Feasibility Analysis of a Fixed Link Crossing the Long Island Sound

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Executive Summary

The following report is the final feasibility analysis for the fixed link crossing the Long Island Sound. A final landing location was determined on the Long Island, NY side of the crossing and 4 alternatives for the landing on the Connecticut side. The proposed structure of the crossing was also determined. The crossing would consist of about 8 miles of trestle, a 4-mile long tunnel, and two one square mile man-made islands to transition from trestle to tunnel sections. The crossing was determined based on the sound depth profile and traveler's ease of access. A maximum depth of 90 feet was able to be achieved. This 4-mile span of depths between 90 and 60 feet would be the location of the tunnel. A crossing from a bridge component to a tunnel requires the use of islands for the transition. Research was done and found that it would be possible to use the sandy silt material along the route of the sound crossing to build these islands. The second parameter in the crossing location was the commuter's convenience for passage. It was defined exactly on the New York landing site to be connected to Sunken Meadow Parkway in Kings Park, NY.

Many design constraints were considered during the course of the feasibility analysis. Several different cross-sections of tunnels were considered, and a final geometry was chosen to have two circular roadway tunnels with 30 foot diameters and two 20 foot diameter tunnels, one used as an escape/ventilation tunnel and the other for a possible railway. The longest underwater roadway tunnel currently is about 2 miles. The design proposes to double that length. This imposes two large problems, life safety and ventilation. These two considerations were studied in depth for this feasibility analysis and displayed in the Appendices.

Air quality is essential for the safety of passengers that cross through a tunnel. Natural ventilation had a calculated carbon monoxide concentration 60 times the acceptable value. This left the two mechanical methods of ventilation, longitudinal and transverse, to be considered. Longitudinal ventilation is more economically beneficially, however it mostly accommodates uni-directional traffic and does not evacuate the smoke from a fire. This would bring concerns of life-safety and air quality. It would also require the crossing to shut down in the case that one tunnel need to be closed for maintenance. Transverse ventilation uses air injection and pollution extraction throughout the length of the tunnel. It is higher in cost, but it is best for life safety and has the lowest carbon monoxide concentration value, making it the best choice for ventilation as well. Transverse ventilation calculations returned a carbon monoxide that was double the acceptable length, so more consideration had to be taken to get this value lower. It was determined that the utilization of the circular geometry tunnel with a dual tunnel for escape and exhaust be used. This allows the escape tunnel to become larger enabling emergency vehicles access. It also lowers the concentration of the carbon monoxide to an acceptable value. This is done by pulling air from the roadway tunnels into the center of the escape/ventilation tunnel. The polluted air would then have jet fans blowing it out of the tunnel, half northbound and half southbound.

The feasibility of the tunnel allowed the analysis to continue for the trestle and island sections of the crossing. The trestle sections were determined to be low level trestle over shallow water between 30 and 60 foot depths. The substructure would consist of cylindrical, hollow, precast, prestressed piles supported by bent caps. The piles would be filled with sand to withstand the shock of a collision. The man-made islands that transition from trestle to the tunnel would be 1 square mile to replace the parkland from the New York landing location. The islands would use a hydraulic fill material from the dredging of the sound bottom for the tunnel and acceptable material that local businesses dispose of. Any additional material would have to be purchased. The construction process requires rock dikes to be placed and then filled with sand and built up this way until it reached a height 30 feet above mean water. Construction of businesses, parking, and green landscapes would then take place on each of the islands.

It was finally shown that this crossing is feasible and the final design process could begin. A cost estimation of $7.5 billion dollars was found. This includes all costs for construction of the crossing over the three year proposed construction length. The additional traffic and environmental impact studies would take place in the final design process. A detailed report on the proposed revenue from the crossing would take place after the traffic studies were completed.

Problem Statement

It has been determined that there is a need for a link from Long Island, New York to Connecticut. The current routes to get from these two locations are not ideal for several reasons. Traffic is a large problem on the three bridges that connect to Long Island and Interstate 95 in New York and Connecticut. The only other alternative is to take the ferry, which is costly and time consuming.

The link will lessen traffic in existing bridges connecting Long Island, New York to northern parts of New York. It will allow commuters from both states a much easier and more convenient route. It will also create jobs and businesses on either side of the link.

The link needs to incorporate both bridge and tunnel technologies to complete the span. Factors such as life safety and ventilation cannot be ignored during the analysis of the structural systems. The feasibility of the decisions made regarding this link will be fully analyzed and assessed.

Methodology

Site and Design Considerations

After determining an approximate location in our initial proposal, we refined the crossing's location, shown in Figure 1, below, after careful analysis of the sound topography. This location lowers the maximum depth to a manageable 90ft.

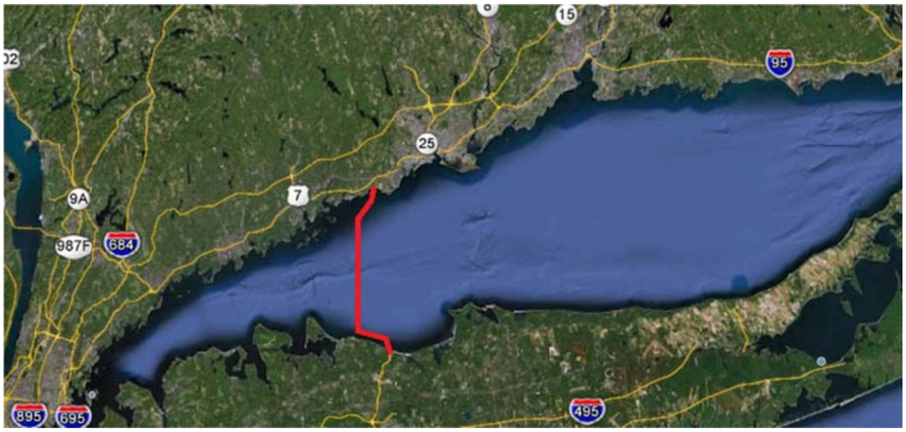


Figure 1: Proposed Crossing Location

With the location finalized, we created a profile of the sound, shown in Figure 2, below. This profile is adequate for our approximations during this feasibility study; however, a higher precision survey will be required for the design and construction phases.

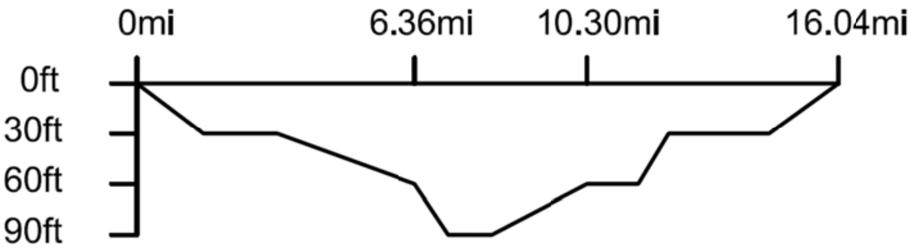


Figure 2: Sound Profile At Proposed Crossing Location

Looking at this profile, it is apparent that a tunnel will be required to transverse the deeper sections. Below a depth of 60ft, a tunnel would become more economically feasible. This results in a tunnel that is approximately 4 miles long, twice as long as any currently constructed tunnel allowing travel of combustion engine vehicles. A reasonable solution would be to have a transport system to take vehicles from one side to the other; however, most Americans prefer to be in control of their own vehicle and this would discourage potential customers. Allowing vehicles to drive through a tunnel of this length, ventilation and life safety become serious issues that we address later in this report.

New York Landing

On the New York side, we have only one viable option, shown in Figure 3, below. An extension of Sunken Meadow Parkway will provide a cost effective option for connection to major arterials in Long Island, NY. This 4 lane highway currently ends at approximately a quarter mile from the coast. Unfortunately and extension will lead through Sunken Meadow State Park. In order to compensate for lost State Park space, we are proposing park space replacement, which will be discussed later in this report.

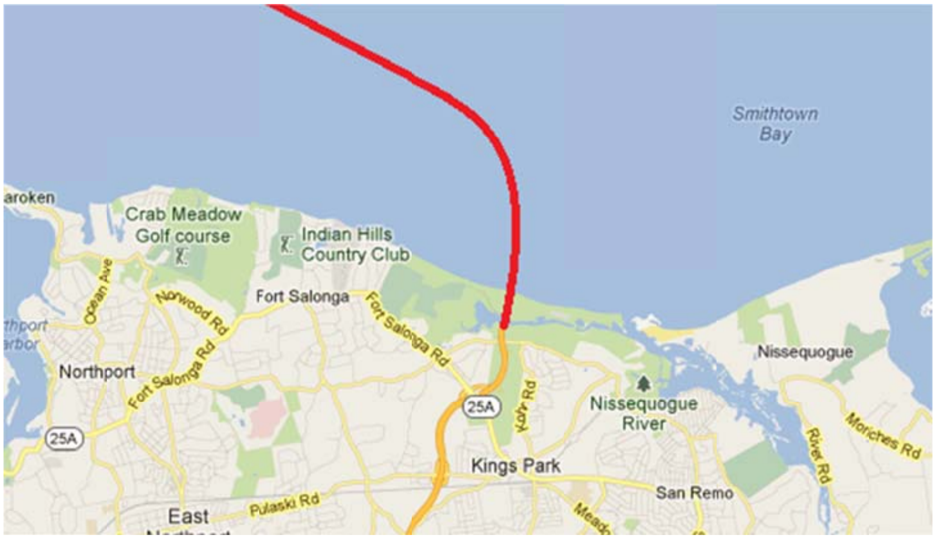


Figure 3: New York Landing Location

Connecticut Landing Alternatives

On the Connecticut side, we have a few alternatives for the landing location. We cannot specify an exact location due to differences in public option. Unlike the New York landing, we have almost endless landing possibilities due to the proximity of I95 to the coastline. We have narrowed down landing alternatives based on several factors, shown in Figure 4, below. The most viable option must be chosen by the authority having jurisdiction as well as the general public.

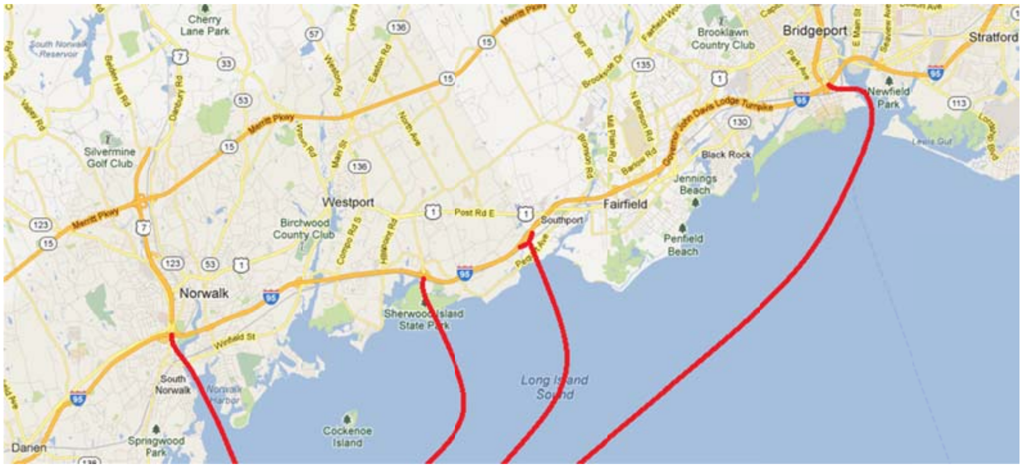


Figure 4: Connecticut Landing Alternatives

Option 1 is located at Norwalk, CT. This will utilize an existing interchange which will save on construction costs and reduce impact during construction. Unfortunately, this option will cross over an active harbor and will disrupt ship traffic.

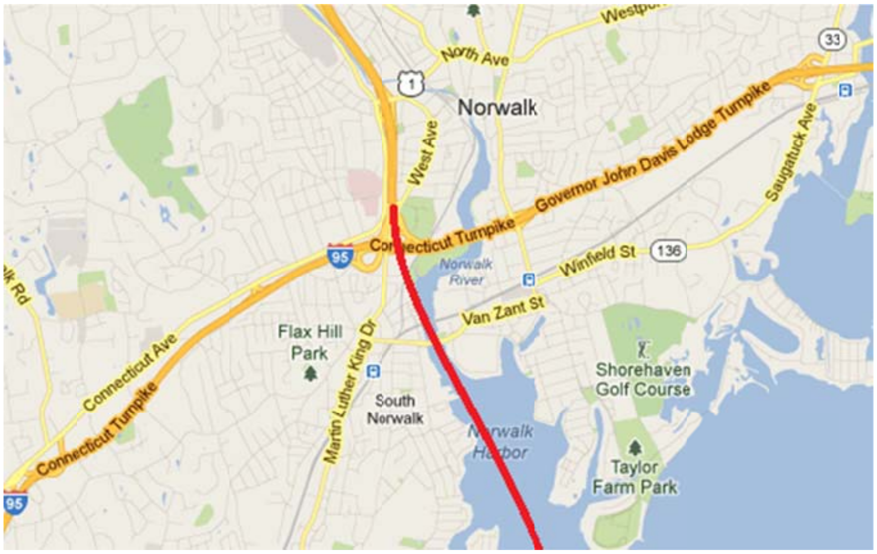


Figure 5: Norwalk, CT Landing Alternative

Option 2 is located at Sherwood Island, CT. This option will also utilize an existing interchange but unfortunately also removes State Park space. Since the only viable option in New York will also remove park space, it is unlikely that the public will agree to loss even more park space.

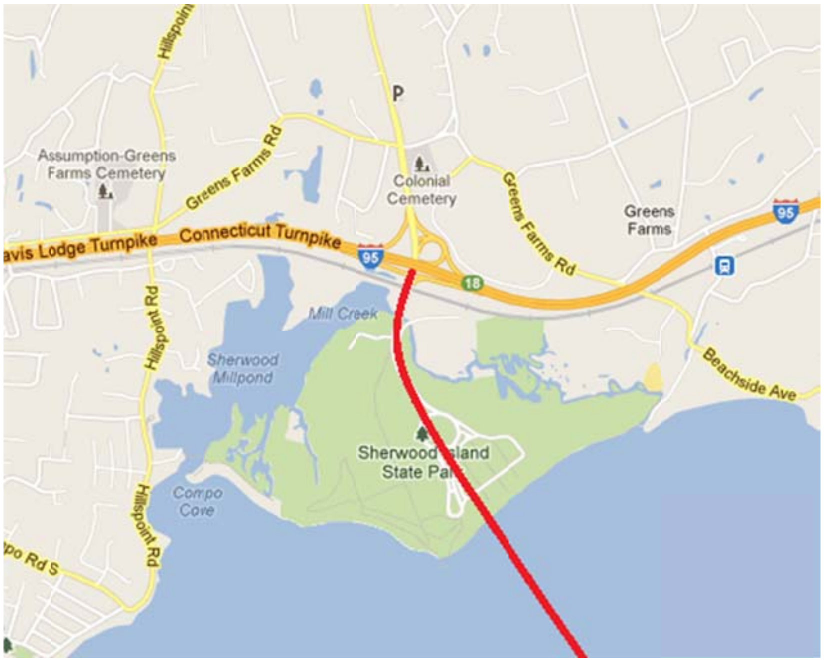


Figure 6: Sherwood Island, CT Landing Alternative

Option 3 is located at Southport, CT. This option will require the construction of a new interchange and has space limitations. Major concerns are private property buyouts and commuter rail interference.

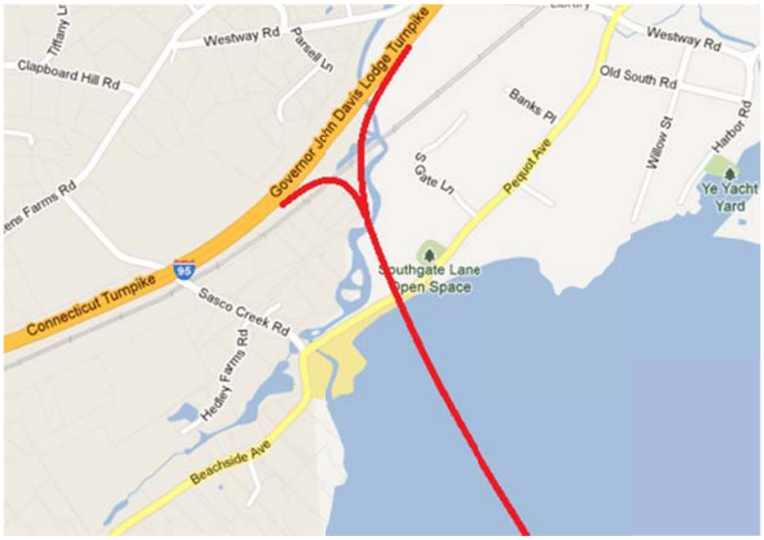


Figure 7: Southport, CT Landing Alternative

Option 4 is located at Bridgeport, CT. This option is our most viable solution and utilizes an existing interchange with minimal private property buyouts. Another positive of this alternative is the connection to Route 8 which extends into Connecticut and connects to other major arterials. A negative of this option is that it will require a 3 mile extension of the bridge as compared to the other alternatives. Although the extension will be in shallow water, construction costs will be at least a hundred million dollars.

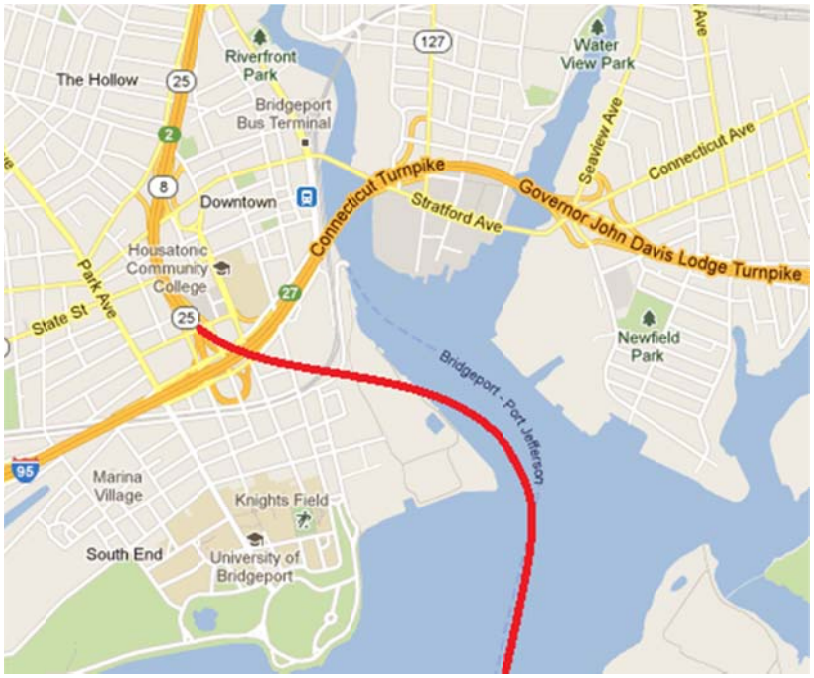


Figure 8: Bridgeport, CT Landing Alternative

Tunnel Dimensions

The cross-section was selected from essential design parameters. The wall thickness was still to be determined. For this determination the load on the tunnel was considered to be the pressure from the water. This is referred to as hydrostatic pressure. Hydrostatic pressure increases with depth. It needed to be calculated how much pressure would be exerted on the tunnel at a depth of 90 feet. This was done using a combination of the hydrostatic pressure equation and the equation for the wall thickness of a pipe. It was found that with a factor of safety of 2.5 the wall thickness would have to be 7.5 feet. The cross section of the final tunnel can be seen in Figure 9, and the detailed calculations in Appendix C.

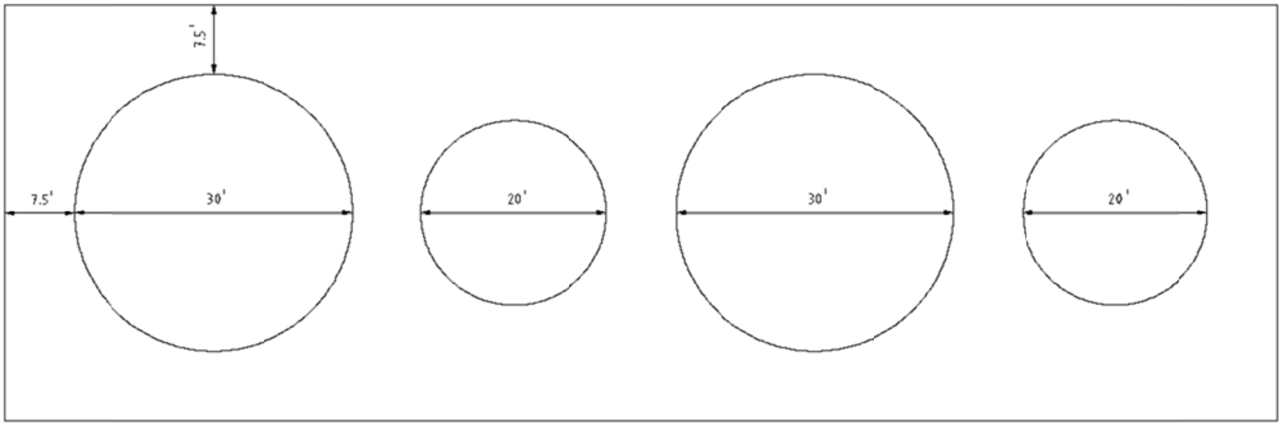


Figure 9: Final Tunnel Cross Section

Tunnel Fabrication & Transportation

In order to withstand hydrostatic pressures, it is necessary to use Cast-in-place concrete tunnel sections for both the durability and versatility. CIP concrete sections allow the designer to use a custom shape such as the unique shape of the tunnel cross-section chosen for this project. The CIP concrete tunnel sections are fabricated in lengths of 300 to 400 feet, and are constructed with watertight joints. It is essential to keep the tunnel sections secured in all aspects of transportation as minor cracking can lead to incidents as small as leaks, or as fatal as full tunnel flooding. This is especially important when floating as there are many opportunities for collisions with waterway traffic and existing structures.

Tunnel Construction Methodology

In order to construct the tunnel sections, the first step is to excavate a trench in the soil bed of the waterway. This most common practice for this kind of trench is to use a clamshell dredger or cutter suction dredger. This process involves two stages, the removal of bulk materials and trimming. The bulk material is removed until the elevation of the trench is approximately 3 feet above the final dredge level, which is when the process changes to trimming methods. The trimming method allows the excavator to polish the bottom of the trench and fine grade it. The material dredged, if suitable, can be used for backfill for the build-up of the islands. This is advantageous because it saves on disposal and material costs. As was shown in the soil information, the dredged material will be acceptable for use as backfill as it is durable enough to withstand the loads of the islands.

After the trench is finalized, the tunnel foundation must be prepared. There are two types of foundations that can be used, continuous bedding and individual supports. Continuous bedding should be 20 inches to no more than 4.5 feet, and the foundation can be placed before or after the tunnel sections are placed. The process in which it is placed before the tunnel elements is called screeding, which is the process in which the material is smoothed in forms until uniformity is reached. The process of inserting the foundation after the tunnel elements have been placed involves, first placing the tunnel elements in the trench on temporary supports. Then processes such as sand jetting, sand flow and injecting grout are used to place the foundation.

Individual support foundations consist of driven piles. The piles are designed to resist all applied compression, uplift and lateral loads, and any down-drag loads from compressible soil. Once the tunnel sections are in their final positions the connections to the piles are made. The space between the bottom of the tunnel and the trench is then filled with granular material. Pile foundations are rarely used, and in the case of this tunnel continuous bedding foundation has been selected.

The next step is to prepare the elements for immersion and lowered. This can be done with a catamaran, pontoons, or cranes. The elements are lowered and placed against the preceding section. The joints are then dewatered. Settlement is essential and must be monitored after placement.

The final process of construction is backfilling. This consists of locking fill, general backfill, and a rock protection blanket. The selected locking fill is placed in the trench to a level of half of the tunnel element height. It should extend 6 feet horizontally and on a slope of 1:2. Locking fill must be granular, clean, sound, hard and durable material. This material may include crushed sound rock or gravel, well graded sub-angular sand, or free-draining sand fill. General backfill is then used to fill the remainder of the trench to the level of the preexisting seabed level. The dredged material from the trench is generally used, and in this case used as the backfill. Finally a protective rock blanket is placed over the general backfill. This material generally consists of dense, clean, angular pieces of 1 – 10 inch newly quarried rocks. Figure 10 shows the cross section of a typical tunnel and the different backfills used.

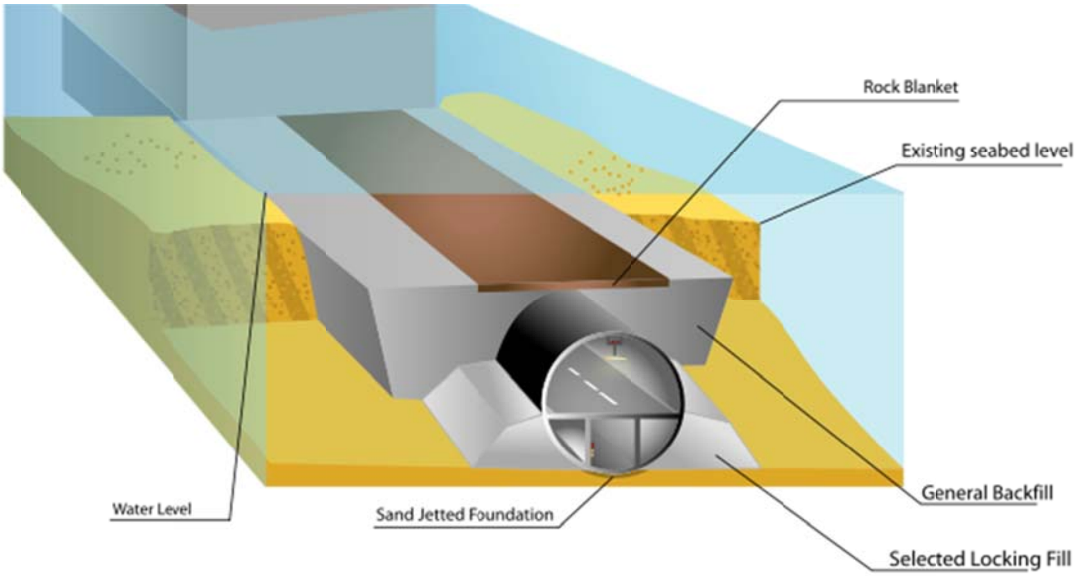


Figure 10: Cross Section of Immersed Tunnel with Backfill

Sea Floor Material

A core sample found the material at the location of the proposed tunnel is gray-brown, moderately well-sorted, medium sand. Appendix D shows the core sample information and the surficial sediment map of the sound. The material is a soft material and will allow for easier removal, as a Tunnel Boring Machine will not be necessary. This material will also be able to be utilized for backfilling of the tunnel. This will save on disposal costs and material costs.

Man Made Islands

For transitioning from the trestle sections into the tunnel, two man made islands will need to be constructed. Both islands will need to be constructed big enough to accommodate this transition as well as space for public use. We are proposing that each island be one square mile in area. This size will provide a more than adequate compensation for the repurposed State Park land utilized for the New York landing. The islands will be constructed with a 2 to 1 slope except where to accommodate the tunnel which requires a slope no greater than 4% as required by code. The island size and slope lead to a total amount of 170 million cubic yards of material needed per island.

The Islands will be constructed by placing a ten foot rock dike perimeter on the seafloor. The dike will then be surrounded with two layers of larger stones and filled with material recovered from dredging for the tunnels as well as from outside sources. Since it is often expensive to dispose of excess soil in Long Island due to space limitations, most of the outside material can be obtained from surrounding construction companies for free or relatively inexpensively.

Public access to the islands must also be considered. On the approaches to each of the islands, a separate lane will run for a quarter mile. This will prevent any disturbance to traffic flow entering the tunnels. On the islands will accommodate three hundred parking spaces which will service both a park and restaurant. Additional amenities for the islands include fishing and boat docks.

Trestle Sections

The Trestle sections are low level trestle over shallow water, with depths between 30 and 60 feet. It will be 30 feet above mean water level to accommodate small boat traffic and protect against waves from strong storms. The trestle structure itself will be made of precast prestressed concrete sections of 75 feet lengths. They will be supported by hollow precast prestressed cylindrical piles. The piles will be filled with sand to withstand any collisions. The piles will be supported by bent caps. The trestle sections were chosen for their ease of construction and construction material. The tunnel elements are also precast concrete. As a part of the final design a concrete casting plant will be constructed along the coastline of either the Connecticut or New York landing. This will be where the tunnel and trestle elements will be fabricated.

Roadway Design

Due to the length of the bridge sections, it is important to consider the lanes available on the bridge. There are two traffic lanes in each direction at twelve foot widths and a six foot shoulder on either side for emergency pull-offs. However, in the event of an emergency, traffic would jam in the two lanes, preventing emergency vehicles from reaching the incident. A solution to this issue would be the insertion of a fifth lane between north and southbound traffic. The lane would only have to be 10 foot wide to accommodate the emergency access and should be enclosed with movable median barrier. As seen on Philadelphia bridges such as the Ben Franklin Bridge, movable barrier and the vehicles to move it are convenient solutions to the need to allow emergency access without disturbing traffic.

Toll Booths

The bridges in Manhattan range from \$5 to \$13 a car and more for 2- and 3-axle trucks. With the estimated income from travelers, the cost of the bridge can be replenished in a matter of a few years depending on the settled cost per vehicle.

The toll booths can also extend to the bike/pedestrian lane. This would allow the authority to close this lane during inclement weather or during times of emergency. By allowing the toll booth to extend, a control over life safety is added.

Summary & Conclusions

During the course of this period, important design factors and criteria were analyzed for consideration of the feasibility analysis. The first factor was the landings on either side of the link. On the New York side, it was determined that the Sunken Meadow Parkway is to be extended through the park and into the bridge approaches. Upon searching through the Connecticut landing, it was found that more research is needed to zone in on one specific point for the bridge approach. This landing was left open ended as I-95 is within a mile of the shore for about a four mile stretch.

The next focus point was the bridge-tunnel system alignment. Prior to the proposal, it was determined that the system had to be a bridge-tunnel based on the sound depths and crossing lengths. It was discovered that based on the contour lines, it was more feasible not to make the crossing straight across the sound, but rather move it with the contours, keeping with the lowest depths possible while making a reasonable crossing shape.

Once it was determined where the link was going to cross, it was necessary to determine how the tunnel section was going to be laid out. Several cross sections were considered, with the third option being the best as it was proposed for a tunnel one and a half times the length of the tunnel section of this crossing. However, ventilation standards had to be met before the cross section could be optimized.

The ventilation calculations including only a light duty fan system resulted in a carbon monoxide concentration over sixty times greater than the required 10mg/m3 from the transportation standards. Calculations were then performed with jet and transverse fans which resulted in 29.23mg/m3 and 20.29mg/m3 respectively. Although this significantly lowered the carbon monoxide, it is still twice the maximum allowed.

Due to the concentration of carbon monoxide being so high, it was decided that a tunnel be added between the two traffic tunnels as it would lower the concentration to approximately the maximum allowable concentration. This makes it plausible to redesign during the next period to optimize the carbon monoxide concentrations in the tunnels. This solution also lends assistance to figuring out the complex needs of life safety. It allows escape through that third tunnel in the event of an emergency such as a fire. The tunnel is also large enough for emergency vehicles to ride through the tunnel to get to an emergency faster and more safely. This decision helped solve the open issues of life safety and ventilation, making it the decision for the design.

The trestle sections and man-made islands were then finalized. The low level trestle will transition to the tunnel and be anchored by the man-made islands. The islands will be constructed with green areas to replace the parklands, a restaurant, docks, and parking spaces. These design ideas will increase the use of the crossing which will increase the revenue.

The completion of the feasibility analysis allows the final design process to begin. In the final design there will be traffic studies and environmental impact studies. Once the traffic studies are completed, the final decision on toll cost will be done. This along with the additional revenue from the islands will produce a revenue estimate. A rough construction cost is included in Appendix E. A Gantt chart is included in Appendix F, which goes over the timeline of completed tasks for the feasibility analysis.

Appendix A – Life Safety

Life Safety

Life safety is a major concern in considerations for tunnel design, especially a tunnel of this length. The major concern for life safety in tunnels is the event of a fire. In order to prepare for such an event there needs to be fire detection, fire protection, emergency egress, communication systems, and an emergency response plan incorporated into the tunnel design. It is also important to consider the structural and electrical elements in the tunnel in case of a fire. Passengers must be able to exit the tunnel safely while smoke it properly removed from the tunnel.

Design factors such as uni-directional or bi-directional traffic flow, mechanical ventilation system, and traffic congestion contribute to life safety design decisions. The two types of mechanical ventilation discussed in the next section respond to smoke from a fire very differently. Figure 11 depicts a fire in a tunnel that is ventilated by a transverse ventilation system. It is seen that the smoke is directly extracted.

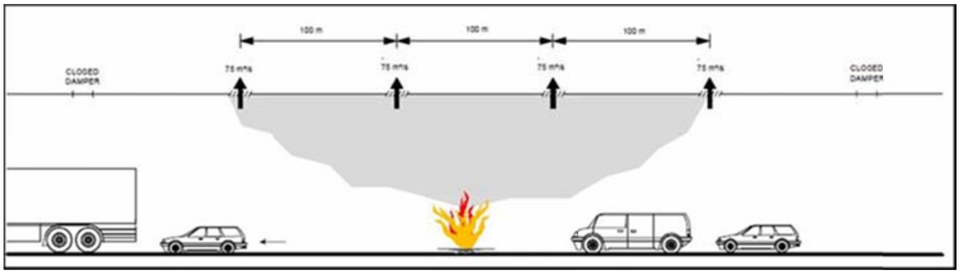


Figure 11: Depiction of a fire in a tunnel with transverse ventilation

Figure 12 shows a fire in a tunnel with a jet fan ventilation system. The smoke is pushed in the direction that the jet fans blow. This could be dangerous because cars past the fires are exposed to smoke that could make visibility difficult and air quality decrease.

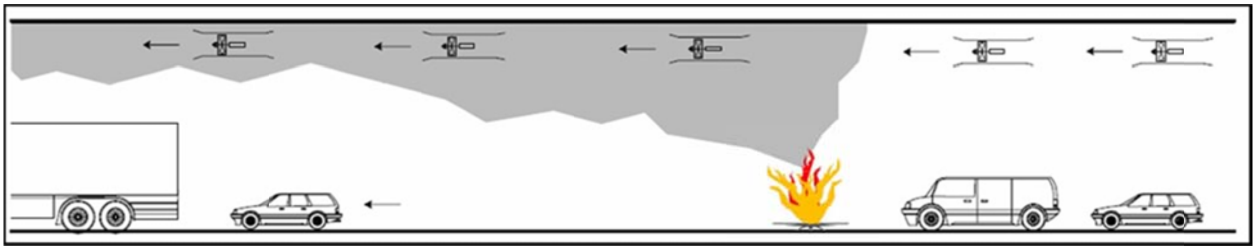


Figure 12: Depiction of fire in a tunnel with longitudinal ventilation

Life safety is one of the main concerns in the design process of a roadway tunnel. It can be seen that this is directly related to ventilation, because the largest life safety threat is a fire.

Appendix B – Ventilation

Ventilation

Ventilation calculations are mandatory for this feasibility analysis as the tunnel needs to maintain a carbon monoxide concentration of less than 10 mg/m3. A first calculation was done using fans blowing at 5 mph. This number is over sixty times too large to meet standards set for carbon monoxide levels in tunnels.

It would be impossible to ventilate a tunnel of this length naturally. There are two different kinds of mechanical ventilation systems used in tunnels. They are longitudinal and transverse ventilation systems. Longitudinal ventilation can be used by injection or jet fans. Transverse systems use either full or semi-transverse processes.

Natural Ventilation

Ventilation calculations are mandatory for this feasibility analysis as the tunnel needs to maintain a carbon monoxide concentration of less than 10 mg/m3. As a first attempt, Equation 1 was used to calculate the exhaust conditions based on a 5mph fan.

$$Equation\ 1: \quad \frac{E}{Q} = \frac{(\#\ of\ vehicles\ per\ hr) * (Length) * (Concentration)}{(Width) * (Height) * (Fan\ Speed)}$$

$$\frac{E}{Q} = \frac{\left(1000\,\frac{veh}{mi}\right) * (4mi) * (49000\,\frac{mg}{veh-mi})}{(4.27m) * (9.14m) * (8046.72\,\frac{m}{hr})}$$

$$\frac{E}{Q} = 624.11\,\frac{mg}{m^3}$$

This number is over sixty times too large to meet standards set for carbon monoxide levels in tunnels. The ventilation system needs to be changed to ensure that the carbon monoxide is brought to a number below the acceptable levels.

Longitudinal Ventilation Systems

Longitudinal ventilation creates a uniform flow of air along the tunnel. It is mostly seen in rectangular geometry tunnels. It is a more economical benefit when compared with transverse ventilation. It does however, have some disadvantages. It is mostly used in unidirectional traffic flow. This would not allow a tunnel to accommodate bidirectional traffic flow in case the other roadway tunnel needs to be shut down for maintenance. It is also a problem when it comes to smoke control from a fire. The smoke is pushed through the tunnel along with the traffic flow. This is an important consideration because of life safety concerns.

In the process of injection ventilation systems air is injected into one end of the tunnel which mixes with air from the piston effect of traffic. This is most effective in unidirectional traffic flow. The benefit is that it uses a small amount of fans and no air ducts.

In the process of using jet fans in longitudinal ventilation systems, jet fans are mounted to the ceiling of the tunnel. It is an advantageous ventilation alternative because it eliminates fans in a separate building. This process increases the dimensions of the tunnel, which along with life safety concerns makes this option less appealing. Figure 13, below, shows how longitudinal ventilation works.

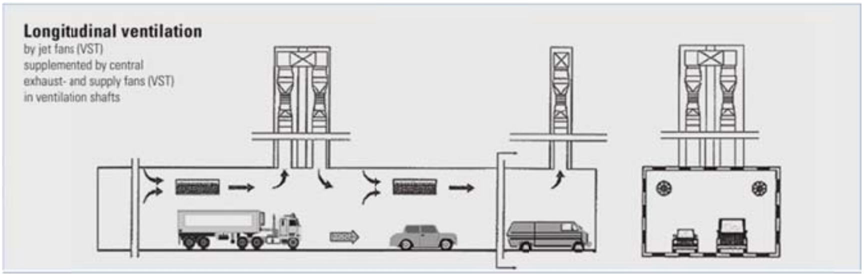


Figure 13: Longitudinal Ventilation Schematic

A calculation was done to determine the carbon monoxide concentration for the 4-mile long tunnel utilizing jet fan ventilation. This was done by using the following process. Equation 2 was used to determine the mean flow velocity of a longitudinal ventilation system.

$$\text{Equation 2: } a*V^2 + b*V + c = 0$$

Where

$$a = \frac{1}{2}*\rho*C_d*A_{vehicle}*N_{vehicle} - \frac{1}{2}*\rho*K_{port} - \frac{1}{2}*\rho*A*f*\frac{L}{Dh}$$

$$b = -\rho*C_d*A_{vehicle}*N_{vehicle}*V_{vehicle} - \rho*N_{fan}*A_{fan}*V_{fan}*\eta_{fan}$$

$$c = \frac{1}{2}*\rho*C_d*A_{vehicle}*N_{vehicle}*V^2_{vehicle} + \rho*N_{fan}*A_{fan}*V^2_{fan}*\eta_{fan}$$

Once the velocity was determined the emission strength was found using Equation 3.

$$\text{Equation 3: } e_c = \frac{N*E*1000000}{1000*Vv*A*3600}$$

The carbon monoxide concentration was then found using Equation 4.

$$\text{Equation 4: } C(x) = \frac{ec}{V}*x + C(0)$$

A value of 29.23 mg/m3 was found from this calculation. It is still above the acceptable limit.

Transverse Ventilation Systems

A semi-transverse ventilation system can work in two ways. The first is by adding fresh air throughout the length of the tunnel. The second is by extracting polluted air throughout the length of the tunnel. These processes still utilize mechanical fans, but they also have separate duct work for the air extraction or supply. This option does allow for the extraction of air flow in the case of a fire; however it does still utilize longitudinal air flow which cannot be controlled.

Full-transverse ventilation uses both fresh air supply and polluted air extraction. This also utilizes separate duct work. Typically fresh air is supplied from the bottom of the tunnel and polluted air is extracted from the top of the tunnel. It is best for fire control because it extracts the smoke and has virtually no longitudinal airflow. It is utilized mostly in longer tunnels because of its high construction and operating costs. Figure 14 demonstrates how the full transverse ventilation system works.

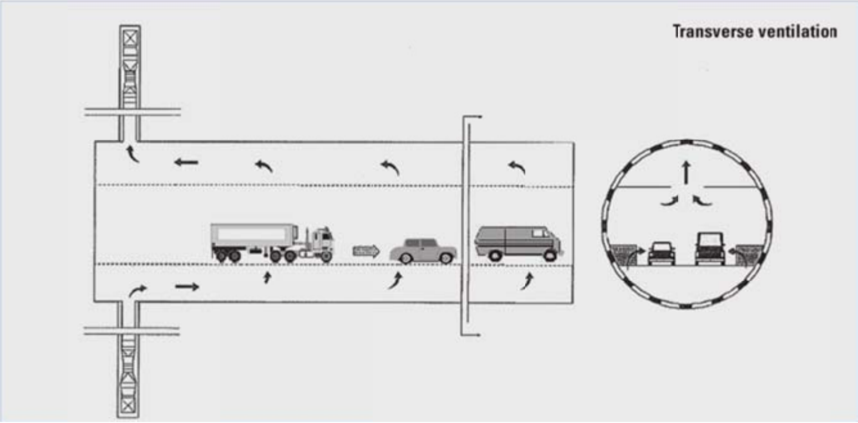


Figure 14: Full Transverse Ventilation Schematic

A calculation was done to determine the carbon monoxide concentration for the 4-mile long tunnel utilizing full-transverse ventilation. The same mean flow velocity was used from the jet fan calculation. An additional parameter of the ventilation flow rate (Q) was used and assumed to be 280 m3/s in equation 5 where qi and q0 are the inflow and outflow rates respectively.

$$Equation\ 5:\ q_i = q_0 = \frac{Q}{AL}$$

The result from Equation 5 was then used in the Equation 6 to determine the carbon monoxide concentration.

$$Equation\ 6:\ C(x) = \frac{ec+0.05}{qi} + \left(C(0) - \frac{ec+0.05}{qi}\right) e^{(-qi*x/V)}$$

Equation 6 yielded a result of 20.29 mg/m^3. This is still above the accepted concentration, meaning that additional alternatives had to be considered.

Re-evaluating the Cross Sections

Due to the reduction of the exhaust coming to just over twice the allowable amount, changes need to be made to the cross section. A separate tunnel needs to be implemented with the main purpose being ventilation. The current two tunnel configuration with air flow that follows the flow of traffic as the siphon effect is the only source of the movement of air. It is proposed that a third tunnel be inserted between the two travel lanes with fan housing at the half way point.

This configuration allows for 25mph fans blowing in either direction in the tunnels. The airflow then changes as shown in Figure 15, below. The air now only has to be moved half the distance and concentrations can be lowered to less than 10 mg/m3. This final cross section design also aids in the development of life safety systems.

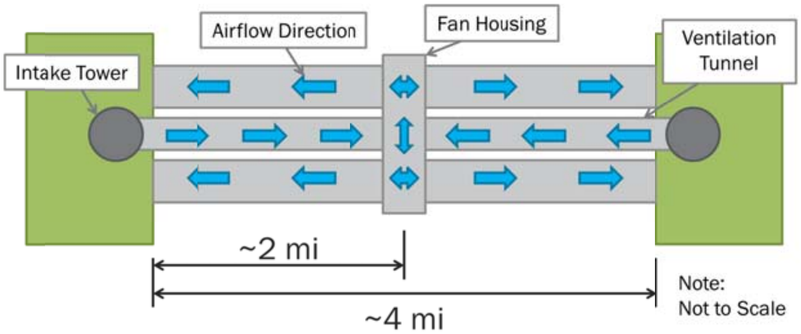


Figure 15: New Airflow Pattern With Separate Ventilation Tunnel

Emergency vehicles can drive through the center tunnel to reach an accident or fire faster. It can also be used as an escape route for people in the event of an emergency. By implementing a sturdy escape/emergency plan, riders will be more comfortable entering a tunnel that they know they can get out of.

Ventilation Parameters

Parameter	Value
Tunnel Length L (m)	62337.38
Tunnel area A (m^2)	56
Hydraulic diameter of tunnel D_h (m)	7.8
Traffic volume N (vehicles/h)	1000
Total number of vehicles in tunnel $N_{vehicle}$	890
Mean velocity of vehicles $V_{vehicle}$ (m/s)	19.44
Vehicle speed V_v (km/h)	70
Mean drag coefficient of sedans C_d	0.25
Mean frontal area of sedans $A_{vehicle}$ (m^2)	2.5
Vehicle CO Emission Rate E (g/vehicle-h)	40
Air density ρ (kg/m^3)	1.18
Friction factor f	0.02
Tunnel entrance loss coefficient K_{port}	0.6
Jet fan number	100
Jet fan diameter d (m)	1.6
Jet fan outlet velocity V_{fan} (m/s)	30
Jet fan efficiency η_{fan}	0.8
CO concentration at tunnel entrance, C(0) ($\mu g/m^3$)	100
CO concentration inflow of transverse ventilation system C_i ($\mu g/m^3$)	10
CO deposition rate k (s^{-1})	0

Appendix C – Tunnel Calculations

The first step in calculating the hydrostatic pressure was to use calculus and the integration method. Figure 16 is a cross section of a typical tunnel at a depth of 90 feet and a diameter of 30 feet. These calculations were done in SI units and later converted to pounds per square inch.

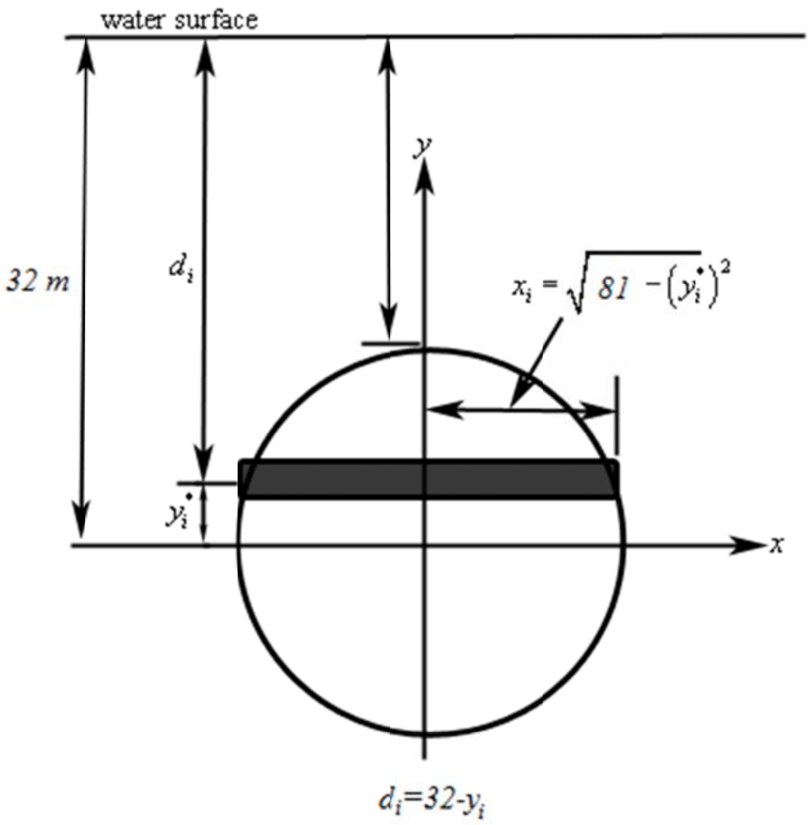


Figure 16: Cross section of a typical tunnel at a depth of 90 feet and a diameter of 30 feet

The depth below the water surface of each strip is,

$$d_i=32-y_i$$

and that in turn gives us the pressure on the strip of:

$$P_i=\rho g d_i = 9810\ kg/m^2s^2(32-y_i)$$

The area of each strip is:

$$A_i = 2\sqrt{81 - yi^2}\ \Delta y$$

The hydrostatic force on each strip is:

$$F_i = P_iA_i = 9810(32-y_i)(2)\sqrt{81 - yi^2}\ \Delta y$$

The total force on the tunnel is:

$$F = \lim_{n\to\infty} \sum 19620\,(32-y_i)\sqrt{81 - yi^2}\ \Delta y$$

$$= 19620 \int_{-9}^{9} (32-y_i)\sqrt{81 - yi^2}\ dy$$

$$= 19620 \int_{-9}^{9} 32\sqrt{81 - yi^2}\ dy - 19620 \int_{-9}^{9} y_i\sqrt{81 - yi^2}\ dy$$

$$= 4071.5$$

$$F = 19620 * 4071.5 = 7.9882 \times 10^7\ \text{kg/ms}^2 = 11586\ \text{psi}$$

The hydrostatic pressure was found to be 11586 psi. This was then used in the wall thickness of a pipe calculation that can be found below.

$$t = \frac{p*d*F.S.}{2*fy}$$

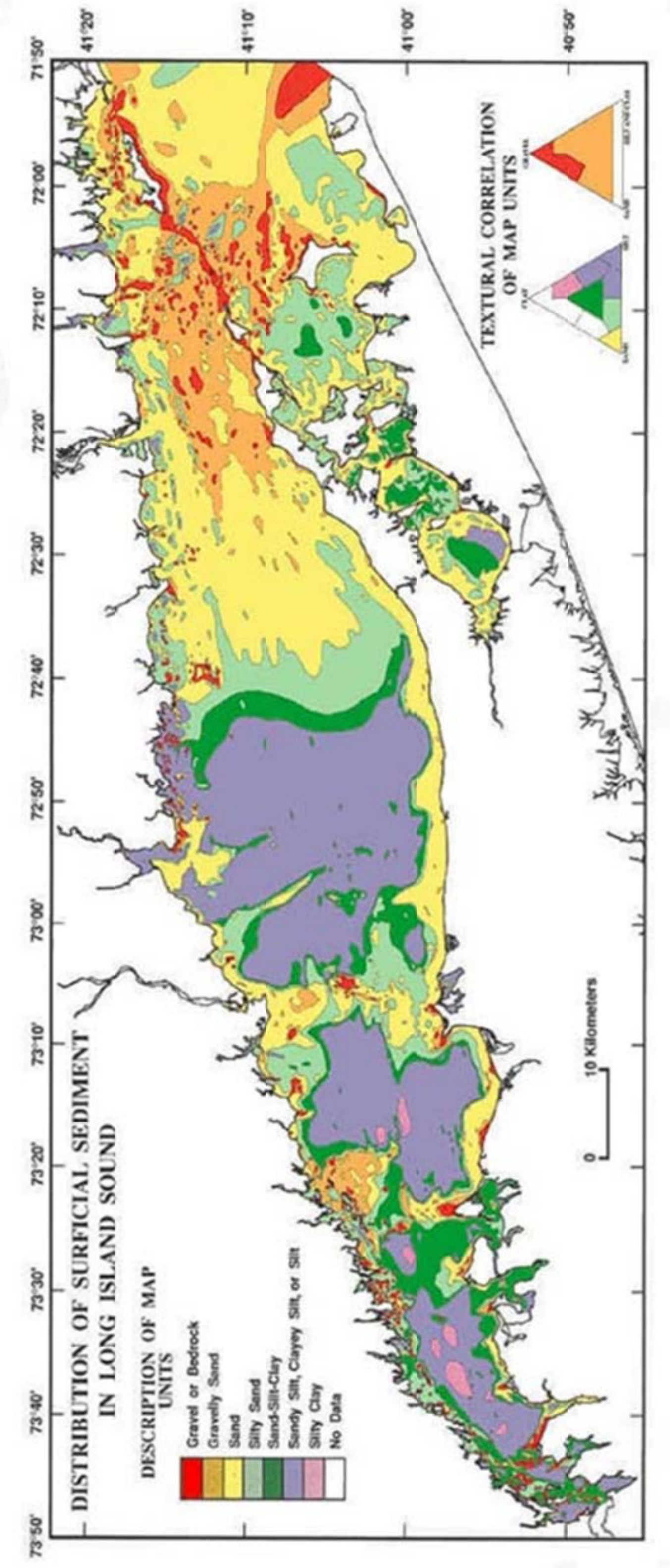
where,

t=thickness of wall
p=hydrostatic pressure
d=tunnel diameter
F.S. = factor of safety
f_y = yield strength of steel reinforcement

$$t = \frac{(11586\ psi)(30ft)(2.5)}{2*60{,}000psi} = 7.2\ \text{ft}$$

A factor of safety of 2.5 was used to get a tunnel thickness of 7.2 feet. The addition of the 7.2 feet walls to the 30 foot height of the tunnel gives a final 44.4 feet.

Appendix D – Soil Sample Map – Long Island Sound



Appendix E – Cost Estimating

Construction Costs

In order to determine total construction costs, current construction rates for building immersed tube tunnels and trestle bridges were used. In today's market, the following numbers apply:

Section	Unit Cost	Quantity	Total Costs
Trestle - Bridge	$250,000/mile	8 miles	$2,000,000
Immersed Tube Tunnel	$1.2 Billion/mile	4 miles	$4,800,000,000
Islands	$500 Million/square mile	2 square miles	$1,000,000,000
Land Buy-Out	$1.5 Billion	1 Lump Sum	$1,500,000,000

The total construction cost is $7,302,000,000.

The Trestle, Tunnel and Island costs are based on 2013 costs for the bridge-tunnel work for the Chesapeake Bay Bridge-Tunnel construction. The land buy out costs are estimated by including the cost to purchase the more expensive private properties in Connecticut as well as the estimated cost to purchase state park land in Long Island, NY. This also includes an estimated budget needed to repair any damages that may occur to remaining park land during construction.

Feasibility Analysis and Design Costs

Feasibility Analysis:

There were 4 engineers that each spent 750 hours on the project. Using a rate of $50 per hour, a total of $150,000 is to be paid for the feasibility analysis performed.

Design Costs:

Design Costs are approximately 3% of the construction costs, which includes payment throughout the project as changes are needed to the designs.

3% X $7,302,000,000 = $219,060,000

Total Project Costs

Construction Cost	$7,302,000,000
Feasibility Analysis	$150,000
Design Costs	$219,060,000
Total Cost	**$7,521,210,000**

Appendix F – Feasibility Analysis Schedule - Complete