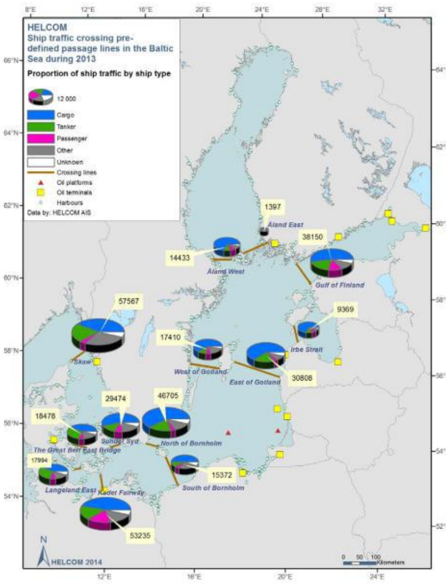


Figure 26: Ship traffic crossing predefined passage lines in the Baltic Sea during 2013 according to their type - Font: Annual report-Shipping accidents in the Baltic Sea in 2013. Riga [101]

The percentage of passenger and tankers respect the overall ships passing the respective line is almost the doble in the Gulf of Finland than the Bothnian sea. However, about what Cargo ships concerns, the proportion of cargo ships in the passage is a 30% bigger in Bothnia's sea than in the Finnish sea.

Table 1 Number of ships crossing AIS fixed lines in the Baltic Sea in 2013 according to the type of the vessels.

Location	Type of ship					
	Passenger	Cargo	Tanker	Other	Unknown	Total
Skaw	2394	24188	10523	17690	2772	57567
Great Belt East Bridge	1544	7961	4925	3079	969	18478
Sundet Syd	2806	16055	3778	5168	1667	29474
Langeland East	1590	7742	4799	2783	1080	17994
KadetFairway	10171	24556	7590	8600	2318	53235
North of Bornholm	1903	27875	9232	5434	2261	46705
South of Bornholm	920	7701	1468	4143	1140	15372
West of Gotland	1498	10502	1850	2835	725	17410
East of Gotland	1220	18926	7010	2149	1503	30808
Åland West	1231	10039	1608	980	575	14433
Åland East	13	593	105	591	95	1397
Gulf of Finland	5261	20113	7118	3975	1683	38150
Irbe Strait	778	6519	1187	532	353	9369
Total	**31329**	**182770**	**61193**	**57959**	**17141**	**350392**
Percentage of total	**9**	**52**	**17**	**17**	**5**	**100**

Table 7:Ship traffic crossing predefined passage lines in the Baltic Sea during 2013 according to their type. - Font: Annual report-Shipping accidents in the Baltic Sea in 2013. Riga [101]

In addition to the number of ships, it is interesting to know their draughs. The draughs of the vessels which crosses the Finnish line will defines the minimal depthness that the immerse tunnels facilities need to have respect of the sea surface. It will permit to avoid vessels colisions with the infraestructures.

Therefore, it can be observed in table 8 that 171 vessels out of 38150 had a draugh bigger of 15 meters. This was the 0,44% of the vessels that crossed the line in 2013, but still have to be taken into account. The resting percentage, 80.95% , of the vessel's draught dimensions used to be under the 7-9 meters.

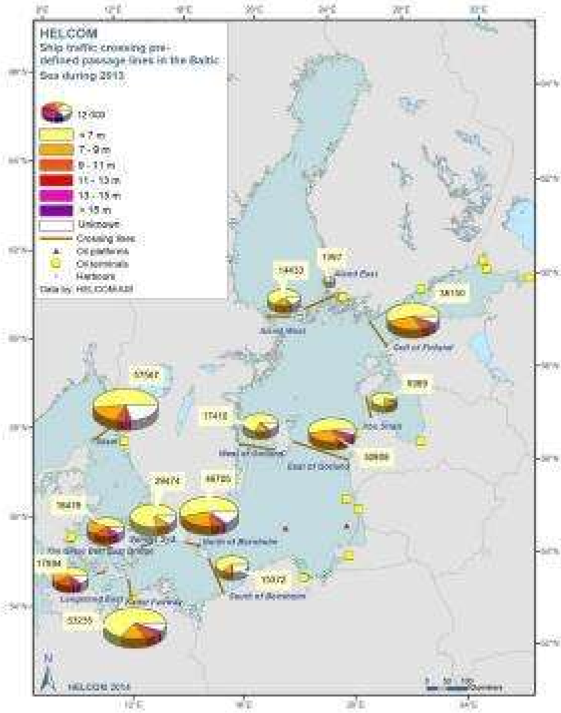


Figure 27: Ship traffic crossing predefined passage lines in the Baltic Sea during 2013 according to their draughts.- Font: Annual report-Shipping accidents in the Baltic Sea in 2013. Riga [101]

Table 2 Number of ships crossing AIS fixed lines in the Baltic Sea in 2013 according to the draught.

Location	Draught							
	<7 m	7-9 m	9-11 m	11-13 m	13-15 m	> 15	Unknown	Total
Skaw	29934	9087	3883	1106	1349	221	11987	57567
Great Belt East Bridge	7620	3545	3193	846	1233	106	1930	18478
Sundet Syd	23023	3461	4	1	0	9	2976	29474
Langeland East	6883	3522	3214	845	1279	100	2151	17994
KadetFairway	34483	9267	3996	833	1276	96	3284	53235
North of Bornholm	25318	10183	3417	698	1192	103	5794	46705
South of Bornholm	9607	1639	440	90	49	0	3547	15372
West of Gotland	11808	2836	429	29	51	2	2255	17410
East of Gotland	16259	7993	3055	579	1222	164	1536	30808
Åland West	9118	2607	495	25	59	2	2127	14433
Åland East	1041	51	7	0	0	0	298	1397
Gulf of Finland	20827	10091	3059	451	935	171	2616	38150
Irbe Strait	7123	1415	443	58	122	2	206	9369
Total	**203044**	**65697**	**25640**	**5561**	**8767**	**976**	**40707**	**350392**
Percentage of tot.	**58**	**19**	**7**	**2**	**3**	**0**	**12**	**100**

Table 8:Ship traffic crossing predefined passage lines in the Baltic Sea during 2013 according to their draughts.- Font: Annual report-Shipping accidents in the Baltic Sea in 2013. Riga [101]

As the exact maximum draught is no given, the research of the draught of the biggest vessel of the world was done.The vessel found with the largest draught in 2018 was the OOCL Hong Kong containers ship, which has a 32,5 meters draught.

Font: https://www.marineinsight.com/know-more/10-worlds-biggest-container-ships-2017/

This kind of boats are not expected to pass through the gulf of Finland and, in the case of passing through, they would be monitored and guided by the VTS (Vessel Traffic Service) as large boats need to be monitored and communicated with the navigational aids centers. They have to accomplish with certain reglaments and their instructions.

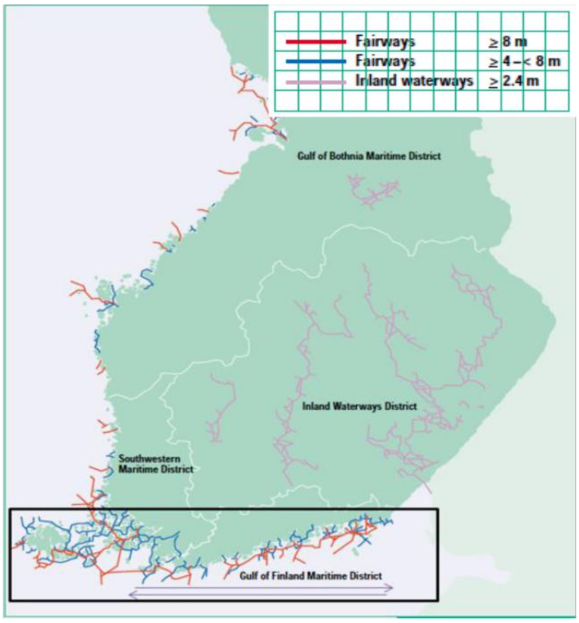


Figure 28: Maximum draught in Finland Maritime District.- Font: Waterways in Finland [103]

The Finnish reglament, also have establishedthe maximum draught for their channels, which can be consulted in the navigational charts.Furthermore, a maximum draught is set for coastal and inland fairways. Differencing the merchant shippings canals from the shallow fairways.

These limits can be seen in the Waterways in Finland report, which was conducted by the Finnish maritime administration. [103] .

Maximum authorized draught of coastal fairways and inland waterways

	MERCHANT SHIPPING FAIRWAYS, maximum authorized draught 4.0-15.3 m	SHALLOW FAIRWAYS, maximum authorized draught < 4.0 m	TOTAL
Coastal	4 606 km	3 619 km	8 225 km
On inland waters	814 km	7 028 km	7 842 km
Total	5 420 km	10 647 km	16 067 km

Table 9: Maximum draught in Finland Maritime District. Font: Waterways in Finland [103]

The depthness to assecure the safety of an immerse tunnel should be at least about 30 meters in the open sea, due to the vessels draugh, and its recomanable to be dredged in the sea bottom in Inland or Fairways zones for avoiding collisions and groundings agains the structure.

The not compliment of the draught limitations, distractions or unexpected relief changes can produce accidents such as groundings or collisions. This groundings can affect immerse tunnels, unless being located in a drilled trench, creating irreparable damages or a possible flooding of whole the tunnel.

It can be seen in figure 2.11 that as big as the draught of the ships are, the probability of grounding is less. This can be justified due to the small vessels do not require traffic control, can be novice captains and then, the tendency to take grounding risks can be greater.

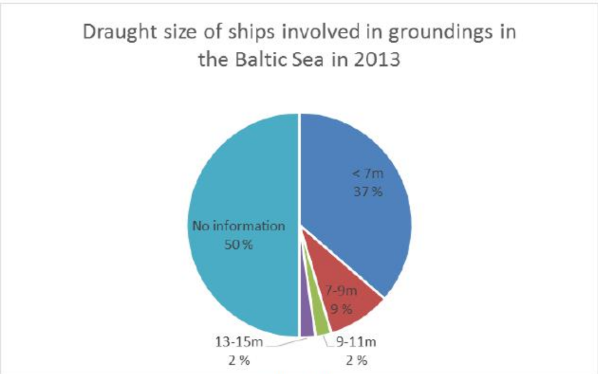


Figure 25

Figure 29: Groundings in 2004-2013. - Font: Annual report- Shipping accidents in the Baltic Sea in 2013. Riga [101]

The Traffic Centers providen information to shipping about specific and urgent situations which could cause conflicting traffic movements and other information concerning the safety of navigation, such as information about weather, ice, water level, navigational problems or other hazards.

There are different competent VTS authorithies along the gulf as there are three countries involved. The gulf area have been spared in several zones which can be seen in picture 2.14 and which are directed from the Tallin traffic center (Dark Blue), from the St. Petesburg traffic center (Light Blue) and Helsinki maritime traffic center (Red).

Figure 30: Area of GOFREP, the mandatory Ship reporting System of the Gulf of Finland. -Font: Development Process of the Gulf of Finland Mandatory Ship Reporting System. [104]

Unless this thesis is using data from 2013 for maritime transports study; we can see in figure 30 that the number of shipping crossing is stable from 2006 to 2013. Therefore, it seems reasonable to use this data because any change of greatest importance about what shipping transport concerns happened in this period of time.

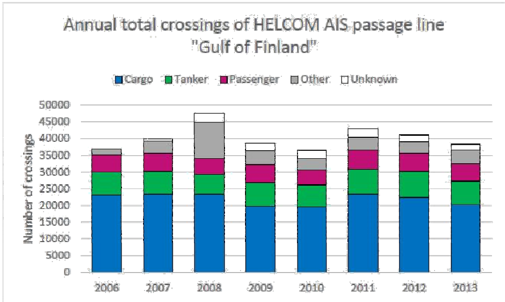


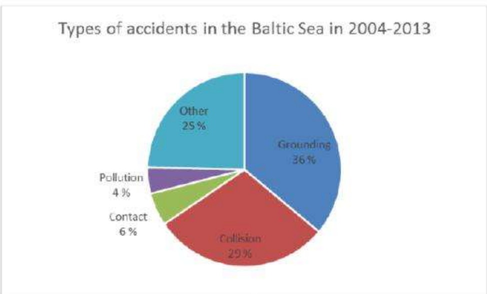
Figure 31: Number of ships crossing the fixed AIS line "Gulf of Finland" during 2006-2013. Shown here grouped by ship type.- Font: Annual report- Shipping accidents in the Baltic Sea in 2013. Riga [101]

However, unless the help of the traffic centers, the establishment of indicators such as leading marks, sector lights, spar buoys, buoys and edge marks; there are still accidents happening in the Baltic sea.

As the collisions agains bridges piers, pontons or immerse tunnel would significate a harmful impact to the infraestructure, they would be the shipping accidents that the thesis would analize in more detail.

In the figure number 31 and 32, it can be seen the evolution of the number of accidents produced in the Baltic sea and the type from 2004 to 2013.

Furthermore, the accidents of 2013 are categorized by location and ships.



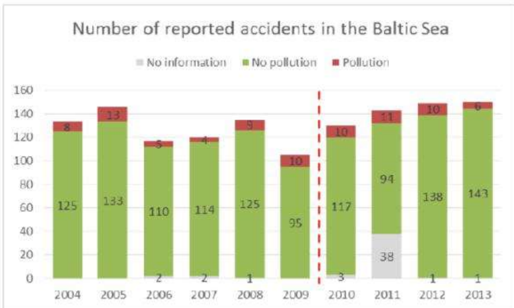


Figure 32, Figure 33: Types of accidents in Baltic Sea in 204-2014. Number of reported accidents in the Baltic Sea. Font: Annual report- Shipping accidents in the Baltic Sea in 2013. Riga [101]

We can see that the number of collisions between 2004-2013 are around 370, with an average collisions number of 37 per year, and the number of groundings was around 460 (46 groundings per year).

These values seems very small for the to the 38.150 boats that crosses the predifined passage lines of the gulf of Finland per year and which have a total area of 29 570 square kilometers. The accidents agains the infrastructure would not be statistically probable if the infrastructure is strategy located. Therefore, as safety is very important, the maximum protection to the infrastructure needs to be studied.

If we study the collisions location, can be seen as its logical, that the most part of them happened in the ports (59,57% in 2012 and 43,85% in 2013 data); the second more typical location for collisions is nearby the port (17% in 2012 and 24.5% in 2013); and the rest happened in open sea or there was not information.

There is a direct relation between the number of facilities and the number of collisions. As our facilities goes along the fairways and open sea, it's important to provide enough depth to avoid the collisions at the 100%.

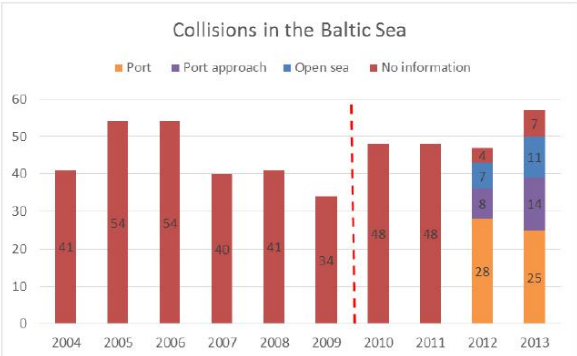


Figure 34: Number of collisions in the Baltic Sea and their location. Font: Annual report- Shipping accidents in the Baltic Sea in 2013. Riga [101]

Figure 35: Number of collisions in the Baltic Sea and their location.- Font: Annual report- Shipping accidents in the Baltic Sea in 2013. Riga [101]

Accidents related with pollution have not been considered as causes a very big enviromental damage but do not represent a risk for the fixed link connection.

3.2.3 Water properties

Density:

The water density was another of the important facts to determine as it would be the enviroment that an immerse tunnel or the bridge piers should have to resits.

Water density in Gulf of Finland	
Min value (g/cm3)	Max Value (g/cm3)
1,00250	1,00525

Table 10: Extreme waves characteristics in Gulf of finland

Velocity:

As the water velocity varies with the depth, the average velocities in funtion of the depth was also obtained.

Current velocity in gulf of Finland	
Depth (m)	Velocity (cm/s)
0	80
5	7
10	9
15 , 20, 30	5

Table 11: Current velocity in gulf of Finland

3.2.5 Direction of the water flow

It can be seen in the next picture, the velocity of the water in the surface as well as its mean circulation direction.

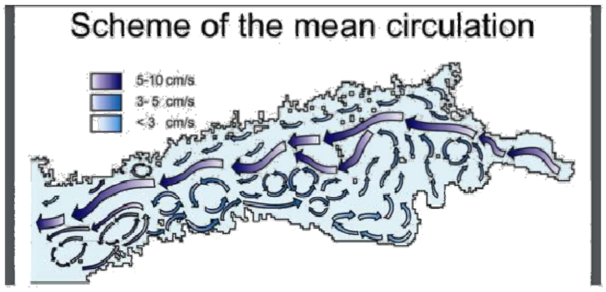


Figure 36: Scheme of mean circulation in the Gulf of Finland

It can be concluded, that the water flow would be mainly perpendicular to a hyphotetical bridge or immerse tunnel's guideline.

3.3 Social and Economical justification

Prefeasibility study summary:

Before approving the execution of a water-crossing project, the cost of the project, safety and the benefits for the society have to be analyzed to determine if the structure in socially and safety feasible. These studies are named as pre-feasibility studies.

In the Helsinki-Tallinn fixed link project, the pre-feasibility study has already been exe-cuted [7] by a joint venture formed by Sweco Projekt AS, Vealeidja OÜ and Finantsakadeemia OÜ. Futhermore, experts from Sweco Finland and Sweco Sweden and from Kohateam Oy and Geological Survey of Estonia were also involved.

SWECO Pre-feasibility study proceeded to the study of the current demographic and economic evolution of Helsinki and Estonia until nowadays, without the existence of a fixed link connection. Furthermore, a prognosis of the Estonian and Finland passengers and cargo traffic until 2080 is also exposed.

Then the impact of a fixed link scenario is done by the study of similar projects such as the channel tunnel, the Øresund Bridge and the Fehmarn Belt, project which is still under development in 2017. (Tunnel, Bridge and Immerse tunnel)

Finally a prognosis of passengers and cargo traffic between Helsinki and Tallin overall is done.

Note: For going deeper on these information, please read through the prefeasibility study .

3.4 Project Solutions

3.4.1 Studied tracks in the prefeasibility study

In the prefeassibility study, other tracks are also considered and the cost of a tunnel is estimated

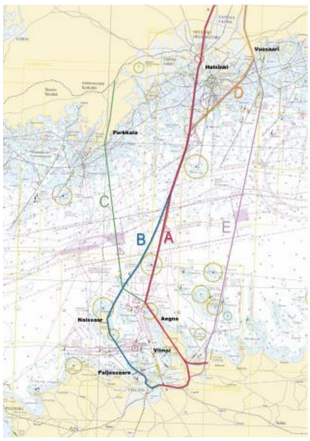


Figure 37

Table 20 Route options A ... E

Line options	Length, km		Cost estimate, EUR	Conclusions
	Tunnel	Surface		
A. Pasila–Muuga–Ülemiste	85	20	7,000–8,800	The quickest alternative for passenger traffic between the city centres of Helsinki and Tallinn. Connections to the existing traffic system are most optimal.
B. Pasila–Naissaar–Paljassare–Ülemiste	77	25	not done in this study	Connection to the existing track network on Estonia's side is challenging. At Paljassaare the track would go through the existing town structure and settlement.
C. Pasila–Porkkala–Muuga–Ülemiste	65	65	not done in this study	The shortest tunnel. Possibly the cheapest. Connections to traffic systems are weak. For passenger traffic, this is a slow connection to Helsinki. Environmental impact in the area of the cape of Porkkala. Geologically complicated.
D. Vuosaari–Aegna–Muuga–Ülemiste	92	20	not done in this study	Several disadvantages for passenger traffic, because it requires a change to subway when travelling from the city centre of Helsinki, which lengthens the travel time. At Vuosaari there is less space for the tunnel exit and a railway station. For cargo traffic, there are good connections to the main track through the tunnel of Savio.
E. Vuosaari–Maardu–Muuga–Ülemiste	82	17	not done in this study	Several disadvantages for passenger traffic, because it requires a change to subway when travelling from the city centre of Helsinki, which lengthens the travel time. At Vuosaari there is less space for the tunnel output and a station. For cargo traffic, there are good connections from Muuga to the main track through the tunnel of Savio.

Table 12: Prefeasibility Routes and costs estimation - Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

3.4.2 Insfraestructures and Construction method in the prefeasibility study

Then a study of the different infraestructures and constructive methods alternatives is done briefly, as can be seen in the next table:

Table 21 Tunnel Types by construction method

	Tunnel type	Construction method	Conclusions
1.	Rock tunnel	by drill and blast or partly TBM	Challenges in weak soil layers on the Estonian coastline. The most feasible route is found. Excavation method and construction time have to be studied more carefully in the next planning. D&B rock material could be used as construction material in this project and for other purposes. Minor environmental impacts (whole tunnel section under seabed).
2.	Rock tunnel , partly bridge	by drill and blast or partly TBM, bridge constructed in traditional way	Tunnel section as in whole rock tunnel type. Naissaar Bridge section does not enable fast train connections (over 250 km/h). Connection to the existing transport system is difficult (Rail Baltica and railway corridor through the city of Tallinn). D&B rock material could be used as construction material in this project and for other purposes. Minor environmental impact on underground sections, major environmental impacts on bridge section.
3.	Immersed tunnel	Immersed concrete elements	Slow and expensive construction: time, excavation on seabed, immersing and connecting elements, system installations. Solution will need landmasses outside of the project. Major environmental impacts. Risks: Underwater construction works Intersecting cable and pipelines, environmental permissions, crossing vessel traffic.

Table 13: Constructing method alternatives considered in the prefeasibility study - Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

Once the tunnel method is elected, different cross-sections are studied.

Table 22 Types by Cross-section

Tunnel type	Cross section	Conclusions
A	Train tunnel (2 rails) + Ventilation tunnel + Service & emergency tunnel + Cross passages approximately 400 m	In train operations a possibility to change rails in the tunnel (in case of passing slower traffic or breakdown). Disadvantages: hard to achieve 250 km/h target speed level.
B	Two separate train tunnels + Combined service and ventilation tunnel in the middle Cross passages approximately 400 m	Enables the speed level of trains 250 km/h = 30 minutes travel time. No possibility to change rails in the tunnel.

Table 14: Cross sections considered in the prefeasibility study.-.Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

The objectives of the project are clearly fixed as:

-To connect to the existing transport system in both cities.

-To achieve a 30-minute travel time between cities.

-To achieve the most feasible combination from the technical perspective (Invesment cost, safety and rescue, maintenance and operation).

The thesis concludes that the solution 1.B of a rock tunnel is the recommended for the fixed link connection. Not considering the SFT tunnels as a posible alternative or other combinations which are going to be proposed.

Figure 30 Option 1.B – a Rock Tunnel with two separate train tunnels

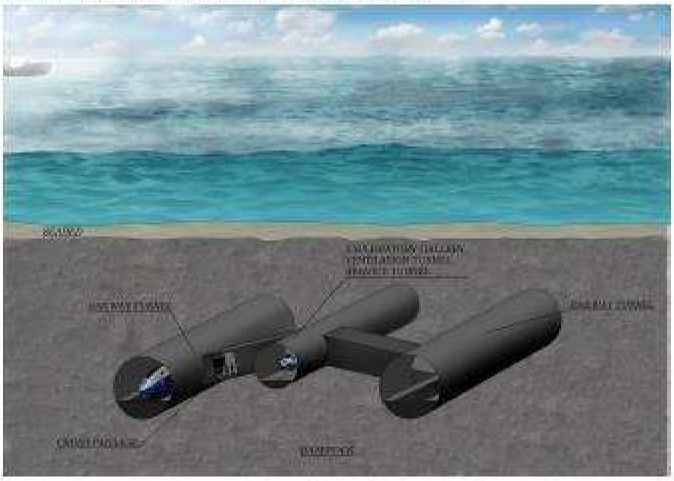


Figure 38: Rock tunnel with two separate train tunnels (Prefeasibility study) -Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

Table 23 Technical cost estimate for tunnel 1.B for route A

Cost types	Low price, MEUR	High price, MEUR
Tunnel with railways, 85 km	3,600	4,100
Surface track sections	700	1,000
All technical systems, maintenance canals, security	2,500	3,300
Finnish cargo terminal and passenger station	200	400
Estonian cargo terminal and extension of passenger station	70	150
Rolling Stock	1,000	1,000
Risk reserves	1,000	3,000
TOTAL COST	9–13 billion euros	

Table 15: Technical cost estimate for tunnel 1.B for route A.-Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

The estimated total cost is between 9-13 billion euros in the prefeaibillity study. The operation cost is also studied as can be seen in the next tables:

Table 24 Estimated operating cost model for total cost calculation

Type	Total, incl. investments		Without investments	
	€/h	€/km	€/h	€/km
Shuttle (passenger, car or truck)	1,030	7.00	442	7.00
High speed train	1,000	6.20	341	6.20
Cargo train	716	5.19	503	5.19

Table 16: Estimated operating cost model for total cost calculation in prefeasibility study -Font: Pre-feasibility study of Helsinki– Tallinn fixed link, Final Report [98]

Table 25 Cost per transport unit calculated on the basis of operation model and basic cost model

Type	Cost per passenger, €/passenger	Cost per unit, €/unit (using double unit)	Link
Passenger shuttle High-speed train	6.40 7.33	- -	Tallinn–Pasila Tallinn – Airport (Hki)
Car shuttle bus shuttle		58.48 (30) 350.74 (176)	Terminal Hki – Tallinn Terminal Hki – Tallinn
Truck, shuttle truck, cargo train		467.55 (234) 181.48	Terminal Hki – Tallinn Riihimäki–Tallinn
Containers, cargo train		83.18	Riihimäki–Tallinn

Table 17: Estimated operating cost model for total cost calculation in prefeasibility study -Font: Pre-feasibility study of Helsinki– Tallinn fixed link, Final Report [98]

Table 26 Cost per transport unit (without investments, estimated loading factor 85%) calculated on the basis of operation model and basic cost model

Type	Cost per passenger, €/passenger	Cost per unit, €/unit (using double unit)	Link
Passenger shuttle high speed train	3.80 4.42	–	Tallinn–Pasila Tallinn – Airport (Hki)
Car shuttle bus shuttle		36.84 221.03	Terminal Helsinki – Tallinn; Terminal Helsinki – Tallinn
Truck, shuttle truck, cargo train		294.71 147.80	Terminal Helsinki – Tallinn; Riihimäki–Tallinn
Containers, cargo train		33.76	Riihimäki–Tallinn

Table 18: Cost per transport unit (without investments, estimated loading factor 85%) calculated on the basis of opration model and basic cost model in the prefeasibility study.-Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

In the case of only one shuttle unit running, the operating cost per train kilometre (without investments) is:

- passenger shuttle: 11.91 €/km (route 90 km, Pasila–Tallinn)
- passenger train: 9.80 €/km (route 120 km, Tallinn–Airport)
- car, bus and truck shuttle: 12.50 €/km (longer terminal times, route 120 km)
- cargo train: 11.48 €/km (containers, route 160 km from Riihimäki)

If is recommended to study tunnel-related operation models and operating costs in more detail in the next planning phase.

Figure 39: Snapshot of the operating cost per train kilometer (without investments) included in the Prefeasibility study -Font: Pre-feasibility study of Helsinki–Tallinn fixed link, Final Report [98]

3.5 Deepening in study of alternatives

3.5.1 Studied Project Tracks

The geological profiles are used to decide which are the posible solutions for the fixed link. As theconsidered tracks, shown in section 2.4.1, were defined for tunnels, maybe they are not the optimal track for bridge. However as they gives an optimal solution for the location of ventilation shafts, using the Tallina madal and other island formations, the tracks are interesting for immerse tunnels alternatives.

On the other hand, the sounding graphs for each of the (ABCDEFG) tracks have executed and can be seen in the geological profile report.

This thesis has decided to use the profile of the option B2 as it was found digitalized in a clear scale and the categorization of type of soils was already done with different colors and reachable online. The option D was also available but seemed not to optimize the length of the project or give the chance to conduct the infrastructure in terrestrial surface again as soon as possible.

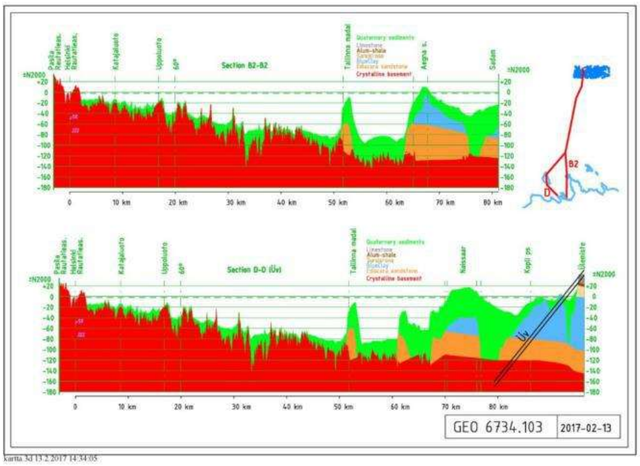


Figure 40: Profiles of geological units and the sea floor relief between Helsinki and Tallinn drawn according to the marine geological survey of GTK. The Precambrian hard crystalline rock is marked with red. A southward-dipping trend is clearly visible in the acoustic cross sections and the bedrock surface dips gradually down to the depth of approximately 120 m under the Cambrian –Ordovician sedimentary rocks on the Estonian coast. The topmost profile B2 goes from Helsinki city centre to Tallinn harbor, and the lower profile D via Navissaar Island to the Ulemiste traffic centre in Tallinn. The soft sedimentary rock units are marked with brown and blue in the profile. The loose Quaternary sedimentary cover is marked with green and it is tens of metres thick on the Estonian coast and just a narrow cover on the bedrock in the Finnish section of the profile. Crystalline bedrock also frequently crops out on the seafloor in the Finnish section. The profile was compiled by the Geotechnical Division of the City of Helsinki based on the acoustic-seismic survey of GTK and available geological mapping data.-Font: New survey of the Helsinki–Tallinn railway tunnel route [105]

A terrestrial access alternative was not considered in B2 track as it was made thinking in tunnel alternative. However, as this thesis also considers immerse tunnels and bridges, which can emerge to the water surface, the quick return of the infrastructure to the terrestrial surface is also to take into account and can be seen in figure 40 (black line).

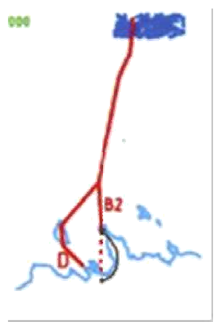


Figure 41: Terrestrial alternative.

These quick connection with the land would reduce the project costs, permit more velocity to the trains and the subsequent reduction in travel time and a shortening of the project duration.

3.5.2 Maps with the viable solutions

All the different type of structures and construction methods, have been taken into account while studying the viability of the different options and their possible combinations.

Some requisites have been demanded for the different types and constructional methods for the safety of the structure.

First of all and as decided for immerse :

> *"To assecure the safety of an immerse tunnel, its depthness should be at least about 30 meters in the open sea and its recomanable to be dredged in the sea bottom in Inland or Fairways zones for avoiding the two accidents whichf could occur agains the Helsinki-Tallin fixed link infraestructure (Collisions and Groundings)".*

For bridges, the height of the bridge have to be reasonable to permit the traffic of high ships (>20 meter above sea) and have different mobile bridges, along the track to permit bigger ships traffic.

Another circumstance to take into account in all the structures but which affect mainly tunnels, are the allowable tunnel's gradients. Because for high speed tunnels gradients are limited and this can be crucial while deciding the tunnel trace.

After studying the parts where each method could be implemented and the security requisites where accomplished; different combinations was considered, giving a total of 6 combinations which are going to be exposed as follows from simple to complex.

Undersea Tunnel

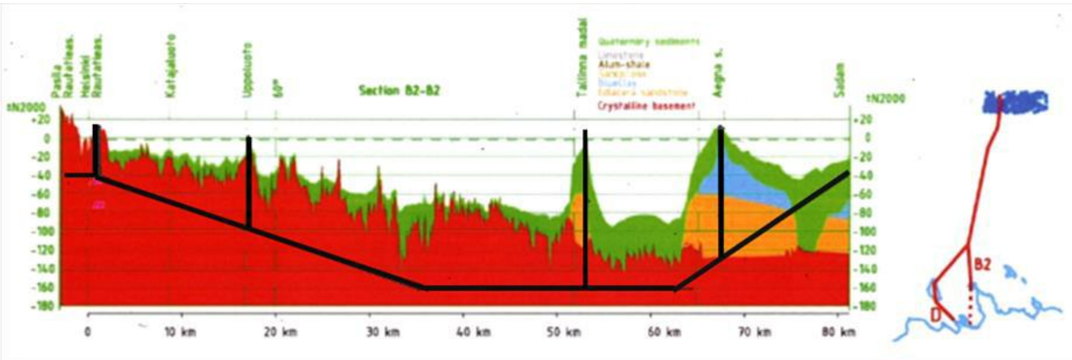


Figure 42: *Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.*

Immerse tunnel and terrestrial access / Bridge

This option considers around of 65 kilometers of immerse tunnel starting from Helsinki, with its posterior terrestrial connection by using a small tunnel (less than 5 kilometers) to return the railway to the terrestrial surface. Once the terrestrial connection is achieved, the rails would continue above land until arriving to the city of Tallin.

The construction method considered for building the full immerse tunnel track was to make it rest over the sea bottom or locate it inside of a trench, however this options was discarded for being very expensive, due to the big amount of subaquatic work and more of 80 meters of depth in some points of the track.
In addition, these options, was not contribuing on shortenning the distance between both the cities and all the mud was needed to be removed as only very small settlements in a high speed tunnel are allowed.
However, this solution advantage was that in farways, where the depth is less than 15 meters, it gaves an extra of safetyness when excavated in a trench, as the collisions would be only posible if a ship sunks over a tunnel section and loads the surrounding material. Motive why it is considered to be combined with other immerse tunnel construcion methods in the alternatives given subsequently for the full immerse tunnel track. Another advantage was that due to rest along all its guideline, the sections length can be as big as able to transport, being an advantage when building very long tunnels.

Another way considerated to construct immerse tunnels was to let the modules flotate and fix them to a competent rock by mean of piers or anchors or gravity based anchors. However, as the 30 meters depth condition is only satisfied from kilometer 25 to 65 starting from Helsinki (40 km out of 80 km), and the immerse tunnel structure must be located under 30 meters for being safe against collisions, this method could not be implemented along full Helsinki-Tallin track.

The combination of the both exposed immerse tunnels was also contamplated for a full immerse tunnel implementation.

The only possibility, for obtaining a proper immerse tunnel, was the use of subaquatical cut and cover for the first 25 kilometers starting from Helsinki, then 40 kilometers of immerse tunnels (if possible with anchors) and the use of a small tunnel or cut and cover to reach the surface from the pk 60 to 70. Once arrived to Aegna surface, the implementation of the terrestrial solution was considered the cheapest clearly.

Another posibility more expensive, but which contribute in shortenning the project length is the construcion of a final bridge in Tallin coast. It would depend on the budget and the reduction in time should be studied.

Should be notice, that due to the length of the tunnel, vertical ventilation shafts have as well been proposed in strategic islands for being secure agains impacts and reducing the dificulty of vertical excavation execution.

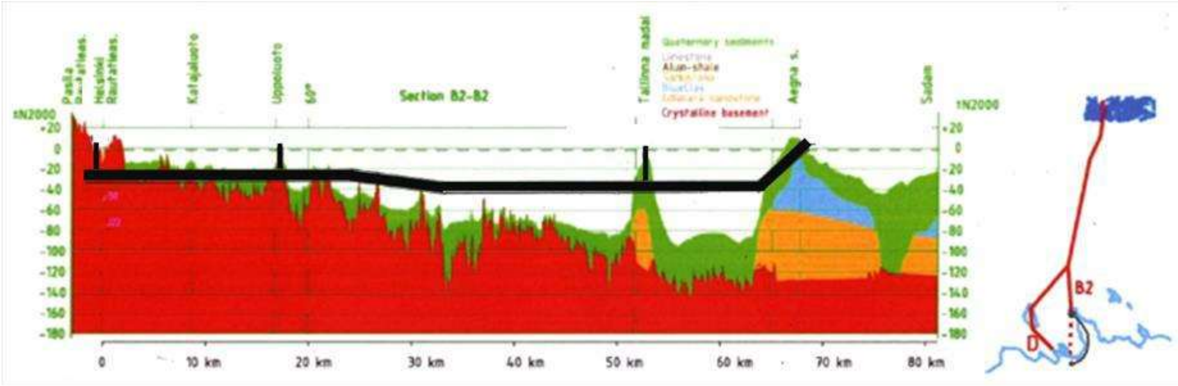


Figure 43: Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.

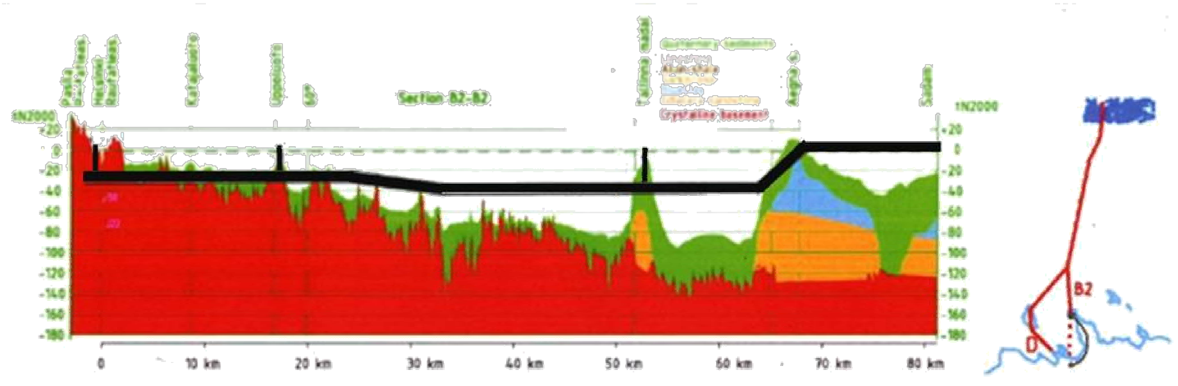


Figure 44: Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.

Bridge

The use of a bridge for the entire track has to deal with some 100 meters piers, which have been already constructed. It would create a new surface, profitable for other future projects as offshore oil stations, renewable energy plants, etc.
However, would also affect the navigation of high vessels and submarines.

The high ships navigation could be easily solved by the use of navigational channels with the creation of mobile spans and the piers can have resistance enough to resist the submarine impacts. However the price is something to analyze in the posterior sections.

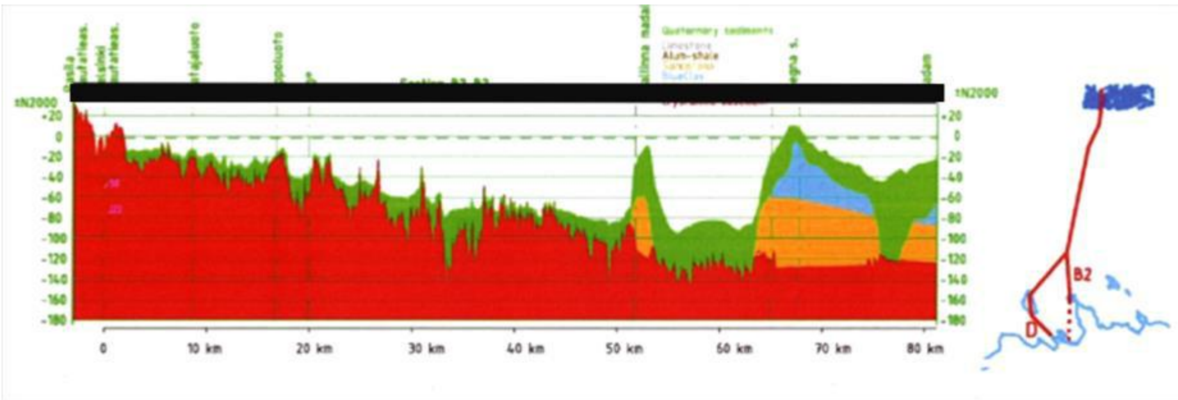


Figure 45: Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.

Bridge, Island tunnel, Immerse tunnel, and Terrestrial connection / Bridge.

This option deals with two types of structures; the tunnels and the immerse tunnels.
As the gulf of Finland do not reach the 30 meter of deepness until being 20 km away of theHelsinki's coast line,it is proposed that unless using cut and cover method, as donein full immerse section, use a bridge and island tunnel for the first 20 kilometers.

The disadvantages of the bridge are minimized in the Helsinki's coast as the deepness is only 20 meters, shortening the piers; the submarines are not going to navigate through the shallow waters and the high vessels can over pass the bridge if a mobile spans are created along the bridge.

The immerse tunnel achieve the safetiness by installing their facilities more than 30 meters depth, reaching the 40 meters in more than 30 kilometers.

The final approach of the track could be done by a tunnel which connect the infraestructure to the terrestrial surface, where the infraestructure would continue until Tallin or another posibility, which is more expensive but would contribute in shortenning the project length, is the construcion of a final bridge in Tallin coast.

This final approach would be determined by the budget and the reduction in time obtained by the second proposal.

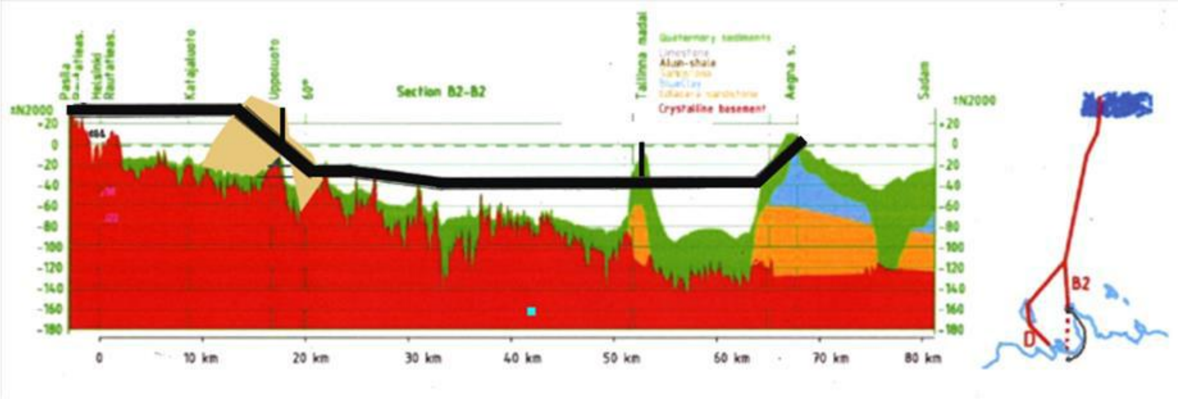


Figure 46: Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.

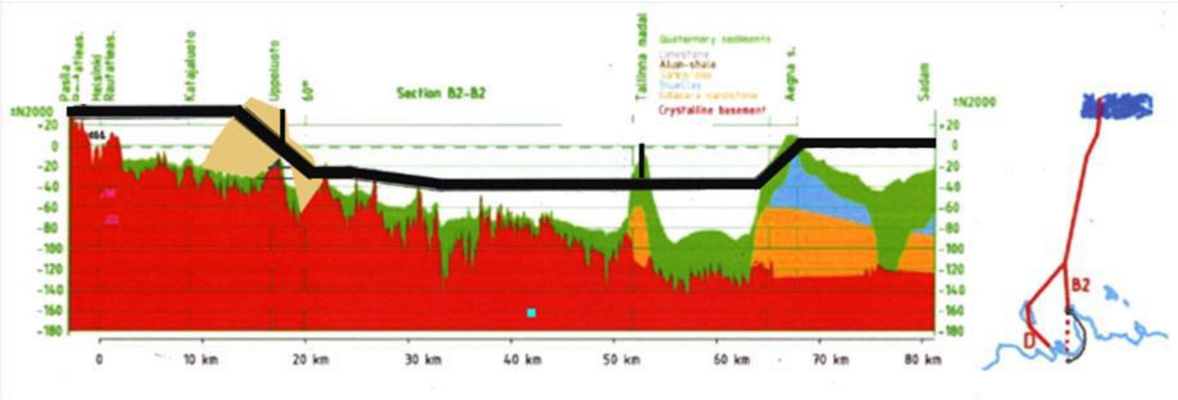


Figure 47: Profiles of geological units and the sea floor relief between Helsinki and Tallinn and overlapped with the alternative proposed in the present thesis.

Results of the considerated alternatives:

The possible alternatives have been studied and are very different. However, as the infrastructure cost has also a big role, in the election of an alternative, the estimation of the infrastructure types are going to be studied.

Chapter 4 - Analysis of the existing water crossings

A big amount of hours were spent on the research and conversion of data about existent water crossing infrastructures. This information was found mainly in English and taken from Journals' articles, online Encyclopedias, Conferences' reports, Magazines' articles, Newspapers' news, construction companies' portfolios, trustful WebPages and travel guides. All the consulted information used along the thesis development is included in the biography and can be found at the end of this document.

4.1 Studied Projects

The starting point was to select the projects which fullfilled the caracteristics to be subject of our study. A lot of 136 projects from nineteen countries of around the world were therefore selected by research. The most part of these projects was located in developed countries where the water represents a challenge for what the country interconnectivity concerns. These countries are Norway, for its Fjords; Japan, for their amount of spared islands; China, due to its coastline shape and others such as Denmark, Sweden, USA and UK. However, the study of some isolated projects located in other countries such as Australia, Netherlands, Iceland, South Korea, Argentina, Turkey, Belgium, New Zealand, Greece, Canada and Saudi Arabia was also taken into account.

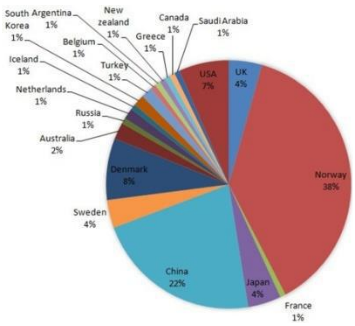


Figure 48: Location of the 136 water crossing projects

Project Name	Total Cost	Countries	Start	End	Infraestructure	Purpose	Construction Method	Lengt (Km)	Max depth (mbsl)	Min rock cover (m)	Geology
The channel tunnel	$21 billion £12 billion	UK & France	1988	1994	Tunnel	Railway	TBM	50	-	22 - 28	Cretaceous strata, marlite strata, having faults
The Seikan tunnel	$7 billion	Japan	1965	1988	Tunnel	Railway	D&B	54	262,5	-	13 kinds of different geologic structures and many faults
Bømlafjord	NOK480 million.	Norway	1997	2000	Tunnel	Road	D&B	7,86	260	35	Gneiss/micachist, Phyllite, Greenstone
Eiksund tunnel	NOK500 million	Norway	2004	2008	Tunnel	Road	D&B	7,8	287	50	Gneiss, gabbro, limestone
Nordkapp (Magerøysund)	NOK/m (2000) - 76000	Norway	-	1999	Tunnel	Road	D&B	6,9	150	-	Mica schist, quartzite
Mageröy	$/m 4500-10,000	-	-	-	Tunnel		-	6,8	220	-	meta-greylvacke, clay schist, sandstone
Severn tunnel (Part of the channel tunnel)	-	UK	1873	1886	Tunnel	Railway	Blasting	7,08	21,33	-	Blue shale, Coal shale, Millstone grit, Clay shale or fire clay, Limestone Boulders, Mountain limestone, there was springs
Vardo tunnel	NOK/m 120000	Norway	1979	1982	Tunnel	Road	D&B	2,6	88	28	Slate, sandstone
Xiang'an Subsea tunnel	¥ 3.25 billion $ 391.5 millions	China	2006	2010	Tunnel	Road	Borehole-blasting Method	8,7	70	-	Granite formation, micro aquifer
Kanmon	-	Australia	-	1958	Tunnel	Road	-	3,461	-	-	
Shin-Kanmon tunnel	-	Japan	1942	1944	Tunnel	Road	Borehole-blasting Method	3,46	66	-	Volcanic geology
Frierfjord	-	Norway	-	1976	Tunnel	Gas	D&B	3,6	253	-	Gneiss, claystone
Vollsfjord	-	Norway	-	1976	Tunnel	Water supply tunnel	D&B	1,5	80	-	Gneiss
Slemmestad	-	Norway	-	1980	Tunnel	Water supply tunnel	D&B	1	93	-	Claystone, limestone, sandstone
Kårstö I	-	Norway	-	1983	Tunnel	Water supply tunnel	D&B	0,4	58	-	Phyllite
Kårstö II	-	Norway	-	1983	Tunnel	Water supply tunnel	D&B	0,3	30	-	Phyllite
Karmsund	-	Norway	-	1984	Tunnel	Gas	D&B	4,7	180	58	Gneiss, phyllite
Fördesfjord	-	Norway	-	1984	Tunnel	Gas	D&B	3,4	160	-	Gneiss
Förlandsfjord	-	Norway	-	1984	Tunnel	Gas	D&B	3,9	170	46	Gneiss, phyllite
Ellingsöy	-	Norway	-	1987	Tunnel	Road	D&B	3,5	140	42	Gneiss
Valderöy	-	Norway	-	1987	Tunnel	Road	D&B	4,2	137	34	Gneiss
Hjartöy	-	Norway	-	1987	Tunnel	Gas	D&B	2,3	110	26	Gneiss
Alvheimsund	-	Norway	-	1987	Tunnel	Gas	D&B	1,3	60	-	Gneiss
Kvalsund	NOK/m 61000	Norway	-	1988	Tunnel	Road	D&B	1,6	56	23	Gneiss
Godöy	NOK/m 61000	Norway	-	1989	Tunnel	Road	D&B	3,8	153	33	Gneiss
Flekkeröy	NOK/m 50000	Norway	-	1989	Tunnel	Road	D&B	2,3	101	29	Gneiss
Hvaler	NOK/m 53000	Norway	-	1989	Tunnel	Road	D&B	3,8	120	35	gneiss
Nappstraum	NOK/m 59000	Norway	-	1990	Tunnel	Road	D&B	1,8	60	27	Gneiss
Maursundet	NOK/m 57000	Norway	-	1990	Tunnel	Road	D&B	2,3	93	-	Gneiss
Fannefjord	NOK/m 48000	Norway	-	1990	Tunnel	Road	D&B	2,7	100	28	Gneiss
IVAR, Jaeren	NOK/m 58000	Norway	-	1991	Tunnel	Water supply tunnel	D&B	1,9	80	-	Phyllite
Kalstö	-	Norway	-	1991	Tunnel	Gas	D&B	1,2	100	-	Greenstone

Project Name	Total Cost	Countries	Start	End	Infraestructure	Purpose	Construction Method	Lengt (Km)	Max depth (mbsl)	Min rock cover (m)	Geology
Byfjord	NOK/m 61000	Norway	-	1992	Tunnel	Road	D&B	5,8	223	34	Phyllite
Mastrafjord	NOK/m 61000	Norway	-	1992	Tunnel	Road	D&B	4,4	132	-	Gneiss
Freifjord	NOK/m 53000	Norway	-	1992	Tunnel	Road	D&B	5,2	130	30	Gneiss
Tromsöysund	NOK/m 133000	Norway	-	1994	Tunnel	Road	D&B	3,4	101	45	Dioritic gneiss
Hitra	NOK/m 61000	Norway	-	1994	Tunnel	Road	D&B	5,65	267	38	Gneiss
Troll	-	Norway	-	1995	Tunnel	Gas	D&B	3,8	260	-	Gneiss
Bjoröy	NOK 59 million	Norway	1993	1996	Tunnel	Road	D&B	2	88	35	Gneiss
Slöverfjord	NOK/m 38000	Norway	-	1997	Tunnel	Road	D&B	3,3	120	-	Gneiss, mangerite
Lysaker	NOK/m 53000	Norway	-	1997	Tunnel	Water supply tunnel	D&B	0,6	73	-	Claystone
Kårstö III	-	Norway	-	1999	Tunnel	Water supply tunnel	D&B	3	60	-	Phyllite
Kårstö IV	-	Norway	-	1999	Tunnel	Water supply tunnel	D&B	0,6	10	-	Phyllite
Oslofjord	NOK/m 70000	Norway	-	2000	Tunnel	Road	D&B	7,3	130	32	Gneiss, amphibolite
Ibestad	NOK/m 49000	Norway	-	2000	Tunnel	Road	D&B	3,4	112	-	Gneiss
Skatestraum	NOK 325 million	Norway	-	2002	Tunnel	Road	D&B	1,9	91	40	Gneiss
Frøya	Estimated: NOK 424 millions GBP 34 millions	Norway	1998	2000	Tunnel	Road	D&B	5,3	164	41	Gneiss
Finnfast	-	Norway	-	2009	Tunnel	-	D&B	7,2	150	44	Gneiss, Amphibolite
Atlanterhavs tunnel	NOK (2005) - 635 million NOK (2008) - 700 million	Norway	-	2009	Tunnel	Road	Blast	5,7	245	-	gneissoid granite with elements of amphibolite, pegmatite and mica rich rock types
Vága tunnel	DKK 302 million	Denmark	2000	2002	Tunnel	-	-	4,9	105	-	Volcanic (extrusive lava flows assessed to be 50 M years old)
Nordoya tunnel	DKK 405 million	Denmark	January 2004	2006	Tunnel	-	-	6,2	150	35	Volcanic (extrusive lava flows assessed to be 50 M years old)
Streymøy	Estimated: NOK 42 million	Denmark	2015	-	Tunnel	-	-	-	230	-	-
Sandøyartunnel	-	Denmark	-	2017	Tunnel	-	-	10,7	160	-	-
Anadyr subsea tunnel	-	Russia	-	-	Tunnel	-	-	-	-	50	-
Xiamen subsea tunnel	4.18 billion $US 650 million	China	-	2010	Tunnel	Road	D&B	5,9	70	-	-
Qingdao subsea tunnel	¥ 3.3 billion US$485 million	China	-	2011	Tunnel	-	D&B	6,17	90	25	Granite and lava
Hadselfjorden	-	Norway	-	-	Tunnel	-	D&B	9	200	-	Gneiss
Hidrasundet	-	Norway	-	-	Tunnel	-	D&B	2,9	127	-	Gneiss
Sande	Estimate: NOK (200 - 360) million	-	-	-	Tunnel	-	D&B	2,4	-	-	Gneiss
Boknafjorden - E39 Rogfast	Estimate: NOK 12,2 billion	Norway	-	2020	Tunnel	Road	D&B	26,66	390	-	Gneiss
Mersey tunnel - Queensway	£8 million	UK	-	1934	Tunnel	-	-	3,24	-	-	-

Project Name	Total Cost	Countries	Start	End	Infraestructure	Purpose	Construction Method	Lengt (Km)	Max depth (mbsl)	Min rock cover (m)	Geology
Mersey tunnel - Kingsway	-	UK	-	1971	Tunnel	-	-	2,483	-	-	-
Bosphorus tunnel	$1.2 billion	Turkey	-	2012	Tunnel	Water tunnel	TMB (Undersea) + Blasting in land	5,55	145	-	-
Halsnøy	-	Norway	-	2008	Tunnel	Road	-	4,12	138	-	-
Bjarkøy	-	Norway	-	2017	Tunnel	Road	-	3,29	127	-	-
Rya	-	Norway	-	2011	Tunnel	Road	-	2,66	87	-	-
Melkøy	-	Norway	-	2003	Tunnel	Road	-	2,3	62	-	-
Karmøy	-	Norway	-	2013	Tunnel	Road	-	7,741	138	-	-
Hovstunilin	-	Denmark	-	2007	Tunnel	Road	-	2,45	-	-	-
Changxing	-	China	-	2009	Tunnel	Road	-	8,95	65	-	-
Quing-Huang (Jiaozhou Bay)	-	China	-	2011	Tunnel	Road	-	7,8	-	-	-
Westerschelde	€/mile 60 milions €726 milion of euros	Netherlands	-	2003	Tunnel	Road	TBM	6,65	65	-	Soft clay
Haicang	-	China	-	2017	Tunnel	-	-	6,335	-	-	-
Hvalfjarðargöng	ISK 5,000 million $70 million	Iceland	1996	1998	Tunnel	Road	-	5,77	165	40	-
Eurasia	$1.2 billion	Turkey	-	2015	Tunnel	Road	-	5,4	106,4	-	-
Clem Jones	-	Australia	-	2010	Tunnel	Road	-	4,8	60	-	-
Nanjing Changjian	-	China	-	2010	Tunnel	Road	TBM	3,71	-	-	-
Wuhan Changjiang	-	China	-	2008	Tunnel	Road	-	3,609	-	-	-
Drogden	-	Denmark	-	2000	Tunnel	Road + Railway	-	3,52	-	-	-
Burnley	-	Australia	-	2000	Tunnel	Road	-	3,4	-	-	-
Muskö	-	Sweden	-	1964	Tunnel	-	-	2,96	65	-	-
Shangzhong	-	China	-	2009	Tunnel	Road	-	2,802	-	-	-
Brooklyn battery tunnel (Hugh L. Carey Tunnel)	$80 million	USA	1940	1950	Tunnel	Road	Shield	2,779	-	-	-
Dapu Lu	-	China	-	1970	Tunnel	Subway	Shield	2,761	-	-	-
Holland	-	USA	-	1927	Tunnel	Road	-	2,608	-	-	-
Xiangyin	US$145.15 million	China	-	2005	Tunnel	Road	-	2,606	-	-	-
Leopold II - Sainctelette	-	Belgium	-	1977	Tunnel	Road	-	2,6	-	-	-
Baltimore Harbour	$130 million	USA	-	1957	Tunnel	Road	520m inmerse	2,332	-	-	-
Yan'an Donglu	-	China	-	1989	Tunnel	Subway	Shield	3,736	-	-	Brown-Yellow Clay, Gray silt & Silt clay, Gray silt, Gray clay
Øresund Bridge and Tunnel	$3 billion	Sweden & Denmark	1993	2000	Tunnel	Road	-	16	-	-	-
Great belt tunnel	€ 700 million	Denmark	1987	1997	Tunnel	Road	TBM	7,41	75	-	-
Hong Kong-Zhuhai Macao (Tunnel only)	¥ 9 billions	China	2008	2017	Tunnel	Road	Bridge + Inmerse + Cut Cover + Island	5,4	28	-	-
Copenhagen	DKK (2004) - 750 millions	Denmark	2002	2010	Tunnel	Heating tunnel	TBM	4	-	-	-

Project Name	Total Cost	Countries	Start	End	Infraestructure	Purpose	Construction Method	Lengt (Km)	Max depth (mbsl)	Min rock cover (m)	Geology
Waitemata harbour crossing	-	New Zealand	-	2004	Tunnel	Road	-	1,7	-	-	-
2nd Yan'an Donglu	-	China	-	1996	Tunnel	-	Shield Construction	2,193	-	-	-

Table 19 : Water Crossings and their conditions

It was seen that water-crossing challenges were solved by the mean of three different infrastructures. These infrastructures includes tunnels, immerse tunnels, bridges or combina-tion of them. From the 136 water-crossing projects, 95 were tunnels, 20 were bridges, 7 were immerse tunnels and finally,14 were mixed water crossing infrastructures. The percentage of each category was limited for the data availability, the number of structures existing in the world and the amount of time inverted in its research. For example, it was complicated to find a large quantity of immerse tunnels to be studied, because unless they have been used since a long time ago (1979 - MTR harbor crossing tunnel) they still have not been widely used.

4.1.1 Parameters considered

However, the cost of each project was only interesting if it was accompanied which other parameters which could explain its variance. Therefore, a sort of additional parameters were selected for each of the infrastructures categories. For tunnels and immerse tunnels the parameters can be found in table 1; For bridges, the parameters can be found in table 2; and for mixed infrastructures, it can be found in table 3.

	Tunnels	Immerse Tunnels	Bridges
Project name	√	√	√
Country	√	√	√
Length	√	√	√
Construction starts	√	√	√
Construction end	√	√	√
Max depth	√	√	√
Minim rock cover	√	χ	χ
Maxim gradients	√	χ	χ
Project Geology	√	√	√
Infrastructure Type	√	√	√
Infrastructure Section	√	√	√
Infrastructure Purpose	√	√	√
Construction Method	√	√	√
Total Cost	√	√	√

Table 20: Location of the 136 water crossing projects

4.2.1 Costs Analysis and Parameters influence

The research started with 136 projects and after the parameters research, they had to be reduced to 77 study cases. For being a suitable candidate to be studied, the data found for each project needed at least to include information about the country, length, infrastructure type, year of completion, depth (for the tunnels), area of the section (for the tunnels) and its wideness (for the bridges). As a big sort of them were developed before the internet emergence, for those who are not very famous, their information was difficultly found online. Should be state though, that despite being this one of the reasons, lot of recent projects was also not reachable.

Countries as Norway, China and Japan must be highlighted for being referents on providing their works documentation. Exposing their water crossing projects properties openly and exhaustively.

These 77 remaining projects were 46 tunnels, 4 immerse tunnels, 11 mixed tunnels and 16 bridges. The most affected group, was therefore the tunnels. Reducing their number to almost the half of its starting point, but still being the most abundant category in what number of projects concerns.

Equivalent cost of the Projects in October 2017

However, for being the cost comparable, another of the important facts to take into ac-count was the prices variation along the time4. For this reason, all the projects' costs had to be updated to the same time reference. October of 2017 was then taken as this reference time, and subsequently the current cost of the projects was obtained. For doing that, the corresponding product's inflation was applied to the projects' cost. As the inflations havebeen different in each region of the world, and as the cost of each project was originated in a certain country, their 2017 prices had to be updated using the inflations produced in the projects place. No seeming reasonable to apply a generic inflation to all the projects.

For this reason, a compilation of the inflation rates per year (YOY) for each of the countries were done. The increment to be applied to the real projects' prices, was calculated as the product of all the yearly inflations rates, which had taken place between the project's comple-tion year until October's 2017. In table 4 can be seen the range of years that the YOY´s were needed to be found for each country and the source where the data was found.

Furthermore, an example of how the increment of prices was calculated, can be seen in the figure 1. Where the increment of the prices for Norwegian products from 1994 to October of 2017 is computed.

Another fact to take into account was the project's cost currencies. As the value of each of the currencies have been changing differently along the time, it seemed reasonable that if the project's cost was not expressed in its own country currency, to convert them by using the historic rate's change at its project's completion year. These historic currencies rate's changes were easily obtained in the WebPages shown in table 5.

Finally, once divided the prices by the infrastructure´s physical or fictional volume, converted the total costs of the projects to its own country currency, applied its corresponding inflation rate and having updated the cost of the projects to Euros, the final 2017 project's cost prices were comparable.

The actual (2017) currencies rates changes used for converting the different currencies to Euros are located in table 6 and the hypothetical final 2017 project's prices obtained after the entire process can be found in table 7 and graph 2.

Mixed projects was not finally used, however they are a very good candidates to calibrate the project's average prices.

Once the sectional area was defined, the cost per unit of volume was obtained very easily as:

$$\frac{\text{Project Cost}}{Volume} = \frac{\text{Project Cost}}{Length(m) * \text{Area of the section}(m^2)}$$

Cost per unit of length:

First of all, the project´s prices were converted to Euros with the historic currencies change. and then, the costs per unit of length was calculated as $\frac{Project\ cost\ (EU)}{Length\ (m)}$. When the plot of the cost of the infrastructures was done, it was very quickly observed, that the costs per unit of length of the projects were presenting very different values.

Cost per unit of Volume:

The first motive found, was that the cross-sectional areas1 and sections wide2, was another element to take into account. Seeming more reasonable to express their costs per unit of volume than unit of length.

	Infraestructure	Final cost in EU 2017/m3	Final cost in EU 2017/km	Final cost in EU 2017
Slöverfjord	Tunnel	100,62 €	5.534.042,90 €	18.262.341,58 €
Freifjord	Tunnel	110,26 €	7.718.533,52 €	40.136.374,32 €
Bjoröy	Tunnel	110,59 €	4.755.156,86 €	9.510.313,72 €
Eiksund tunnel	Tunnel	112,85 €	8.012.245,83 €	62.495.517,50 €
Bømlafjord	Tunnel	120,18 €	8.893.600,49 €	69.903.699,84 €
Nordoya tunnel	Tunnel	126,23 €	8.205.052,72 €	50.871.326,89 €
Byfjord	Tunnel	126,91 €	8.883.595,19 €	51.524.852,09 €
Mastrafjord	Tunnel	126,91 €	8.883.595,19 €	39.087.818,83 €
Hitra	Tunnel	126,91 €	8.883.595,19 €	50.192.312,81 €
Vága tunnel	Tunnel	127,54 €	8.289.810,59 €	40.620.071,90 €
Eurasia	Tunnel	141,17 €	11.999.866,32 €	64.799.278,12 €
Westerschelde	Tunnel	141,85 €	114.412.256,19 €	760.841.503,66 €
Oslofjord	Tunnel	145,63 €	10.194.289,56 €	74.418.313,79 €
Nappstraum	Tunnel	156,22 €	8.592.329,77 €	15.466.193,59 €
Flekkeröy	Tunnel	158,30 €	7.281.635,40 €	16.747.761,42 €
Xiang'an Subsea tunnel	Tunnel	162,38 €	59.429.857,38 €	517.039.759,24 €
Fannefjord	Tunnel	162,57 €	6.990.369,98 €	18.873.998,96 €
Ibestad	Tunnel	165,95 €	7.136.002,69 €	24.262.409,15 €
Tromsöysund (two tubes)	Tunnel	169,90 €	19.369.150,16 €	65.855.110,56 €
Hvaler	Tunnel	171,52 €	7.718.533,52 €	29.330.427,39 €
Godöy	Tunnel	185,07 €	8.883.595,19 €	33.757.661,71 €
Maursundet	Tunnel	193,05 €	8.301.064,36 €	19.092.448,02 €
Qingdao subsea tunnel	Tunnel	204,29 €	89.332.131,85 €	551.179.253,53 €
Kvalsund	Tunnel	206,60 €	8.883.595,19 €	14.213.752,30 €
Atlanterhavs tunnel	Tunnel	209,63 €	14.883.550,66 €	84.836.238,76 €
Nordkapp (Magerøysund)	Tunnel	257,40 €	11.068.085,81 €	76.369.792,08 €
Frøya	Tunnel	280,28 €	12.052.208,45 €	63.876.704,78 €
Great belt tunnel, Denmark	Tunnel	285,85 €	137.510.927,42 €	1.018.955.972,15 €
Hvalfjarðargöng	Tunnel	290,59 €	17.435.165,01 €	100.600.902,12 €
Mersey tunnel - Queensway	Tunnel	299,18 €	168.766.882,24 €	546.804.698,47 €
Vardo tunnel	Tunnel	329,73 €	17.475.924,96 €	45.437.404,90 €
Copenhagen district heating tunnel, Denmark	Tunnel	385,26 €	31.480.614,07 €	125.922.456,29 €
Xiangyin	Tunnel	398,53 €	70.425.244,33 €	183.528.186,71 €
Lysaker	Tunnel	438,65 €	8.334.257,00 €	5.000.554,20 €
Xiamen subsea tunnel	Tunnel	509,22 €	124.248.882,58 €	733.068.407,20 €
IVAR, Jaeren	Tunnel	514,98 €	10.299.676,19 €	19.569.384,76 €
Hong Kong-ZhuhaiMacao, China (Tunnel only)	Tunnel	535,52 €	214.208.333,33 €	1.156.725.000,00 €
The Seikan tunnel	Tunnel	540,22 €	147.523.109,64 €	7.966.247.920,69 €
Skatestraum	Tunnel	555,80 €	23.899.519,70 €	45.409.087,43 €
Øresund Bridge and Tunnel	Tunnel	709,16 €	236.634.149,24 €	3.786.146.387,90 €
The channel tunnel	Tunnel	1.071,60 €	466.464.676,57 €	23.323.233.828,41 €
Baltimore Harbour	Tunnel	1.868,56 €	143.879.490,13 €	335.526.970,99 €

Bosphorus tunnel	Tunnel	2.176,96 €	246.208.868,41 €	1.366.459.219,67 €
Brooklyn battery tunnel (Hugh L. Carey Tunnel)	Tunnel	4.902,50 €	196.100.130,22 €	544.962.261,87 €
Bjørvika immersed tunnel, Norway	Inmerse tunnel	495,90 €	212.168.899,26 €	190.952.009,33 €
Marieholmstunnel, Sweden	Inmerse tunnel	1.946,65 €	583.994.456,88 €	291.997.228,44 €
Söderströmstunnel, Sweden	Inmerse tunnel	2.000,53 €	400.106.911,57 €	136.036.349,94 €
Western Immersed Tube - Hong kong	Inmerse tunnel	5.480,06 €	1.046.472.267,30 €	1.318.555.056,80 €
Golden Gate	Bridge	68,03 €	11.020.320,37 €	29.754.865,00 €
Runyang Bridge, China	Bridge	139,02 €	32.697.629,38 €	1.165.997.463,52 €
Jiaozhou Bay bridge or Quingdao haiwan bridge	Bridge	181,78 €	38.174.306,14 €	1.621.644.524,70 €
Hangzhou Bay Bridge	Bridge	321,02 €	63.562.259,77 €	2.269.172.673,87 €
Donghai Bridge, China	Bridge	321,35 €	60.735.539,81 €	1.973.905.043,94 €
King Fahd Causeway	Bridge	352,03 €	49.002.116,82 €	1.225.052.920,56 €
Jintang Bridge	Bridge	360,07 €	48.739.752,96 €	1.244.813.290,50 €
Xihoumen Bridge, China	Bridge	566,06 €	83.211.238,83 €	441.019.565,78 €
Nanjing 4th Yangtze River Bridge, China	Bridge	871,33 €	199.708.623,18 €	1.085.815.784,23 €
Jiangyin Yangtze River Bridge, China	Bridge	1.029,48 €	232.868.492,73 €	715.139.141,17 €
Monitor–Merrimac Memorial Bridge–Tunnel	Mixed	1.125,07 €	82.300.917,33 €	609.026.788,25 €
The Øresund bridge (Only bridge)	Bridge	1.246,22 €	436.863.044,76 €	3.407.531.749,11 €
The Confederation Bridge	Bridge	1.327,59 €	87.620.686,42 €	1.130.306.854,86 €
Hardangar Bridge, Norway	Bridge	1.591,92 €	191.030.558,33 €	263.622.170,50 €
Bandra–Worli Sea Link (Rajiv Gandhi Sea Link)	Bridge	7.224,69 €	1.743.461.964,92 €	9.763.387.003,53 €
Tsingma Bridge	Bridge	13.615,00 €	5.728.540.205,60 €	12.430.932.246,16 €

Table 21: Remaining tunnels and price per cubic meter after applying the inflation (2017 prices).- Own development

For the bridges, the hypothetical section area3 had to be equivalent to the obtained for tunnels. Therefore, the area of a square, with the bridge wide as a base and six meters of height was considered. This six meters height was reasonable as trucks can fit in and still there was a reasonable leeway. On the other hand, for the tunnels, this area was taken directly from its sectional geometry.

The resulting area of the cross section for the bridges is summarized in the next table:

	Number of lands	Wide to m	wide/lanes	ALTURA CAMION 4m	Purpose	Total m3/m
Hong Kong-ZhuhaiMacao, China (Bridge)	6	-	-	6	Road	203,0412
The Øresund bridge (Only bridge)	4 + 2 train	30,5	7,625	6	Road and Rail	350,55
Jiaozhou Bay bridge or Quingdao haiwan bridge	8	35	4,375	6	Road	210
Donghai Bridge, China	6	31,5	5,25	6	Road	189
Jintang Bridge	4	-	-	6	Road	135,3608
Hangzhou Bay Bridge	6	33	5,5	6	Road	198
King Fahd Causeway	4	23,2	5,8	6	Road	139,2
Bandra–Worli Sea Link (Rajiv Gandhi Sea Link)	8	40,22	5,0275	6	Road	241,32
Golden Gate	6	27	4,5	6	Road + pedestrian	162
Monitor–Merrimac Memorial Bridge–Tunnel	4	12,192	3,048	6	Road	73,152
The Confederation Bridge	2	11	5,5	6	Road	66
Xihoumen Bridge, China	4	24,5	6,125	6	Road	147
Runyang Bridge, China	6	39,2	6,533333333	6	Expressway	235,2
Nanjing 4th Yangtze River Bridge, China	6	38,2	6,366666667	6		229,2
Jiangyin Yangtze River Bridge, China	6	37,7	6,283333333	6	Road	226,2
Tsingma Bridge	8 + 2 railway	36	6	6	motor and railway	420,752
Hardangar Bridge, Norway	2 + pedestrian and bicicles lane	20	6,666666667	6	Pedestrian, cycle, road	120
		Wide/lanes mean	5,640033333			

Table 22: Bridges' cross section.

The cost categorized by infrastructure type can be seen in next figure:

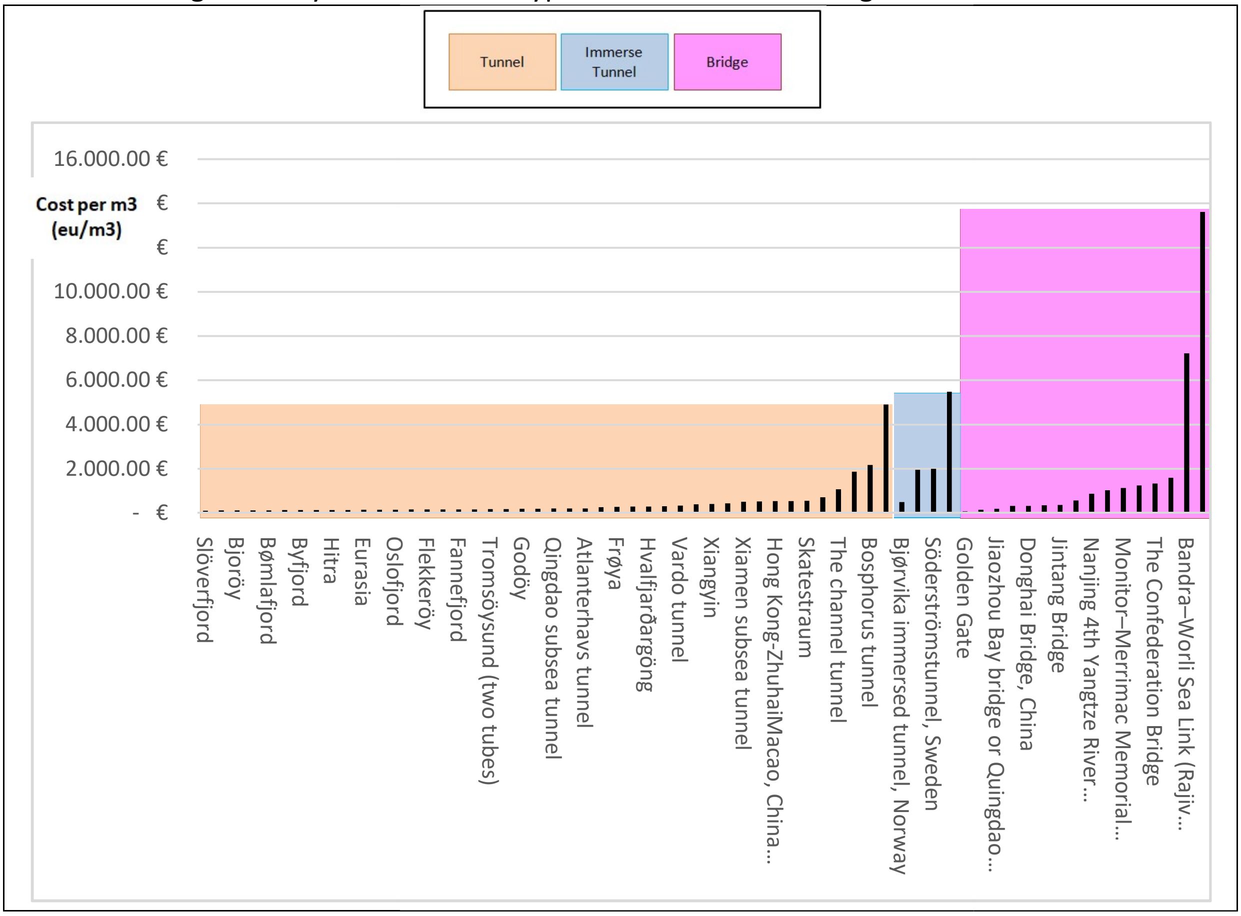


Figure 49: Remaining tunnels and price per cubic meter after applying the inflation (2017 prices). Orange: Tunnel; Blue: Immerse tunnels; Grey: Bridges – Own development.

In the final table, it can be seen that the dispersity of the costs per cubic meter is so large, so that a more complex analisis need to be done for being able to predict the Helsinki-Tallin fixed link cost.

	Min	Average	Max
Tunnels	101 €	457 €	4.903 €
Immerse tunnels	495,9 €	2.481 €	5.480 €
Bridges	68 €	1.896 €	13.615 €

Table 23: Min, Max and Average prices for the remaining tunnels (prices per cubic meter after applying the inflation (2017 prices)). Orange: Tunnel; Blue: Immerse tunnels; Grey: Bridges.

Stadistical Analisis:

In this section, a multiplelinear regression modelis proposed for trying to find out which parameters have influence in the final projects' prices. The election of this model was chosen for its simplicity; as the costshas a big variability andneeds to be predicted by mean of multiple inputs; and because the variable to predict was not categorical, so the logistic regresion model was not apropiate.

The multiple linear regression models are used to explain the relation between one continuous dependent variablein function of two or more independent variables.

The multiple linear regression equation is defined as:$\mathrm{Y} = \beta_0 + \beta_1 \cdot \mathrm{X}_1 + \beta_2 \cdot \mathrm{X}_2 + \cdots + \beta_n \cdot \mathrm{X}_n$,Where Y represents the dependent variable; βs are the fitted model coefficients, which determines the influence of each independent variable; and finally the Xs are the independent variables, which can be either categorical or numerical.

In the thesis, the cost per km will be used as a response variable, because the cost per cubic meter of the bridges needed the invention of an excavation cross section area which seemed not accurated for realizing the stadistical analisis.

Others parameters defined in previous sections such as start year, end year, length, depth, rock cover, gradients, shipping clearance, span length, infrastructure cross section area, inflation rate will be used as continuous explanatory variables. Finally, other parameters such asthe project's country, infrastructure purpose, infrastructure type,construction methodology will be introduced as well as categorical explanatory variables.

Apart of those parameters, in this section other parameters have been considered interesting to be generated such as the desviation from the average $d_i = \bar{x} - x_i$ for the numerical explanatory of the tunnels. As well as the A2 (square of the cross section area) and L2 (Square of the infraestructure length)

Despite of exhausting research and the big amount of time in data research, all the parameters was not able to be found due to the lack of data availability.
The study of the frequency of non available values “NA”, the minimum value and the maximum value is calculated for the numerical variables in order to determine its quality.The same comprovation is done for categorical variables, but in this case it is analysed the number of register in each subcategory and the number of “Na.

For doing so, the dataset is loaded in the R-Studio program. These are the obtained results and its interpretation:

Categorical variables:

Country:

It can be observed that from the 135 infraestructures considered in the historical data there are only missing two values. It can be also observed there are lot of countries which have not a big number of values. For this reason, the categorical variable “Continents” is derivated from this one.

ARGENTINA	AUSTRALIA	BELGIUM	CANADA	CHINA	DENMARK	GREECE	ICELAND	INDIA	JAPAN	KOREA	NETHERLANDS	N. ZEALAND	NORWAY	RUSSIA	SAUDI ARABIA	SWEDEN	TURKEY	UK	USA	Total
1	3	1	1	30	11	1	1	1	6	2	2	1	51	1	1	5	2	5	9	135/137

Table 24: Location of the 137 water crossing projects

Agrouping the contries by **continent** it is obtained a categorical variable with the next frequencies:

Continent:

AMERICA	ASIA	EUROPE	OCEANIA
10	42	79	4

Table 25: Continent of the water crossing projects

In this case, as is derivated from contry, there are also 2 infrastructure registers with “Na” out of the 137 registers.Continent seems a parameter which have a good quality because there aren’t lots of empty registers. Hereunder we will see if it has any influence in the cost prediction.

Infraestructure:

Infraestructure			
Bridge	Inmerse tunnel	Mixed	Tunnel
14	3	11	45

Table 26: Number of each kind of infrastructure present in the historical data.

From the 63 infraestructures which has cost per km, 45 are tunnels, 14 are bridges and 3 are immerse tunnels.

The mixed tunnels have to be deleted from the data set as any project cost was obtained and therefore was not suitable for the cost per km prediction.

Purpose:

GAS	RAILWAY	ROAD	ROAD + RAILWAY	WATER	NA's
8	9	77	5	11	27

Table 27: Frequency of each infrastructures purpose present in the historical data.

In the purpose frequency, we can observe there is a 5% of NaNs, which is a reduced number of non available values and therefore can be used for cost estimation.

Construction method:

D&B	SIMPLE	SUSPENSION	TBM	NA's
51	7	14	10	55

Table 28: Number of each kind of constructive method present in the historical data.

In construction method register, there is a bigger number of non available values (40,14%), however as this parameter seems very interesting for cost prediction will remain initially as an input to the regression. However should be improved.

Numerical variables:

Start and End:

Start						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
1873	1988	1996	1991	2004	2015	87

End						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
1886	1988	1998	1994	2008	2017	6

Table 29, Table 30: Start and End year summary.

It can be observed that in start year of the contruction there is lot of uncertainty as there are only 50 of 137 projects with starting year. Therefore, it seems initially that will not contribute in the cost estimation and if so, will not be representative due to the amount of missigness registers which will not take place in the regression.

For what End parameters respect,there are only 6 missing values, which is a good quality indicator. Nevertheless, oldest project considerated is from 1886;which maybe will not be representative for our cost estimation, as despite of having update the cost to 2017 prices, the difference with the other costs can be large and non significant for our predictions. However, initially all the values of the End variable are considerate and will be rejacted in the case they do not fit in the model.

Length:

Length						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
0.300	2.359	3.560	7.212	6.571	64.000	3

Table 31: Length parameter summary.

The length is in kilometers and as can be seen there are only 3 “NA” in this parameter.
It initially seems will have influence in the cost per km, because as long as the infrastructure will be the price should be reduced. However, it was deduced by common sense and maybe the influence is much reduced compared with other factors.

Depth:

Depth is considered for tunnels and bridges. These data was very difficult to be obtained and there is a lot of uncertainty about if the data is real. However, an effort was done to try to aggregate this parameter and see if it is influent.

max depth						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
10.0	60.0	100.0	111.7	150.0	287.0	57

Table 32: Depth parameter summary.

It can be observed there are 57 “NA” which is a big amount, despite of immerse tunnels do not considere it, and is keep in the dataset but with certain displeasure.

Max slope:

The gradients are considered basically for tunnels, and it was not easy to be found. From the 45 tunnels with cost, 29 registers has the gradient.

Max gradients						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
1.100	5.000	8.000	7.158	10.000	10.000	88

Table 33: Max gradient parameter summary.

By mean of the a boxplot, it can be seen the railways has needs of small gradients (<1.5%) and Roads haven't this limitations.

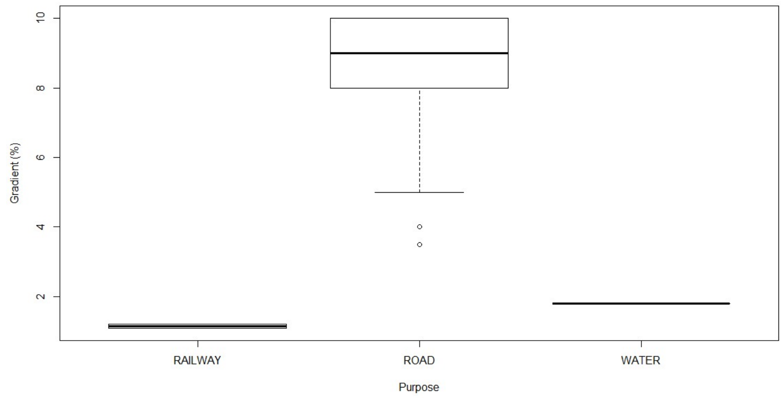


Figure 50:Box plot- Gradient / Purpose

Max shiping clearance:

This parameter have been decided to be discarded, as it was not clear which to consider the Max shiping clearance because of the presence of mobile spans. Therefore with 134 non available values out of the 137 registers are definetly not representative for the little amount of data reached.

Shiping clearance						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
40.00	45.00	50.00	50.67	56.00	62.00	134

Table 34: Shipping clearance parameter summary.

Max span length:

The reason for that big number of NA is that it is only considered in bridges. From the 14 bridges with cost per km available, the maximum span length is provided for 10 of these 14 registers.

Max Span						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
90.8	534.0	1377.0	1116.0	1454.0	1991.0	122

Table 35: Max Span parameter summary.

Area of the infrastructure cross section:

There are only 46 NA which 11 are from the mixed tunnels. However as we decided not to use in bridges the area of the cross section, the only important is the number of Na's for the tunnels which have cost per km.

From the 45 tunnels with data the 100% of the registers has the area of the cross section. This is a good point as it seems that as big the diameter of the tunnel, the cost will increase.

m3/m						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
10.0	43.0	71.0	155.3	227.7	806.6	46

Table 36: Cross section area parameter summary.

Infraestructures' cost per km:

We can observe that the range of the cost per km is very large, from 4,76 milion of euros to 600 M euros. Therefore, will be complicated to predict that large variability with only certain parameters.

M EU/km						
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
4,76 M€	8,88 M€	43,46 M€	223,50 M€	185,50 €	559,00 M€	71

Table 37: Cost per km parameter summary.

However, it have been detected in the next box plot that the infrastructure type has a big influence on its price.

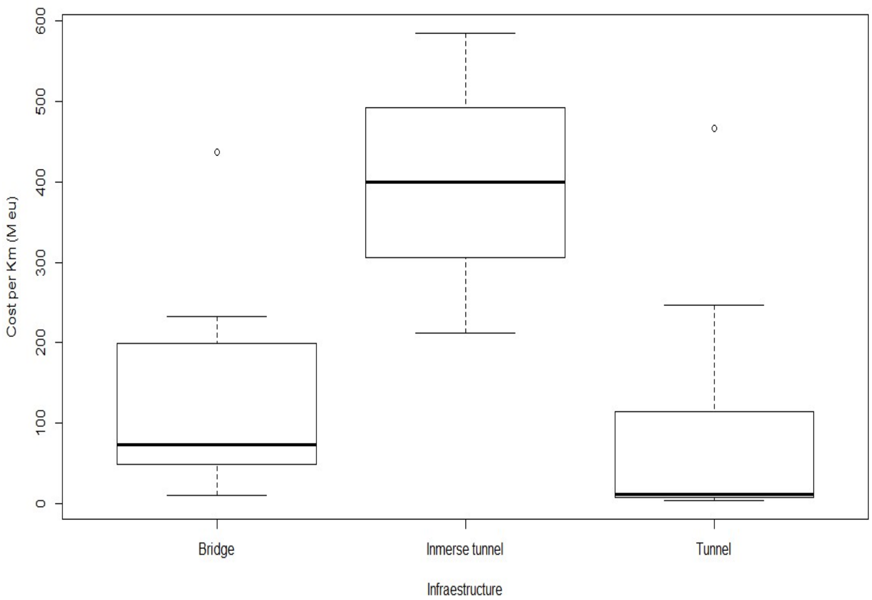


Figure 51: Box plot- Infraestructure type / Cost per km

The fact is that if we create a model with all this data, we will obtain a mean cost per km as if the structure was compose by the three kinds of infraestructures. It seems that do not have lot of sense as our objective is to obtain more accurate cost per km estimations.

We can observe that by splitting the dataset by infrastructure type the variability of the cost is reduced.

An as it's seen in the box plot that tunnels in general are the cheapest, apart of been the safers and as it is the kind of infrastructure which counts on the support of more expertise than immerse tunnels or long maritime bridges; it will be the one which will be chosen and tried to modelise.

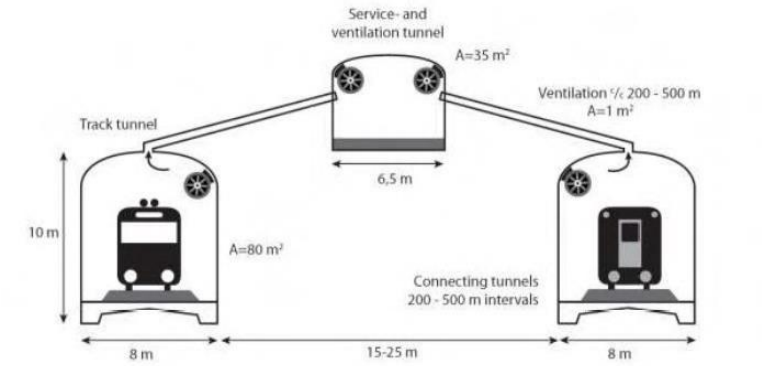


Figure 52 :Cross section exposed in the prefeasibility study made by SWECO.

For the infrastructure defined for the Helsinki-Tallin connection, the area of the tunnel would be around: $A = 10 * 8 * 2 + 35 = 195\ m3$

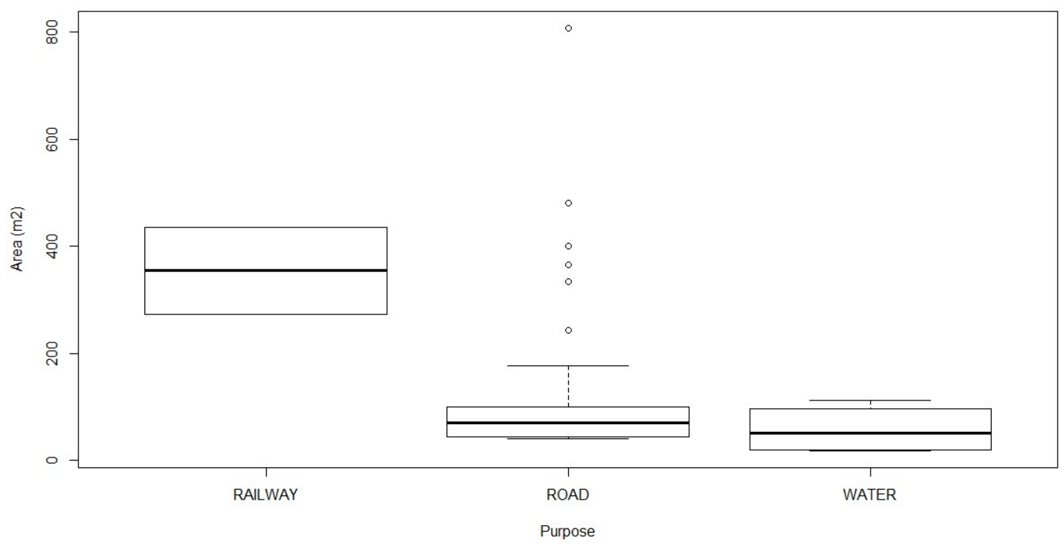


Figure 53: Box plot- Infraestructure type / Cross section Area

Despite of trying to modelise a Railway structure, the cost of the tunnel will be predicted as if it was a road tunnel.

Despite of the fact that it can appear to be contradictory, after analising the area of our tunnel and its complexity, low; the tunnel requeriments were found more similar to the road tunnels than the from the considered railway.

Five out of the fourteen railways were tunnels which included boths, road landsand railway tracks, in the same section dealing with cross section areas of more than 300 square meters. The others nine had a bigger area than the area specified for our railway. Therefore, as the complexity of the historical railway tunnels was much larger, they are non representative for the thesi's tunnel cost estimation and road tunnel are considered more suitable for its determination.

Should be not that the regression would have sense always than the gradient do not have an important impact on the cost determination.

It can also be seen that by selecting thedata of road tunnels, the variability of the cost per km its once more reduced. Furthermore, as there is a little overlap between the cost per km of railway tunnels and road tunnels, our previous assumptions seem to have sense.

Cost estimation using a regression:

In the following lines the steps followed with R-studio for fitting the regression to the roads' cost per km historical data is explained.

First of all, all the data from an excel is load to R-studio with the "Import dataset" tool.

Afterwards, the registers are splitted in different matrices by infrastructure type with the "$Subset()$" command.

```
DR2_tunnel<-subset(DR2, Infra=="Tunnel")
DR2_bridge<-subset(DR2, Infra=="Bridge")
DR2_itunnel<-subset(DR2, Infra=="Inmerse tunnel")
```

The same procedure is applied to the tunnels for separating the tunnels by purpose.

```
DR2_tunnel_Railway<-subset(DR2_tunnel, Purpose=="RAILWAY")
DR2_tunnel_Road<-subset(DR2_tunnel, Purpose=="ROAD")
DR2_tunnel_water<-subset(DR2_tunnel, Purpose=="WATER")
```

From the resulting matrices, the needed one is the one which contains the tunnels with a road purpose. (DR2_tunnel_Road). This matrix contains 35 road tunnels with its cost per km and other parameters which will be used for developing the regression

Once having the data the elimination of outliers is considered. It is done by deleting the values which are over or lower than the demarkation lines for outliers, in the box-and-whisker plot, which was created by John Tukey. He stablished the upper and lower limits as $Q3 + 1{,}5 * IQM$and$Q1 - 1{,}5 * IQM$respectively[106]. Where IQM is the interquartile range and is calculated as the difference between the third quartile and the first:

$$IQM = Q3 - Q1$$

For doing so in R the following code is executed, obtaining a Q1=8446697 and Q3=64927551.

```
DR2_tunnel_Road_Ckm_Q1=quantile(DR2_tunnel_Road$Ckm , 0.25)
DR2_tunnel_Road_Ckm_Q3=quantile(DR2_tunnel_Road$Ckm , 0.75)
```

For computing the interquartile range, the difference between Q3 and Q1 is done:

```
DR2_tunnel_Road_Ckm_IQR=DR2_tunnel_Road_Ckm_Q3-DR2_tunnel_Road_Ckm_Q1
```

Obtaining a IQR=56480854. With this value the upper and lower limits are calculated.

```
#Upper tail: Q3+1.5*IQR
DR2_tunnel_Road_Ckm_UT=DR2_tunnel_Road_Ckm_Q3+1.5*DR2_tunnel_Road_Ckm_IQR
#Low tail: Q1-1.5*IQR
DR2_tunnel_Road_Ckm_LT=DR2_tunnel_Road_Ckm_Q1-1.5*DR2_tunnel_Road_Ckm_IQR
```

Resulting to be $\mathrm{Low}_{\mathrm{lim}} = -76274584$ and $p_{lim} = 149648832$.

The values of cost are positive so will not be affected by the lower limit, however 4 outliners are detected above the upper boundary and are deleted by mean of the following code:

```
#Neteja Outliners:
DR2_tunnel_Road_Noutliners<-subset(DR2_tunnel_Road, Ckm>DR2_tunnel_Road_Ckm_LT &
Ckm<DR2_tunnel_Road_Ckm_UT )
#S'eliminen 3 registres.
```

Afterwards, when having the definitive data, the resulting matrix is transformed to the correct format. Converting the categorical variables from text to factors with the "as.factor()" function and defining the numerical variables as doble parameters.

```
#Creació de nous factors
DR2_tunnel_Road_Noutliners$Des_Cover<-DR2_tunnel_Road_Noutliners$Cover-
mean(DR2_tunnel_Road_Noutliners$Cover, na.rm = TRUE)
DR2_tunnel_Road_Noutliners$Des_Area<-DR2_tunnel_Road_Noutliners$Area-
mean(DR2_tunnel_Road_Noutliners$Area, na.rm = TRUE)
DR2_tunnel_Road_Noutliners$Des_end<-DR2_tunnel_Road_Noutliners$End-
mean(DR2_tunnel_Road_Noutliners$End, na.rm = TRUE)
DR2_tunnel_Road_Noutliners$Des_Depth<-DR2_tunnel_Road_Noutliners$Depth-
mean(DR2_tunnel_Road_Noutliners$Depth, na.rm = TRUE)
DR2_tunnel_Road_Noutliners$Des_Length<-DR2_tunnel_Road_Noutliners$Length-
mean(DR2_tunnel_Road_Noutliners$Length, na.rm = TRUE)
DR2_tunnel_Road_Noutliners$Des_Grad<-DR2_tunnel_Road_Noutliners$Grad-
mean(DR2_tunnel_Road_Noutliners$Grad, na.rm = TRUE)
```

The next step followed was to observe the correlation between the numerical variables, as for obtaining the best regression the explanatory variables needs to be independents.
Therefore, parameters which have a correlation of more than $\pm 70\%$ will be inserted separetly in the regression when trying to find out the best combination of the explanatory parameters.

For obtaining all the combination of the correlations between the numerical parameters, a matrix with the numerical variables was extracted and therefore, by mean of a for loop, all the correlations was calculated and saved to an excel file:

```
# Independencia de les variables numeriques:

DR2_tunnel_Road_Noutliners_num=DR2_tunnel_Road_Noutliners[,c(4,5,9,10,11,12,15,16,17,18,19,20,21,22,2
3,24,25,26,27,28,29)]
DR2_tunnel_Road_Noutliners_num_cor<-array(NA,c(22,22))
n=ncol(DR2_tunnel_Road_Noutliners_num)
for(i in 1:n){
 for(u in 1:n){
```

```
  DR2_tunnel_Road_Noutliners_num_cor[i,u]          <-          cor(DR2_tunnel_Road_Noutliners_num[,i],
DR2_tunnel_Road_Noutliners_num[,u], use="pairwise.complete.obs")
 }
}

library(rJava)
library(xlsx)
write.xlsx(DR2_tunnel_Road_Noutliners_num_cor,
"D:/Dades_regresió/Final/DR2_tunnel_Road_NoOutliners_num_Cor.xlsx")
```

The final result of the correlations can be easily seen in the next table. It can be seen that the diagonal is full of ones as expected, because the correlation of a numerical data with itselve is 1. Then the correlation between Start and End was expected, because the duration of the projects can be more or less the same an there is a same numerical tendence in both. Start and End is correlated with the cover, which is quite weird as well as with the desviation of the area. Finally, it can be observed that the cost_km has a high correlation with the area, duration and desviation of the rock cover.

This table will be taken into account when building up the model for not adding redundant parameters as inputs.

	Start	End	Length	Depth	Cover	Grad	Area	Inflation	Cm3	Ckm	C	Vol	Dur	A2	L2	Des_Area	Des_Cover	Des_end	Des_Depth	Des_Length	Des_Grad
Start	1,00	0,96	0,64	0,45	0,90	0,65	0,02	-0,08	-0,63	-0,21	-0,10	0,13	-0,25	-0,07	0,65	0,90	0,02	0,96	0,45	0,64	0,65
End	0,96	1,00	0,53	0,18	0,75	0,26	0,27	-0,64	-0,58	-0,10	0,18	0,31	0,04	0,19	0,52	0,75	0,27	1,00	0,18	0,53	0,26
Length	0,64	0,53	1,00	0,45	0,49	-0,07	0,43	-0,19	-0,24	0,19	0,44	0,54	0,35	0,33	0,98	0,49	0,43	0,53	0,45	1,00	-0,07
Depth	0,45	0,18	0,45	1,00	0,57	0,19	-0,31	-0,03	-0,28	-0,37	-0,32	-0,26	-0,32	-0,29	0,40	0,57	-0,31	0,18	1,00	0,45	0,19
Cover	0,90	0,75	0,49	0,57	1,00	0,37	0,46	0,08	0,11	0,35	0,61	0,52	0,26	0,46	0,47	1,00	0,46	0,75	0,57	0,49	0,37
Grad	0,65	0,26	-0,07	0,19	0,37	1,00	-0,44	-0,09	0,23	-0,03	-0,06	-0,25	-0,15	-0,39	-0,10	0,37	-0,44	0,26	0,19	-0,07	1,00
Area	0,02	0,27	0,43	-0,31	0,46	-0,44	1,00	-0,09	-0,02	0,70	0,86	0,98	0,85	0,96	0,44	0,46	1,00	0,27	-0,31	0,43	-0,44
Inflation	-0,08	-0,64	-0,19	-0,03	0,08	-0,09	-0,09	1,00	0,92	0,47	0,11	-0,12	-0,26	-0,10	-0,18	0,08	-0,09	-0,64	-0,03	-0,19	-0,09
Cm3	-0,63	-0,58	-0,24	-0,28	0,11	0,23	-0,02	0,92	1,00	0,61	0,23	-0,07	0,13	-0,05	-0,22	0,11	-0,02	-0,58	-0,28	-0,24	0,23
Ckm	-0,21	-0,10	0,19	-0,37	0,35	-0,03	0,70	0,47	0,61	1,00	0,89	0,66	0,93	0,58	0,21	0,35	0,70	-0,10	-0,37	0,19	-0,03
C	-0,10	0,18	0,44	-0,32	0,61	-0,06	0,86	0,11	0,23	0,89	1,00	0,86	0,92	0,72	0,46	0,61	0,86	0,18	-0,32	0,44	-0,06
Vol	0,13	0,31	0,54	-0,26	0,52	-0,25	0,98	-0,12	-0,07	0,66	0,86	1,00	0,79	0,93	0,56	0,52	0,98	0,31	-0,26	0,54	-0,25
Dur	-0,25	0,04	0,35	-0,32	0,26	-0,15	0,85	-0,26	0,13	0,93	0,92	0,79	1,00	0,90	0,36	0,26	0,85	0,04	-0,32	0,35	-0,15
A2	-0,07	0,19	0,33	-0,29	0,46	-0,39	0,96	-0,10	-0,05	0,58	0,72	0,93	0,90	1,00	0,34	0,46	0,96	0,19	-0,29	0,33	-0,39
L2	0,65	0,52	0,98	0,40	0,47	-0,10	0,44	-0,18	-0,22	0,21	0,46	0,56	0,36	0,34	1,00	0,47	0,44	0,52	0,40	0,98	-0,10
Des_Area	0,90	0,75	0,49	0,57	1,00	0,37	0,46	0,08	0,11	0,35	0,61	0,52	0,26	0,46	0,47	1,00	0,46	0,75	0,57	0,49	0,37
Des_Cover	0,02	0,27	0,43	-0,31	0,46	-0,44	1,00	-0,09	-0,02	0,70	0,86	0,98	0,85	0,96	0,44	0,46	1,00	0,27	-0,31	0,43	-0,44
Des_end	0,96	1,00	0,53	0,18	0,75	0,26	0,27	-0,64	-0,58	-0,10	0,18	0,31	0,04	0,19	0,52	0,75	0,27	1,00	0,18	0,53	0,26
Des_Depth	0,45	0,18	0,45	1,00	0,57	0,19	-0,31	-0,03	-0,28	-0,37	-0,32	-0,26	-0,32	-0,29	0,40	0,57	-0,31	0,18	1,00	0,45	0,19
Des_Length	0,64	0,53	1,00	0,45	0,49	-0,07	0,43	-0,19	-0,24	0,19	0,44	0,54	0,35	0,33	0,98	0,49	0,43	0,53	0,45	1,00	-0,07
Des_grad	0,65	0,26	-0,07	0,19	0,37	1,00	-0,44	-0,09	0,23	-0,03	-0,06	-0,25	-0,15	-0,39	-0,10	0,37	-0,44	0,26	0,19	-0,07	1,00

Table 38: Correlation between numerical parameters

Before inserting variables to the multiple linear regresion model, different simple regressions with the cost per km as response variable are done. The unique explanatory parameter is:(one by one) the area, duration and desviation of the rock cover. They had a big correlation and therefore, it will be observed the individual influence of each parameter in the cost per km estimation for developing afterwards the bigger regresion.

1. **Linear regression model (Cost per km ~ Area):**

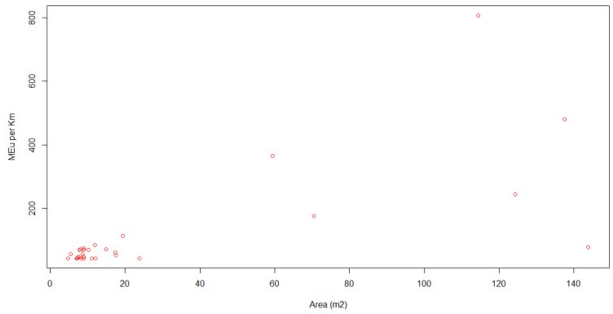


Figure 54: Plot– Cost per km / Area

```
plot(DR2_tunnel_Road_Noutliners_num$Ckm/1000000,DR2_tunnel_Road_Noutliners_num$Area,
xlab="Area (m2)" , ylab="MEu per Km", col="red")

model_area<-lm(DR2_tunnel_Road_Noutliners$Ckm/1000000 ~ DR2_tunnel_Road_Noutliners$Area)
summary(model_area)
```

It can be concluded that as bigger the area, bigger the cost. However, the R2 of the model is only 0.49 and therefore can not be explained with only this variable.

```
Coefficients:
                                Estimate Std. Error t value Pr(>|t|)
(Intercept)                      8.09163    6.77345   1.195    0.242
DR2_tunnel_Road_Noutliners$Area  0.18297    0.03433   5.329 1.02e-05
***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 30.39 on 29 degrees of freedom
Multiple R-squared:  0.4948,   Adjusted R-squared:  0.4774
F-statistic:  28.4 on 1 and 29 DF,  p-value: 1.016e-05
```

However, as the intercept do not have significance (P.value of 0.242) it is deleted from the model an it is runned on more.

```
model_area<-lm(DR2_tunnel_Road_Noutliners$Ckm/1000000 ~ -1 +
DR2_tunnel_Road_Noutliners$Area)
summary(model_area)
```

```
lm(formula = DR2_tunnel_Road_Noutliners$Ckm/1e+06 ~ -1 +
DR2_tunnel_Road_Noutliners$Area)

Residuals:
    Min      1Q  Median      3Q     Max
-52.762  -5.625  -1.922   2.648 127.920

Coefficients:
                                Estimate Std. Error t value Pr(>|t|)
DR2_tunnel_Road_Noutliners$Area  0.20727    0.02786    7.44 2.73e-08
***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 30.6 on 30 degrees of freedom
Multiple R-squared:  0.6485,   Adjusted R-squared:  0.6368
F-statistic: 55.35 on 1 and 30 DF,  p-value: 2.726e-08
```

Now, the R2 is 0,6486 so 64,86% of the cost can be explained just by this parameter. Also the Fstatistics is big so the null hyphothesis is discarded and the model estimates that for each square meter incremented in the cross section are, the cost per km of the tunnel increments 0.21 million of euros.

Another thing to observate is that any register have been deleted due to missingness (NA values).

2. **Linear regression model (Cost per km ~ Duration):**

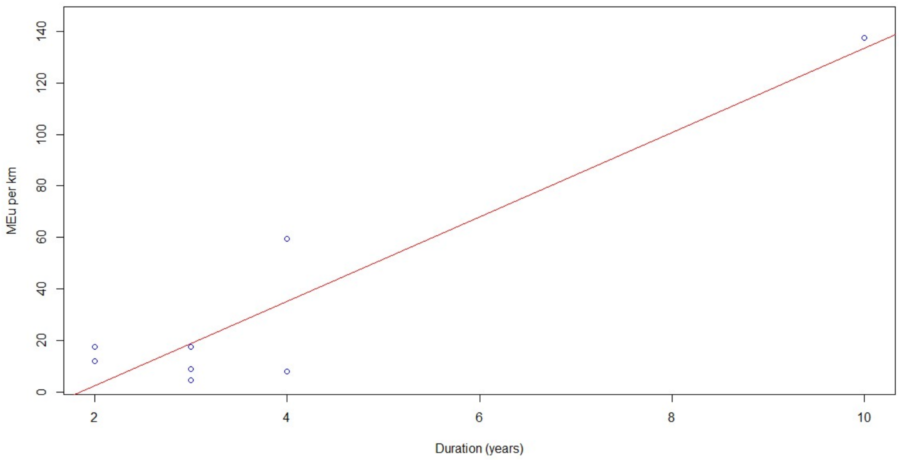


Figure 55: Plot- Cost per km / Duration

Despite of having only the duration of 8th projects (reason for which are 23 observations deleted fue to missingness), the duration has a extraordinary correlation with the cost estimation, only with this parameter can be predicted the 86.54% of the project cost.

As the estimate is 16.387, per each year of construction works, the project is going to cost 16.387 millions of euros per km more.

```
Call:
lm(formula = DR2_tunnel_Road_Noutliners_num$Ckm/1e+06 ~
DR2_tunnel_Road_Noutliners_num$Dur)

Residuals:
    Min      1Q  Median      3Q     Max
-27.232 -10.998   1.281  10.929  24.186

Coefficients:
                                   Estimate Std. Error t value
Pr(>|t|)
(Intercept)                         -30.306     12.055  -2.514
0.045657 *
DR2_tunnel_Road_Noutliners_num$Dur   16.387      2.638   6.211
0.000804 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 18.06 on 6 degrees of freedom
  (23 observations deleted due to missingness)
Multiple R-squared:  0.8654,	Adjusted R-squared:  0.843
F-statistic: 38.58 on 1 and 6 DF,  p-value: 0.0008039
```

3. **Linear regression model (Cost per km ~ Rock cover’s deviation):**

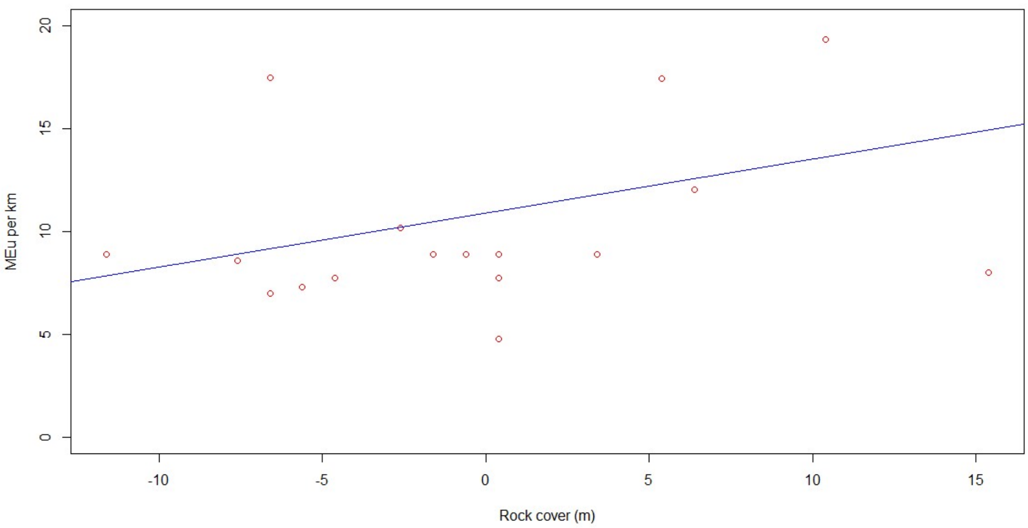


Figure 56: Plot– Cost per km / Rock Cover

Despite of having a big correlation, the rock cover desviation achieves a R2 of only 0.154 and a p-values of 0.154. It means that the parameter is not very good for estimating the cost per km.

```
plot(DR2_tunnel_Road_Noutliners_num$Des_Cover,DR2_tunnel_Road_Noutliners_num$Ckm/1000000,
ylim=c(0, 20),xlab="Rock cover (m)",ylab="MEu per km",col="red")

par(new=TRUE)

abline(model_cover<-
lm(DR2_tunnel_Road_Noutliners_num$Ckm/1000000~DR2_tunnel_Road_Noutliners_num$Des_Cover),
l="blue")
summary(model_cover)
```

```
Call:
lm(formula = DR2_tunnel_Road_Noutliners_num$Ckm/1e+06 ~ 
DR2_tunnel_Road_Noutliners_num$Des_Cover)

Residuals:
    Min      1Q  Median      3Q     Max 
-6.9126 -2.1514 -1.7093  0.7844 11.6001 

Coefficients:
                                         Estimate Std. Error t value
Pr(>|t|)    
(Intercept)                               10.8846     1.1693   9.308
7.38e-08 ***
DR2_tunnel_Road_Noutliners_num$Des_Cover   0.2625     0.1756   1.495
0.154    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.961 on 16 degrees of freedom
  (13 observations deleted due to missingness)
Multiple R-squared:  0.1226,	Adjusted R-squared:  0.06776 
F-statistic: 2.236 on 1 and 16 DF,  p-value: 0.1543
```

Finally the multiple linear regresion is performed. It has been decided to use the additive method, which is an iterative method that consists on the one by one addition of the parameters, for identifying their significance in the model, and making the decision of reject or include them in the model.

After the iterations performance the best cost per km is obtained by the area, the area square and the end year.

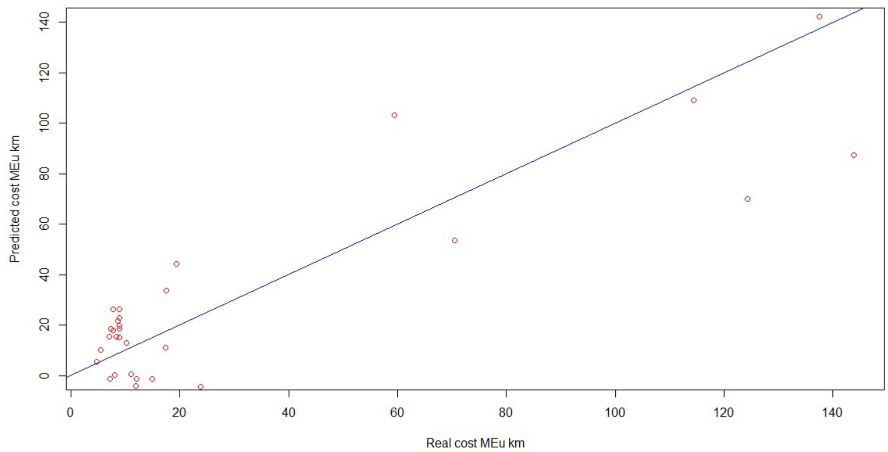


Figure 57: Plot– Predicted cost per km / Real Cost per km

The blue line represents the 1:1 relation and in the x and y axis are represented the real and predicted values of the cost per km of the Road tunnel. As much close to the blue line as much accurate the prediction.

```
model_tunnel_Road<-lm(DR2_tunnel_Road_Noutliners$Ckm ~ Area+End,data=DR2_tunnel_Road_Noutliners)
summary(model_tunnel_Road)
plot(DR2_tunnel_Road_Noutliners$Ckm/1000000, DR2_tunnel_Road_Noutliners$preic/1000000, col="red", xlab="Real cost MEu km", ylab="Predicted cost MEu km", ylim=c(0,140))
par(new=TRUE)
abline(0,1,col="blue")
plot(model_tunnel_Road)
```

```
Call:
lm(formula = DR2_tunnel_Road_Noutliners$Ckm ~ Area + A2 + End,
    data = DR2_tunnel_Road_Noutliners)

Residuals:
      Min        1Q    Median        3Q       Max
-43860951 -12132895  -4787090   9554751  56387972

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.278e+09  7.999e+08   4.099 0.000341 ***
Area         5.826e+05  9.166e+04   6.356 8.32e-07 ***
End         -1.652e+06  4.018e+05  -4.111 0.000329 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 21940000 on 27 degrees of freedom
Multiple R-squared:  0.7547,   Adjusted R-squared:  0.7275
F-statistic: 27.69 on 3 and 27 DF,  p-value: 2.154e-08
```

Then, the plots are revised:

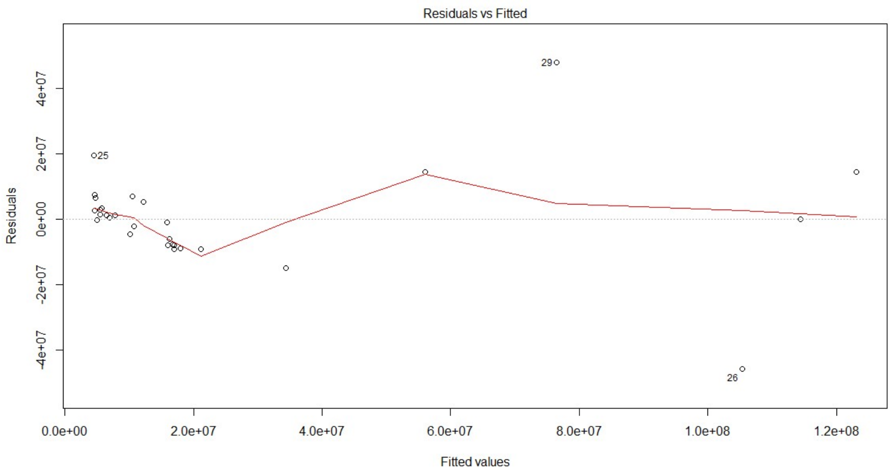


Figure 58: Verification plot (Residual vs Fitted)

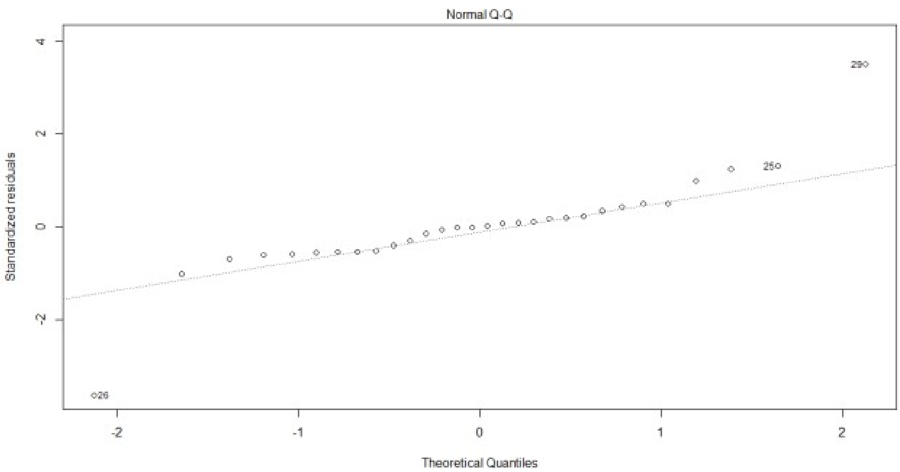


Figure 59: Verification plot (Normal Q-Q)

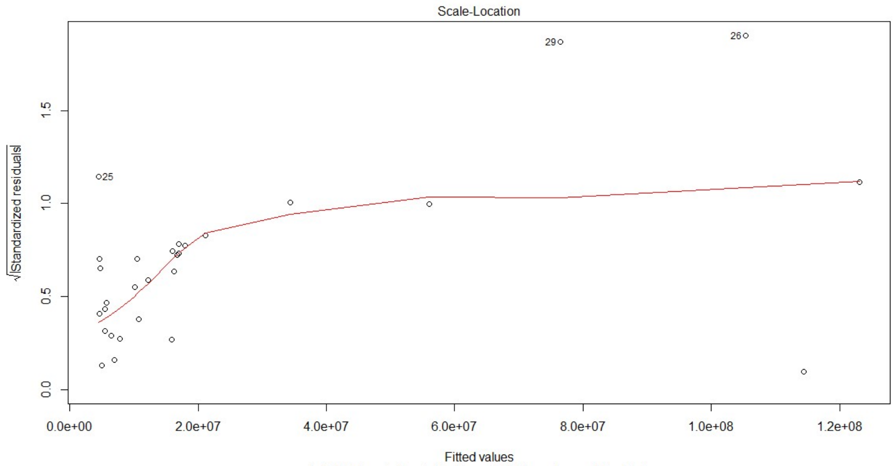


Figure 60: Verification plot (Scale-Location)

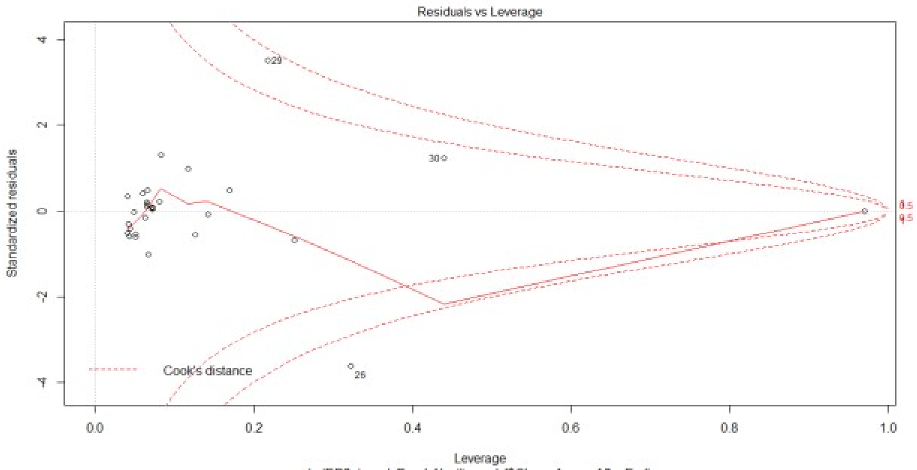


Figure 61: Verification plot (Residual vs Leverage)

The graphs are correct and therefore, the multiple regression model is obtained and defined by the following coefficients:

Intercept	-1086344086
Area	180800,7
End	546046,1

Table 39: Coefficients summary.

Therefore the resulting equation is:

$$\mathrm{Y} = -1086344086 + 180800{,}7 * \mathrm{Area} + 546046{,}1 * \mathrm{End}$$

Defined the parameters of our structure (Area=195 m3 and End=2017) the prediction of the cost per km can be done.

$$\mathrm{Y} = 1086344086 + 180800{,}7 * 195 + 546046{,}1 * 2017$$
$$\mathrm{Y} = 50.287.034{,}7 \text{ eu} \rightarrow 50 \text{ Meu per km}$$

The total length is 80 km and therefore the project cost would be (50*80) = 4 bilions of euros.

Chapter 5 – Conclusions

In this thesis, the advantages and disadvantages of the different water crossing infrastructures and their respectively construction methods were studied as well as their prices.

After having recompiled all the information, it was concluded that tunnels seems to be the optimal election as the risk agains superficial and submerged collisions; such as ships impacts or submarines; are discarded. This kind of infrastructures have been widely used for land tunnels and after the historical projects research, it can be concluded it is as well by large the most used infrastructure for water crossings infrastructures until 2018. This gained experience seems a favorable point of the tunnels respect the immerse tunnels; which have been used only in small tracks of a reduced number of projects; as it reduce the uncertainty against unexpected budged increments during the construction works operations.
For what the historical projects' price respects, the average price of the tunnels was found the minimum between the three considered infrastructures, seeming also the optimal for what project cost respects.

Due to the complexity of the tunnels cost estimation, a multiple linear regression was used as the method to identify the influent parameters and obtain a cost estimation equation based on the historical data.

The resulting equation is [$\mathrm{Y} = -1086344086 + 180800{,}7 * \mathrm{Area} + 546046{,}1 * \mathrm{End}$] for the cost per km estimation.

It can be seen that the influent parameters are the cross section area and the year of constructions' ending. Which seems reasonable as bigger the cross section area, more expensive and as one year finished later represents also an increase in the projects' prices. The cost of excavation of 1 m3 more in the cross section represents and increment of 180.800,7 eu per kilometer and one year of delay represents 546.046,1 eu per kilometer more in the final cost of the structure.

After having studied the Helsinki-Tallin boundaries and once applied the cross section area of 195 m3 and Ending year at 2017, the cost per km for the Helsinki-Tallin tunnel link was obtained, needing 4 bilion of euros for excavating the tunnel through their 80 km length, which seems a reasonable value. However, the stadistical analisis was done with road tunnels and not railways tunnels. Therefore, it is clear that the additional cost for installing the railway system should be added to obtain the real cost of the project.

Once compared the Tunnel excavation cost estimated by SWECO in the prefeasibility study and the obtained in this project, can be seen that the predictions are similar. Seeming the result is more than acceptable.

Because SWECO estimated the tunnel and railways cost between 3,6 – 4 MEUR and our prediction was 4MEUR.

Cost types	Low price, MEUR	High price, MEUR
Tunnel with railways, 85 km	3,600	4,100

Figure 62: Cost estimation of the tunnel+railways made by SWECO in their Prefeasibility Study [98].

Furthermore, SWECO estimated that the railway system implementation would be between 5,47 bilion of euros and 8.85 bilion of euros.

Cost types	Low price, MEUR	High price, MEUR
Tunnel with railways, 85 km	3,600	4,100
Surface track sections	700	1,000
All technical systems, maintenance canals, security	2,500	3,300
Finnish cargo terminal and passenger station	200	400
Estonian cargo terminal and extension of passenger station	70	150
Rolling Stock	1,000	1,000
Risk reserves	1,000	3,000
TOTAL COST	9–13 billion euros	

Figure 63: Cost estimation made by SWECO in their Prefeasibility Study [98].

Therefore, our final projects cost using the same estimations made by SWECO, for what railway system concerns, the final project price would be between 9.47 and 12,85 bilion of euros. Which is very close to the 9-13 bilions range defined by the prefeasibility study.

The quality of our cost estimation is limited by the availability of data, as influent parameters such as the geology or duration could not be incorporated as an explanatory parameter due to the large quantity of non available values. Furthermore, for doing this kind of analysis, bigger quantity of registers is usually used, but in our case, the number of watercrossing infraestructures was limited by the number of existing water crossing infraestructures and it could not be larger. For what the cost estimation made by SWECO it is not indicated how the estimation is done, so it's hard to analyze the accuracity of the estimation.

At the end of this thesis, the final project cost for the Helsinki-Tallin fixed link connection is estimated to cost between 9,47 and 12,85 bilion of euros. Cost estimation which is similar to the estimated in Sweco's prefeasibility. Therefore, the predictions done during this thesis development seems to be reasonable.

Appendix

Projects' historical data:

The projects historical data used during the Helsinki-Tallinn cost estimation can be found in the excel file added and published in upcommons. The name of the file is "Historical_data.xlsx".

Inflation rates Arabia Saudí

inflation (yearly basis)	inflation %
january 1986 - january 1985	-3,20
january 1987 - january 1986	-1,50
january 1988 - january 1987	0,90
january 1989 - january 1988	1,00
january 1990 - january 1989	2,10
january 1991 - january 1990	4,90
january 1992 - january 1991	-0,10
january 1993 - january 1992	1,10
january 1994 - january 1993	1,10
january 1995 - january 1994	4,90
january 1996 - january 1995	1,2
january 1997 - january 1996	0,00
january 1998 - january 1997	-0,40
january 1999 - january 1998	-1,30
january 2000 - january 1999	-1,10
january 2001 - january 2000	-1,10
january 2002 - january 2001	0,20
january 2003 - january 2002	0,60
january 2004 - january 2003	0,3
january 2005 - january 2004	0,70
january 2006 - january 2005	2,20
january 2007 - january 2006	4,2
january 2008 - january 2007	9,90
january 2009 - january 2008	5,10
january 2010 - january 2009	5,3
january 2011 - january 2010	5,80
january 2012 - january 2011	2,9
january 2013 - january 2012	3,50
january 2014 - january 2013	2,70
january 2015 - january 2014	2,20
january 2016 - january 2015	3,50
january 2017 - january 2016	-0,40

Inflation rates South Korea

january 2009 - january 2008	3,75
january 2010 - january 2009	3,52
january 2011 - january 2010	3,44
january 2012 - january 2011	3,35
january 2013 - january 2012	1,63
january 2014 - january 2013	1,08
january 2015 - january 2014	0,97
january 2016 - january 2015	0,62
january 2017 - january 2016	2,03
inflation (monthly basis)	**inflation**
february 2017 - january 2017	0,33
march 2017 - february 2017	0,02
april 2017 - march 2017	-0,13
may 2017 - april 2017	0,14
june 2017 - may 2017	-0,13
july 2017 - june 2017	0,18
august 2017 - july 2017	0,6
september 2017 - august 2017	0,11
october 2017 - september 2017	-0,18
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,12

Inflation rates Denmark

inflation (yearly basis)	inflation %
january 1989 - january 1988	4,59
january 1990 - january 1989	3,68
january 1991 - january 1990	2,52
january 1992 - january 1991	2,12
january 1993 - january 1992	1,53
january 1994 - january 1993	1,78
january 1995 - january 1994	2,22
january 1996 - january 1995	1,65
january 1997 - january 1996	2,7
january 1998 - january 1997	1,73
january 1999 - january 1998	1,70
january 2000 - january 1999	3,16
january 2001 - january 2000	2,34
january 2002 - january 2001	2,49
january 2003 - january 2002	2,62
january 2004 - january 2003	1,13
january 2005 - january 2004	1,03
january 2006 - january 2005	2,13
january 2007 - january 2006	1,81
january 2008 - january 2007	2,94
january 2009 - january 2008	1,82
january 2010 - january 2009	2,04
january 2011 - january 2010	2,66
january 2012 - january 2011	2,76
january 2013 - january 2012	1,27
january 2014 - january 2013	1,02
january 2015 - january 2014	-0,10
january 2016 - january 2015	0,61
january 2017 - january 2016	0,91
inflation (monthly basis)	inflation
february 2017 - january 2017	0,8
march 2017 - february 2017	0,1
april 2017 - march 2017	0,2
may 2017 - april 2017	-0,1
june 2017 - may 2017	-0,1
july 2017 - june 2017	0,79
august 2017 - july 2017	-0,29
september 2017 - august 2017	0,1
october 2017 - september 2017	0,1
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,6

Inflation rates Japan

inflation (yearly basis)	inflation %
january 1989 - january 1988	1,01
january 1990 - january 1989	3,34
january 1991 - january 1990	3,98
january 1992 - january 1991	1,76
january 1993 - january 1992	1,22
january 1994 - january 1993	1,31
january 1995 - january 1994	0,50
january 1996 - january 1995	-0,49
january 1997 - january 1996	0,6
january 1998 - january 1997	1,87
january 1999 - january 1998	0,19
january 2000 - january 1999	-0,68
january 2001 - january 2000	-0,29
january 2002 - january 2001	-1,46
january 2003 - january 2002	-0,40
january 2004 - january 2003	-0,3
january 2005 - january 2004	0,20
january 2006 - january 2005	-0,10
january 2007 - january 2006	0
january 2008 - january 2007	0,70
january 2009 - january 2008	0,00
january 2010 - january 2009	-0,99
january 2011 - january 2010	-0,60
january 2012 - january 2011	0,1
january 2013 - january 2012	-0,25
january 2014 - january 2013	1,36
january 2015 - january 2014	2,47
january 2016 - january 2015	-0,10
january 2017 - january 2016	0,50

inflation (monthly basis)	inflation
february 2017 - january 2017	-0,2
march 2017 - february 2017	0,1
april 2017 - march 2017	0,4
may 2017 - april 2017	0,1
june 2017 - may 2017	-0,2
july 2017 - june 2017	-0,1
august 2017 - july 2017	0,2
september 2017 - august 2017	0,2
october 2017 - september 2017	-
november 2017 - october 2017	-
december 2017 - november 2017	-
	0,5

Inflation rates Canada

inflation (yearly basis)	inflation %
january 1998 - january 1997	1,11
january 1999 - january 1998	0,66
january 2000 - january 1999	2,19
january 2001 - january 2000	2,99
january 2002 - january 2001	1,35
january 2003 - january 2002	4,51
january 2004 - january 2003	1,27
january 2005 - january 2004	1,94
january 2006 - january 2005	2,75
january 2007 - january 2006	1,11
january 2008 - january 2007	2,19
january 2009 - january 2008	1,07
january 2010 - january 2009	1,86
january 2011 - january 2010	2,35
january 2012 - january 2011	2,46
january 2013 - january 2012	0,5
january 2014 - january 2013	1,48
january 2015 - january 2014	0,97
january 2016 - january 2015	2,01
january 2017 - january 2016	2,13

inflation (monthly basis)	inflation
february 2017 - january 2017	0,15
march 2017 - february 2017	0,15
april 2017 - march 2017	0,38
may 2017 - april 2017	0,08
june 2017 - may 2017	-0,08
july 2017 - june 2017	0
august 2017 - july 2017	0,08
september 2017 - august 2017	0,23
october 2017 - september 2017	0,08
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,07

Inflation rates Greece

january 2004 - january 2003	3,14
january 2005 - january 2004	2,93
january 2006 - january 2005	4,03
january 2007 - january 2006	3,24
january 2008 - january 2007	2,73
january 2009 - january 2008	3,90
january 2010 - january 2009	1,76
january 2011 - january 2010	2,38
january 2012 - january 2011	5,2
january 2013 - january 2012	0,20
january 2014 - january 2013	-1,47
january 2015 - january 2014	-2,84
january 2016 - january 2015	-0,73
january 2017 - january 2016	1,16
inflation (monthly basis)	**inflation**
february 2017 - january 2017	-0,29
march 2017 - february 2017	1,79
april 2017 - march 2017	0,64
may 2017 - april 2017	-0,89
june 2017 - may 2017	0,62
july 2017 - june 2017	-1,67
august 2017 - july 2017	-0,45
september 2017 - august 2017	1,89
october 2017 - september 2017	0,1
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,64

Inflation rates Netherlands

january 2004 - january 2003	1,36
january 2005 - january 2004	1,49
january 2006 - january 2005	1,27
january 2007 - january 2006	1,42
january 2008 - january 2007	2,03
january 2009 - january 2008	1,93
january 2010 - january 2009	0,82
january 2011 - january 2010	1,97
january 2012 - january 2011	2,5
january 2013 - january 2012	3,00
january 2014 - january 2013	1,40
january 2015 - january 2014	0,00
january 2016 - january 2015	0,60
january 2017 - january 2016	1,70
inflation (monthly basis)	**inflation**
february 2017 - january 2017	0,69
march 2017 - february 2017	0,3
april 2017 - march 2017	0,58
may 2017 - april 2017	-0,34
june 2017 - may 2017	-0,39
july 2017 - june 2017	0,33
august 2017 - july 2017	0,35
september 2017 - august 2017	0,03
october 2017 - september 2017	-
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,55

Inflation rates Turkey

january 2013 - january 2012	7,31
january 2014 - january 2013	7,75
january 2015 - january 2014	7,24
january 2016 - january 2015	9,58
january 2017 - january 2016	9,22
inflation (monthly basis)	**inflation**
february 2017 - january 2017	10,13
march 2017 - february 2017	11,29
april 2017 - march 2017	11,87
may 2017 - april 2017	11,72
june 2017 - may 2017	10,9
july 2017 - june 2017	9,79
august 2017 - july 2017	10,68
september 2017 - august 2017	11,2
october 2017 - september 2017	11,9
november 2017 - october 2017	-
december 2017 - november 2017	-
	99,48

Inflation rates Iceland

january 1999 - january 1998	1,27
january 2000 - january 1999	5,80
january 2001 - january 2000	3,56
january 2002 - january 2001	9,46
january 2003 - january 2002	1,40
january 2004 - january 2003	2,41
january 2005 - january 2004	3,96
january 2006 - january 2005	4,40
january 2007 - january 2006	6,86
january 2008 - january 2007	5,82
january 2009 - january 2008	18,58
january 2010 - january 2009	6,56
january 2011 - january 2010	1,85
january 2012 - january 2011	6,53
january 2013 - january 2012	4,20
january 2014 - january 2013	3,10
january 2015 - january 2014	0,82
january 2016 - january 2015	2,15
january 2017 - january 2016	1,92

inflation (monthly basis)	inflation
february 2017 - january 2017	0,72
march 2017 - february 2017	0,06
april 2017 - march 2017	0,51
may 2017 - april 2017	0,19
june 2017 - may 2017	0
july 2017 - june 2017	-0,03
august 2017 - july 2017	0,26
september 2017 - august 2017	0,13
october 2017 - september 2017	0,47
november 2017 - october 2017	-
december 2017 - november 2017	-
	2,31

Inflation rates Great Britain UK

inflation (yearly basis)	inflation %
january 1995 - january 1994	2,42
january 1996 - january 1995	2,72
january 1997 - january 1996	2,07
january 1998 - january 1997	1,47
january 1999 - january 1998	1,67
january 2000 - january 1999	0,77
january 2001 - january 2000	0,87
january 2002 - january 2001	1,61
january 2003 - january 2002	1,38
january 2004 - january 2003	1,36
january 2005 - january 2004	1,65
january 2006 - january 2005	1,93
january 2007 - january 2006	2,69
january 2008 - january 2007	2,23
january 2009 - january 2008	3,03
january 2010 - january 2009	3,4
january 2011 - january 2010	4,00
january 2012 - january 2011	3,59
january 2013 - january 2012	2,63
january 2014 - january 2013	1,96
january 2015 - january 2014	0,30
january 2016 - january 2015	0,20
january 2017 - january 2016	1,91

inflation (monthly basis)	inflation
february 2017 - january 2017	0,69
march 2017 - february 2017	0,39
april 2017 - march 2017	0,39
may 2017 - april 2017	0,39
june 2017 - may 2017	0
july 2017 - june 2017	-0,1
august 2017 - july 2017	0,58
september 2017 - august 2017	0,29
october 2017 - september 2017	0,1
november 2017 - october 2017	-
december 2017 - november 2017	-
	2,73

Inflation rates Sweden

inflation (yearly basis)	inflation %
january 1987 - january 1986	3,11
january 1988 - january 1987	4,74
january 1989 - january 1988	6,63
january 1990 - january 1989	8,40
january 1991 - january 1990	10,39
january 1992 - january 1991	5,23
january 1993 - january 1992	4,80
january 1994 - january 1993	1,64
january 1995 - january 1994	2,53
january 1996 - january 1995	1,58
january 1997 - january 1996	-0,06
january 1998 - january 1997	0,70
january 1999 - january 1998	-0,22
january 2000 - january 1999	0,45
january 2001 - january 2000	1,50
january 2002 - january 2001	2,71
january 2003 - january 2002	2,66
january 2004 - january 2003	0,72
january 2005 - january 2004	-0,03
january 2006 - january 2005	0,61
january 2007 - january 2006	1,94
january 2008 - january 2007	3,20
january 2009 - january 2008	1,28
january 2010 - january 2009	0,31
january 2011 - january 2010	2,46
january 2012 - january 2011	1,86
january 2013 - january 2012	0,05
january 2014 - january 2013	-0,20
january 2015 - january 2014	-0,21
january 2016 - january 2015	0,77
january 2017 - january 2016	1,40

inflation (monthly basis)	inflation
february 2017 - january 2017	0,7
march 2017 - february 2017	0,02
april 2017 - march 2017	0,58
may 2017 - april 2017	0,06
june 2017 - may 2017	0,07
july 2017 - june 2017	0,53
august 2017 - july 2017	-0,16
september 2017 - august 2017	0,14
october 2017 - september 2017	-0,07
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,87

Inflation rates China

inflation (yearly basis)	inflation %
january 1986 - january 1985	7,10
january 1987 - january 1986	5,10
january 1988 - january 1987	9,30
january 1989 - january 1988	27,40
january 1990 - january 1989	4,3
january 1991 - january 1990	2,20
january 1992 - january 1991	5,50
january 1993 - january 1992	10,3
january 1994 - january 1993	21,1
january 1995 - january 1994	24,1
january 1996 - january 1995	9
january 1997 - january 1996	5,9
january 1998 - january 1997	0,30
january 1999 - january 1998	-1,20
january 2000 - january 1999	-0,20
january 2001 - january 2000	1,20
january 2002 - january 2001	-1,01
january 2003 - january 2002	0,37
january 2004 - january 2003	3,21
january 2005 - january 2004	1,80
january 2006 - january 2005	2,29
january 2007 - january 2006	2,2
january 2008 - january 2007	7,11
january 2009 - january 2008	0,96
january 2010 - january 2009	1,4
january 2011 - january 2010	5,00
january 2012 - january 2011	4,6
january 2013 - january 2012	2,02
january 2014 - january 2013	2,51
january 2015 - january 2014	0,71
january 2016 - january 2015	1,81
january 2017 - january 2016	2,57
inflation (monthly basis)	**inflation**
february 2017 - january 2017	0,78
march 2017 - february 2017	0,98
april 2017 - march 2017	1,18
may 2017 - april 2017	1,67
june 2017 - may 2017	1,68
july 2017 - june 2017	1,38
august 2017 - july 2017	1,77
september 2017 - august 2017	1,66
october 2017 - september 2017	1,86
november 2017 - october 2017	-
december 2017 - november 2017	-
	12,96

Inflation rates US

inflation (yearly basis)	inflation %
january 1956 - january 1955	0,37
january 1957 - january 1956	2,99
january 1958 - january 1957	3,62
january 1959 - january 1958	1,4
january 1960 - january 1959	1,03
january 1961 - january 1960	1,71
january 1962 - january 1961	0,67
january 1963 - january 1962	1,33
january 1964 - january 1963	1,64
january 1965 - january 1964	0,97
january 1966 - january 1965	1,92
january 1967 - january 1966	3,46
january 1968 - january 1967	3,65
january 1969 - january 1968	4,4
january 1970 - january 1969	6,18
january 1971 - january 1970	5,29
january 1972 - january 1971	3,27
january 1973 - january 1972	3,65
january 1974 - january 1973	9,39
january 1975 - january 1974	11,8
january 1976 - january 1975	6,82
january 1977 - january 1976	5,22
january 1978 - january 1977	6,84
january 1979 - january 1978	9,28
january 1980 - january 1979	13,91
january 1981 - january 1980	11,83
january 1982 - january 1981	8,39
january 1983 - january 1982	3,71
january 1984 - january 1983	4,19
january 1985 - january 1984	3,53
january 1986 - january 1985	3,89
january 1987 - january 1986	1,46
january 1988 - january 1987	4,05
january 1989 - january 1988	4,67
january 1990 - january 1989	5,20
january 1991 - january 1990	5,65
january 1992 - january 1991	2,60
january 1993 - january 1992	3,26
january 1994 - january 1993	2,52
january 1995 - january 1994	2,80
january 1996 - january 1995	2,73
january 1997 - january 1996	3,04
january 1998 - january 1997	1,57
january 1999 - january 1998	1,67
january 2000 - january 1999	2,74
january 2001 - january 2000	3,73
january 2002 - january 2001	1,14
january 2003 - january 2002	2,60
january 2004 - january 2003	1,93
january 2005 - january 2004	2,97
january 2006 - january 2005	3,99
january 2007 - january 2006	2,08
january 2008 - january 2007	4,28
january 2009 - january 2008	0,03
january 2010 - january 2009	2,63
january 2011 - january 2010	1,63
january 2012 - january 2011	2,93
january 2013 - january 2012	1,59
january 2014 - january 2013	1,58
january 2015 - january 2014	-0,09
january 2016 - january 2015	1,37
january 2017 - january 2016	2,50

inflation (monthly basis)	inflation
february 2017 - january 2017	0,58
march 2017 - february 2017	0,31
april 2017 - march 2017	0,08
may 2017 - april 2017	0,3
june 2017 - may 2017	0,09
july 2017 - june 2017	0,09
august 2017 - july 2017	-0,07
september 2017 - august 2017	0,53
october 2017 - september 2017	-0,06
november 2017 - october 2017	-
december 2017 - november 2017	-
	1,85

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