

Selection of alignment and tunnelling methods in urban settings

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SYNOPSIS: One of the challenges of the 21st century in urban settings is to provide solutions to increasing traffic. The Capitol Region around Washington D.C., USA and the Dulles Corridor Metrorail Project (DCMP), an extension to Dulles Airport (IAD), Virginia is representative of this task. Due to the congestion at the surface, the use of underground space is very often the only means of building new arteries through urban areas. This paper discusses the selection of alignment and tunneling methods in urban settings using the example of the Tysons Corner Tunnel, one keystone of the DCMP. A wide range of alignments and tunnel options was considered for the Tysons Corner segment that involves about 6 km of track and four stations. After consideration of many options that involved deep EPBM single track tunnels, shallow NATM tunnels, and a double track large bore tunnel with stations concept for the entire Tysons Corner alignment, the design now being implemented in the construction involves two 520 m long soft ground NATM tunnels with adjoining cut-and-cover sections. This paper discusses the process that led to the selection of the short NATM tunnels as the most feasible of the options considered for Tysons Corner.

1. INTRODUCTION

Worldwide, urban areas are becoming more and more congested. With the growth of these regions, traffic is increasing. Space on the surface is available only in a limited amount. However, with the overall growth, the value of space on the surface also increases or is simply no longer available. Very often there is just one last opportunity – to go “underground”. One major challenge during the early design phase of transportation projects is to find a feasible and reasonable alignment. The impacts on this decision process are manifold and can be driven by economic interest, budget constraints, impact on the environment, political interests, schedules, or technical considerations. All of these impacts are elements of a complex matrix and influence each other to some degree. A very tight link exists between the selection of an alignment and technically and economically feasible tunneling methods. Tunnelling technology nowadays in both machine- and conventionally-driven tunnels has very few limits and a wide range of solutions is available. This article focuses on finding an alignment and a tunnelling method to realize a mass transit project in a rapidly growing

business corridor and urban setting. To exemplify this process, it will be illustrated by the example of the Dulles Corridor Metrorail Extension Project (DCMP) through Tysons Corner in Northern Virginia, USA.

The region around Washington D.C., including southern parts of Maryland and Northern Virginia is known as the Capitol Region and is similar to various conurbations around the globe. The public transportation in this region is served by the Washington Metropolitan Area Transit Authority (WMATA), which operates a bus as well as metrorail system. The purpose of the 37 km long Dulles Corridor Metrorail Extension Project (DCMP) is to improve the service of the metrorail system in the Capitol Region in Northern Virginia and to connect the Washington Dulles International Airport (IAD) with Washington D.C. through the so-called “Dulles Corridor.”

The implementation of the project began with preliminary engineering in mid-2004 under a public-private partnership agreement between the Virginia Department of Rail and Transportation (DRPT) and Dulles Transit Partners (DTP), a Joint Venture led by Bechtel, the design-builder of this project. Other partners in financing the project and

approving the engineering for the design-build effort are the Federal Transit Administration (FTA), DRTP, the Metropolitan Washington Airports Authority (MWAA), Fairfax and Loudoun counties, the towns of Reston and Herndon, and WMATA as the technical reviewer which will operate the system. At the end of 2006, ownership of the project was transferred from DRPT to MWAA, which engaged a Program Management Support Services (PMSS) consultant team that is led by Carter-Burgess.

Figure 1 displays the project alignment within the Dulles Corridor and shows the location of the Tysons Corner section (Figure 2), which is part of the 19 km Phase 1 of the project from Falls Church

to Wiehle Avenue. This segment is scheduled to be operational by 2013. The alignment of Phase 1 is generally at grade or elevated, with the exception of a short underground section at Tysons Corner. Tysons Corner is a local business center and includes two large shopping malls. The 6 km long Tysons Corner alignment includes four Stations: Tysons East, Tysons 123 (at State Route 123), Tysons Central 7 (at State Route 7), and Tysons West (see Figure 2). The tunnels at Tysons Corner are located between Station 123 and Tysons Central 7. The final design for the tunnel segment is completed and expected to be issued for construction in 2008 and tunnel construction is scheduled to begin in late 2008/early 2009.

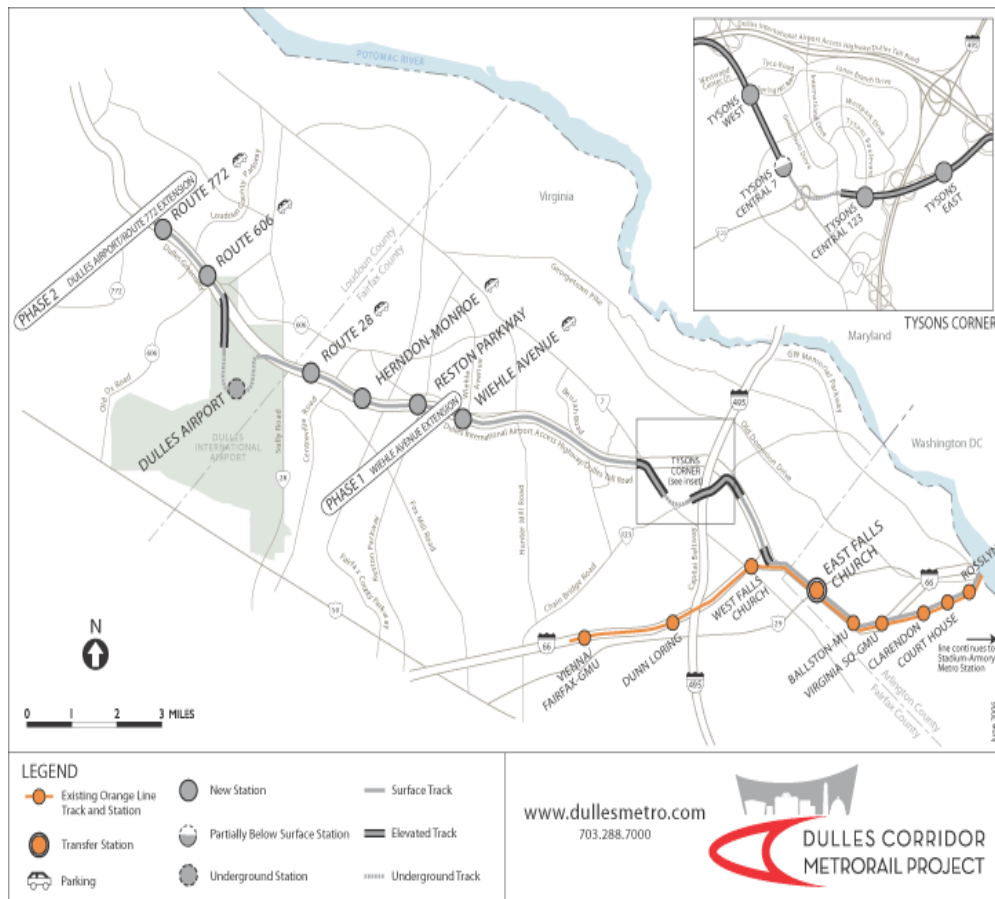


Figure 1. Dulles corridor Metrorail project (DCMP)

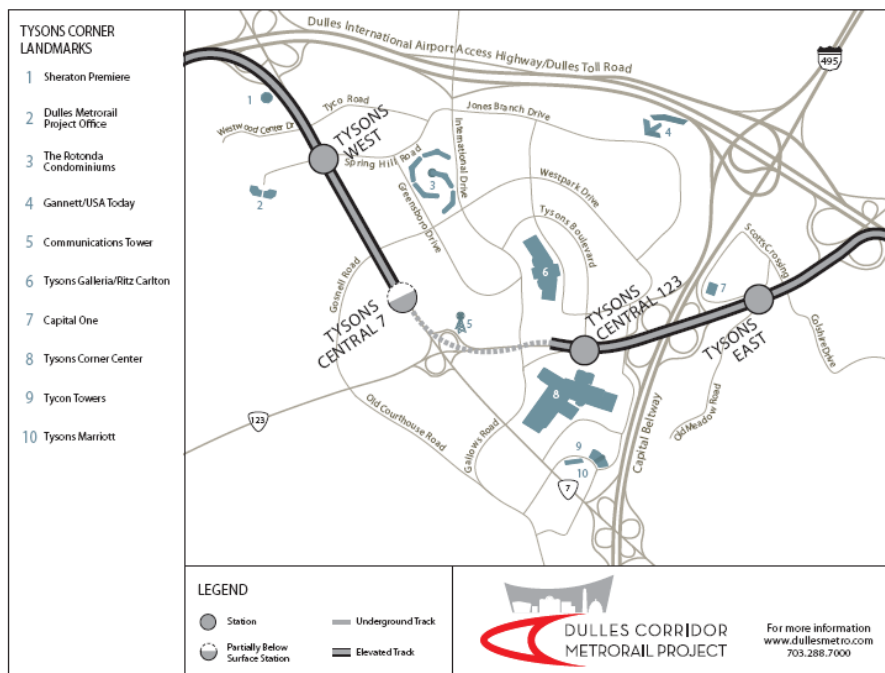


Figure 2. Project alignment at Tysons corner

2. SELECTION PROCESS IN TUNNELLING

Usually large transportation projects have several design stages in which the design becomes more defined and detailed from one step to the next. One very important milestone in these stages is the establishment of the final alignment of the project. This milestone was reached during the Final Environmental Impact Statement (FEIS) (FTA, 2004). The FEIS reviewed several feasible alternative routes through Tysons Corner. Of these alternatives, the Locally Preferred Alternative (LPA) (DRPT, 2002) was selected by WMATA and approved by all other agencies.

During Value Planning and at the beginning of the Preliminary Engineering (PE) a number of horizontal and vertical alignment adjustments within the boundary of the LPA through Tysons Corner were considered and adopted for cost reduction. Finally, at mid-point of the PE stage, on request of the local County government, a new alignment option at a critical area of Tysons Corner was introduced to pursue with the PE. With this change the alignment was moved to the median of the divided, wide artery (Route 7) with four traffic

lanes in each direction. The new alignment was established to lessen the impact on the adjacent properties. It went through a supplementary FEIS process and was approved for final development of PE documents as the modified LPA Alignment. This modified LPA went again through a series of vertical alignment adjustments mainly to reduce project costs to meet a formula for Federal funding requirements.

During the advanced stage of the PE an unsolicited concept for a large bore tunnel alignment through entire Tysons Corner (approximately 6 km) was introduced. On the client's request this proposal had to be evaluated and virtually stopped the PE process for several months.

This paper discusses the options of long versus short tunnels and the decision process that led to the final design. For the short tunnel alignment, it discusses several different tunneling methods, including cut-and-cover, TBM, and NATM.

The soils encountered along the tunnel alignment include mainly residual soils and soil-like completely decomposed rock. The residual soils are

the result of in-place weathering of the underlying bedrock and are typically fine sandy silts, clays and silty fine sands. According to the project classification, the residual soils are identified as Stratum S, which can be divided into two substrata (S1 and S2) based on the consistency and degree of weathering.

Within the tunnel alignment for the low overburden alternative (shallow NATM option), the thickness of substratum S1 varies considerably, from 0 – 0.6 m to almost 10 m. The lower substratum, S2, is similar to S1, but typically exhibits higher strength and is made up of more granular particles. Its thickness within the tunnel alignment ranges from 1.2 m to 18 m. Substrata S1 and S2 will be the predominant soil types encountered during tunnel construction. Only where the tunnel is located deeper in the mid portion of the alignment will tunneling encounter decomposed rock referred to as "D1" in bench and invert. The decomposed rock is a soil-like material but has higher strength. Ground water at portal locations is generally at invert elevation, at the mid-point of the tunnel alignment it rises up to the tunnel spring line.

For the shallow overburden alignment, International Drive is located about 4.6 m above the crown. Deepest overburden cover exists at about mid-point of the alignment with nearly 11.6 m. At the west portal and the transition to the cut-and-cover box the overburden is about 6 m. A plan view indicating arrangement of the tunnels, the shallow location near International Boulevard and the parking garage is shown in Figure 4.

The deeper alignment alternatives with higher overburden require tunneling through a variety of strata and generally have a higher portion in the harder bedrock strata D; typically, the strength increases with higher depth due to the decreasing weathering. The length of tunnel under the groundwater table becomes larger with higher overburden.

Prominent building and infrastructure elements located in the tunnel's vicinity include an underground parking garage at a distance of about 8 m from the outbound tunnel wall and bridge piers of the Route 123/Route 7 overpass, at a clear distance of approximately 14 m from the inbound tunnel. International Drive, a six-lane divided road, is traversed by the tunnel. Overburden above the future tunnel crowns depends on the chosen alternative.

2.1 Large bore tunnel versus short tunnel

Late in the preliminary engineering of Phase 1 a large bore tunnel alternative was proposed by WMATA, in conjunction with an external group. The large bore tunnel alternative would be roughly 6 km long and situate all stations under ground. The envisioned tunnel would have been a large bore, 12.2 m diameter driven tunnel to accommodate two tracks, partially over/under and stacked station platforms inside the tunnel and it would require large and deep excavations for station entrances and for ventilation structures.

The large diameter tunnel option significantly deviated from the selected and approved alignment as portrayed in the FEIS and the preliminary engineering documents; therefore, this new tunnel concept would have involved another environmental approval process, and additional geotechnical studies to be followed by new preliminary engineering design. Consequently, the project would have been delayed by 2^{1/2} to 3 years. The additional projected cost for the tunnel alternative would have likely led to the loss of funding by the Federal Transit Administration (FTA) and substantially delayed the project or possibly jeopardized the entire rail line construction. These factors, and the fact that an additional three years would have postponed traffic congestion relief, made the all-tunnel scheme very problematic.

This underground option has the major advantage that the impact on the surface after project completion is minimized, so a large completely underground option was originally supported by several local developers. As a result, several peer reviews intensively investigated the large bore tunnel option; these reviews focused on environmental impacts on the adjacent environments and structures, new right-of-way (ROW) for cut-and-cover construction of deep entrances and ventilation/egress shafts, construction costs, operating and maintenance costs, and overall project risks.

The longer tunnel alignment led to several additional crossings with a creek and several existing structures. A highway bridge of the Dulles Toll Road would have to be crossed with the 12.5 m bore with only 4.6 m overburden to the bridge pier foundation. Another sensitive crossing would be the drive under a culvert of the environmentally sensitive Scott Run with just 3 m separation. These

crossings present more risks in general, in particular when cutting with a large diameter TBM and an overburden less than one third of the tunnel diameter.

One of the peer reviews studied the existing design and the proposed large bore tunnel with respect to long-term maintenance and operations cost and "non-quantifiable" items. This review concluded that although the cost of rehabilitating the tunnel might be lower, the net savings over 30 years would be about US \$60 million; with respect to overall budget costs, these savings were not significant for the purpose of option evaluation (APTA, 2007).

Although many involved parties supported an underground option, it would have cost from \$250 million to over \$800 million more (based on various estimates) than the mostly elevated and partially at-grade alignment, including short twin single track NATM soft ground tunnels. The DRPT cost estimate was \$500 million more than the LPA-based aerial design through Tysons Corner. Just comparing the cross sections, the large bore is four times larger in volume than one single-track tunnel, and two times larger than two single-track Metro tunnels. In fact, the factor would be even higher than two when comparing the concrete volume installed in the large bore versus two single-track tunnels.

An FTA-requested review report further stated that the large bore tunnel proposal was not "biddable" per FTA or industry standards and lacked a bottom-up cost estimate to provide a confidence level in the project cost. Other serious deficiencies identified included a longer construction schedule, the need for a new subsurface exploration program, and the necessity for additional agency/owner/operator/local coordination that could cause major scope increases during final design and construction (FTA, May 2007).

Finally, the funding parties confirmed that the large bore tunnel option would be more expensive and cause significant project delays and funding risk. The project was requested to continue PE development based on the County modified LPA alignment option for Tysons Corner.

2.2 *Intermediate tunnelling method and combination options*

According to the alignment of the General Plans of the Locally Preferred Alternative (LPA), the Tysons Central 7 Station (Figure 2) and adjoining ancillary rooms were to be constructed in deep cut-and-cover using slurry wall for support of excavation, a TBM for the majority of the deep tunnel alignment, and transition tunnels by cut-and-cover at the ends of the alignment. The two running tunnel sections were divided into two sections:

Section 1 located at the east end of the alignment is 180 m long and has shallow overburden. The crown is generally above the groundwater table in soft ground. Section 2, the remainder of the alignment, is 1,300 m long and generally deeper and below the groundwater table in soft ground and in mixed face conditions.

At the east section of the alignment, the tunnels were to pass underneath International Drive, a busy, six-lane divided road and underneath Route 123, close to an underground parking garage. At its west end it would have been located just south of Route 7 approximately 24.5 m below the surface.

Past WMATA tunneling experience (Rudolf et al., 2007) provided insight into feasible tunnel methods for the geological conditions anticipated. Based on this local tunneling experience and experience from similar underground transit projects, possible tunnel construction methods included: (a) pressure face machines (EPBM) for deep overburden, (b) Shielded TBM, including open-face shields and the New Austrian Tunnelling Method (NATM) for shallow overburden, and (c) cut-and-cover methods.

Due to the ground conditions some of these tunneling methods would have required the use of ground modification methods, predominantly dewatering, but possibly also deep soil mixing, jet grouting, and/or permeation grouting, with the possible need for compensation grouting to limit settlement.

Four alternative construction approaches were developed for the underground structures during the early stages of the preliminary engineering. For each alternative, the running tunnels were divided into two reaches as summarized in Table 1.

Table 1. Alternatives for tunnel construction methods and sections

Alternative	1	2	3	4
Section 1	Cut-and-Cover	NATM	TBM	NATM
Section 2	TBM	NATM	TBM	TBM

The tunnel construction methods were compared using the following criteria:

- Potential for excessive surface settlements or heave
- Tunneling safety
- Potential for uncontrollable ground inflow
- Adaptability to geologic uncertainty and buried obstructions
- Severity of required surface disruption
- Right-of-way and construction easement requirements
- Tunnel construction duration

Advantages of concepts, including NATM, in areas of adaptability and construction easement requirements were offset by construction duration advantages of mechanized (TBM) concepts. TBM concepts had additional advantages over NATM concepts in controlling risks associated with ground inflows in areas of high hydraulic head when using Earth Pressure Balance Machines (EPBM). The cut-and-cover concepts had the significant disadvantages of high surface disruption, construction easement requirements, and construction duration. To further investigate the tunnel construction methods, a formalized risk and cost analysis was undertaken to evaluate the methods considered. A summary table of the findings is presented in Tables 2 and 3.

Based upon the evaluation of these tunnel construction methods and their impacts on the surrounding community, the Combined NATM/TBM Concept, Alternative 4, was recommended for further design development because it allowed mined tunneling methods earlier on in the construction phase, with less surface disruption potential and smaller right-of-way and construction easement requirements. It resulted in the lowest project risk and the most cost-effective

combination of tunneling concepts. Alternative 4 tunneling in Section 2 utilized closed face TBM methods with an Earth Pressure Balance Machine (EPBM); tunneling under the shallow overburden, in particular underneath International Drive, was according to the NATM. The NATM tunneling was laid out to create a tunnel for use as a launch chamber for the TBM. EPBM tunneling was to use a one-pass lining, with gaskets between pre-cast lining segments.

2.3 Final tunnel alignment

Upon completion of the design portrayed in Paragraph 2.2 to a 50% preliminary engineering (PE) level, a cost estimate was developed for this project. As the overall project cost for Phase 1 was significantly higher than that included in the FEIS, a formal cost evaluation and value-engineering program was undertaken. This program demonstrated that major cost savings (approximately \$200 million) would be achieved by building Tysons Central 7 Station as an at-grade structure rather than 24.5 m underground, and by eliminating the tunnels west of that station. Consequently, the at-grade Tysons Central 7 Station configuration was chosen, leading to a modification of the tunnel alignment. The tunnel alignment was lifted significantly in order to situate tunneling favorably with respect to the ground water elevation. A schematic comparison of the 50% PE alignment versus the final PE alignment is shown in Figure 3. These changes led to the shortening of the tunnels by over 50%. This alignment was incorporated into the preliminary engineering plans and became the basis of the design-build contract. The changes to the FEIS alignment, by moving to the median of Route 7, were significant enough to require a supplemental Environmental Impact Statement, which was approved in mid-2006.

Table 2. Tunnelling methods risk comparison matrix

Alternative		1		2		3		4	
Section: Tunneling Method		1: C&C	2: EPBM	1: NATM	2: NATM	1: EPBM	2: EPBM	1: NATM	2: EPBM
Workers' Safety	HIGH								
	MEDIUM								
	LOW								
Cost Overrun	HIGH								
	MEDIUM								
	LOW								
Schedule Overrun	HIGH								
	MEDIUM								
	LOW								
Surface/Utility Disruption	HIGH								
	MEDIUM								
	LOW								
Excessive Surface Settlement	HIGH								
	MEDIUM								
	LOW								
RISK AVERAGE	HIGH								
	MEDIUM								
	LOW								

Table 3. Tunnelling methods cost comparison matrix in US\$ millions

COST COMPARISON	above 58				
	above 54				
	above 50	51.6	59.0	56.8	50.8
	above 46	102 %	116 %	112 %	100 %

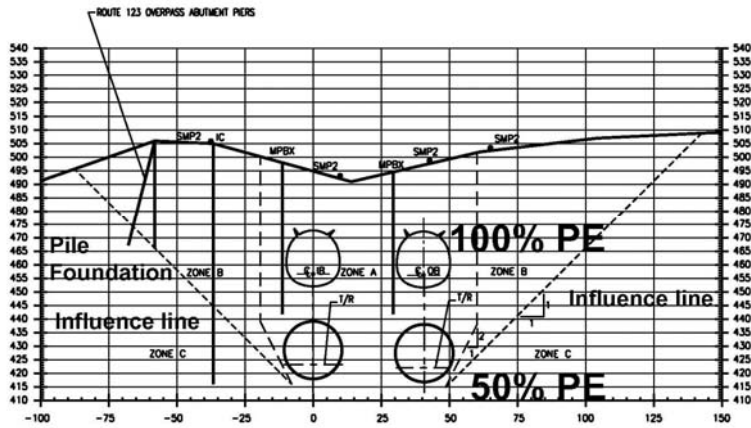


Figure 3. Deep tunnels of the FEIS alignment vs. shallow tunnels of the preliminary engineering

The mined tunnel segment of the final design includes twin single-track NATM tunnels at a length of approximately 520 m each. A short cut-and-cover section adjoins the NATM tunnels at the east portal and a longer cut-and-cover section exists at the west portal. These tunnels will be constructed

in soft ground and will be located adjacent to existing structures and utilities that are sensitive to ground movements. The alignment and elements of the short tunnels at Tysons Corner are shown in Figure 4.

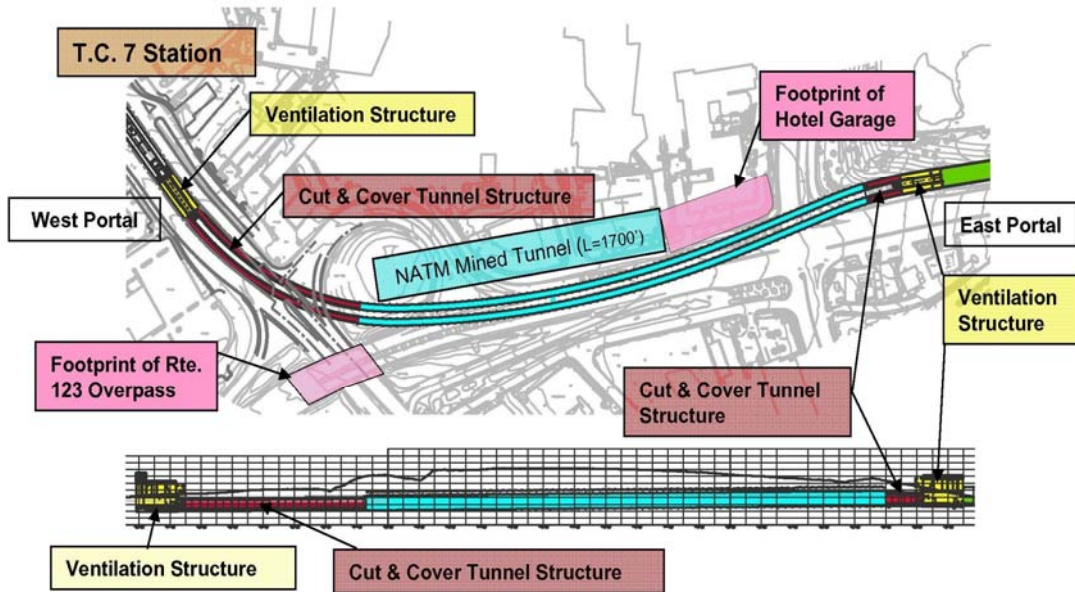


Figure 4. Design-build tunnel alignment

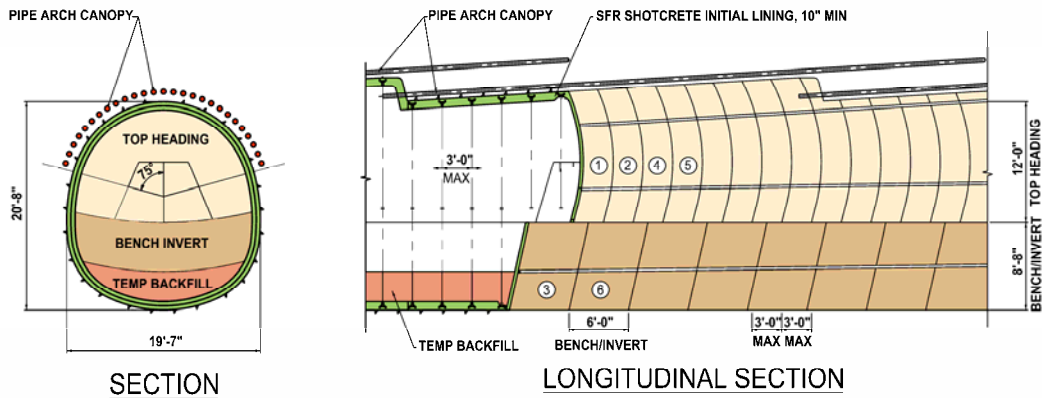


Figure 5. NATM Tunnel with double pipe arch pre-support for shallow tunnelling

Because of the shallow depth, the prevailing soft ground conditions, the relatively short tunnel length, and the need to control settlements, the NATM has been chosen as the preferred tunneling method over open face shield options. To enhance stand-up time of the soils and minimize settlements, a grouted pipe arch canopy will be utilized for the entire length of the tunnels. This will be sufficient for pre-support where the overburden is greater and surface structures are less sensitive. An additional row of pipe arch umbrellas, using closely spaced approximately 114 mm diameter grouted steel pipes will be used on the first 90 m length at the east portal where tunneling is shallow with 4.6 m overburden. The pipes will be installed at 30 cm center-to-center distances around the tunnel crown. Figure 5 displays the double row pipe arch umbrella above a typical single track NATM tunnel with shotcrete initial lining driven in a top heading, bench/invert sequence.

3. CONCLUSION

This paper discussed the process that led to the selection of an alignment and appropriate tunneling methods in an urban setting using the example of the Tysons Corner Tunnel of the Dulles Corridor Metrorail Extension Project in Northern Virginia, a major part of the greater Washington, DC area. This selection process is representative of large transportation projects including underground sections. First, a large bore tunnel solution was converted to a shorter tunnel with lower

overburden. For the solution with the lower overburden, different construction methods (cut-and-cover, NATM and TBM) were compared, using the risk comparison method. The selected solution and the arguments for this particular solution were shown.

The design and completion of transportation projects in urban settings is a highly complex process. One major driver in the decision process is obvious - project costs - but this is not the only aspect. Many more aspects have to be taken into consideration, such as safety, schedule, funding, overall realization risks, environmental impact, right-of-way/accessibility, impacts on the surface/utilities/adjacent buildings, vehicular traffic, public/political support and acceptance. Most of these issues influence and are dependent upon each other.

Regardless of the number of aspects and options considered, the final technical solution can just be a compromise between the necessities and wishes of the involved parties. The role of the tunneling experts in this complex decision-making process should be to provide objective technical and economic tunneling facts. These facts should build a neutral and solid technical foundation in support of the decision-making process. It is the authors' belief that this offering of professional knowledge serves society's transportation needs, and at the same time is the basis of the long-term success of tunneling and creation of public transportation facilities.

REFERENCES

1. Capital Transit Consultants, (2002), Engineering Design Report for Dulles Corridor Rapid Transit Project, Virginia Department of Rail and Public Transportation and Washington Metropolitan Area Transit Authority.
2. Virginia Department of Rail and Public Transportation and Washington Metropolitan Area Transit Authority, (2002), Dulles Corridor Rapid Transit Project, Engineering Design Report, September 2002.
3. Federal Transit Administration, Virginia Department of Rail and Public Transportation, Washington Metropolitan Area Transit Authority in Cooperation with the Federal Aviation Administration (2004). Dulles Corridor Rapid Transit Project Final Environmental Impact Statement and Section 4(f) Evaluation, July 2004.
4. American Public Transportation Association, (April, 2007). APTA Peer Review for Washington Metropolitan Area Transit Authority, Dulles Corridor Metrorail Project - Aerial vs. Tunnel Analysis, April 12, 2007.
5. Federal Transit Administration Project, (May, 2007), Management Oversight Program, Review of DRPT Evaluation of Tysons Tunnel, Inc. - Proposal for Large Bore Tunnel, Report, May 15, 2007.
6. Rudolf, J. and Gall, V. (2007), The Dulles Corridor Metrorail Project – Extension to Dulles International Airport and its Tunneling Aspects, Rapid Excavation and Tunneling Conference Proceedings, June 10-13, 2007.

BIOGRAPHICAL DETAILS OF THE AUTHORS



John Rudolf, a Registered Professional Engineer has over forty years of experience in design and construction management of underground and above ground structures. John has been directly involved for 30 years with design and construction of the 106 miles of the Washington Metrorail, which included 18 years service as the Chief Structural Engineer in WMATA. During construction of

approximately 40 miles of the Metro tunnels in past three decades, John's tunneling experience involved Conventional Tunneling with open and breasted face, deep Cut and Cover, TBM, EPBM & NATM tunneling in soft ground and rock. John is employed by Bechtel Civil as Chief/Project Engineer for Dulles Transit Partners managing the Final Design of Tunnels, Aerial Structures and Geotechnical Engineering/Foundations for 37 kilometers of Metro Rail Extension to Dulles Airport, a \$5 Billion Design/Build Project.



Vojtech Gall has extensive experience in the design, supervision and construction management for underground projects. Having held key positions in fields ranging from structural engineering to project management and project oversight, he was directly involved in all aspects of tunnel engineering; evaluation of geologic conditions, compilation of geotechnical data for structural analyses carried out by numerical methods, design and design coordination, preparation of contract drawings and specifications. On numerous tunneling projects, he has managed construction phase services. He has been instrumental in introducing the flexible membrane based waterproofing technology for cut-and-cover transit structures.



Axel Nitschke has 15 years of experience covering all stages of tunneling projects, with special emphasis to the New Austrian Tunneling Method (NATM). He has held various positions in which he has been assigned as NATM Manager, Contract/Claim Manager, Risk Manager, and Project Manager on projects in the US and Europe. His experience is built on a solid knowledge of tunneling, which he gained during his graduate studies and post-graduate studies as research assistant at Bochum University in Germany. His key skills are the technical development of special solutions for tunneling in urban areas using NATM methods applied with a variety of ground improvement or pre-support methods as well as site and project management during the design, construction preparation and the construction stage.