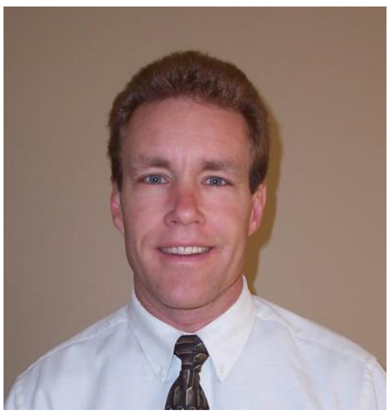
DESIGN AND CONSTRUCTION OF STEEL TRANSIT BRIDGE STRUCTURES IN THE CONTEXT OF A LARGE DESIGN-BUILD PROJECT



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BIOGRAPHY

Greg Shafer is a Bridge Technical Manager for Parsons and has been working in the field of bridge design and construction for 32 years. Mr. Shafer graduated Magna Cum Laude from the University of Delaware with a Bachelor of Science in Civil Engineering degree and has also earned a Master of Science Degree from the University of Colorado. He has been involved with numerous large bridge projects utilizing structural steel bridge solution including the $650 million replacement of the Woodrow Wilson Bridge and the new $350 million John James Audubon Bridge in St. Francisville, Louisiana.

J. Ross Burhouse is a Senior Associate in the Fairfax, Virginia office of Dewberry, where he has served as a bridge engineer since 2002. Prior to joining Dewberry he worked for five years in the Major Bridge Division of Parsons Transportation Group. He holds a Bachelor's degree in Civil Engineering from Princeton University and a Master's degree in Civil Engineering from the University of Maryland. Mr. Burhouse is a registered professional engineer in the Commonwealth of Virginia, and a member of the American Society of Civil Engineers and Sigma Xi Society.

SUMMARY

The Dulles Corridor Metrorail Phase 2A or Silver Line is an extension of the Washington, DC Metro system from Reston to Loudoun County, Virginia including a station at Dulles Airport. The alignment of the guideway generally falls in the median of the Dulles International Airport Access Highway (DIAAH) on the east side of the airport and the median of the Dulles Greenway on the north side of the airport.

Due to severe limitations on the track profile and clearance over existing roads in the median of the DIAAH, ballasted steel through-girder structures were utilized to span Centerville Road and Horsepen Run. The through-girder design provided a sufficiently rigid structure to meet the strict vibration criteria as well as the other operational requirements for the facility, with a structural depth of just 30 inches below the ballast.

An additional bridge over Broad Run was built in the narrow median of the Greenway on the north side of Dulles Airport. With two existing highway bridges already crossing stream, there was just 2 feet clear on either side of the new transit bridge to the highway bridges. This necessitated a structural scheme that could accommodate the existing bridges in erection of the transit bridge girders.

The details of the design and construction of these unique transportation structures will be discussed in the context of the design-build contract in which they were executed.

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Introduction

The Metropolitan Washington Airports Authority (MWAA) is constructing the 23-mile Silver Line extension of the existing Metrorail system, which will be operated by the Washington Metropolitan Area Transit Authority (WMATA) in Northern Virginia from East Falls Church to Washington Dulles International Airport west to Ashburn. Dulles Airport was constructed in the early 1960's in Northern Virginia, 30 miles west of Washington DC. While the city has had the WMATA Metro system for a long time, the train did not go to Dulles Airport. The Silver Line now makes this connection to the airport and the growing suburbs beyond.

The project is being built in two phases and includes 11 new stations. Phase 1 is complete and open to revenue service from East Falls Church to Wiehle Avenue in Reston with five stations. Phase 2 will run from Wiehle Avenue to Rt. 772 in Loudoun County with six stations including one at Dulles International Airport. The Phase 2 alignment is illustrated in Figure 1.

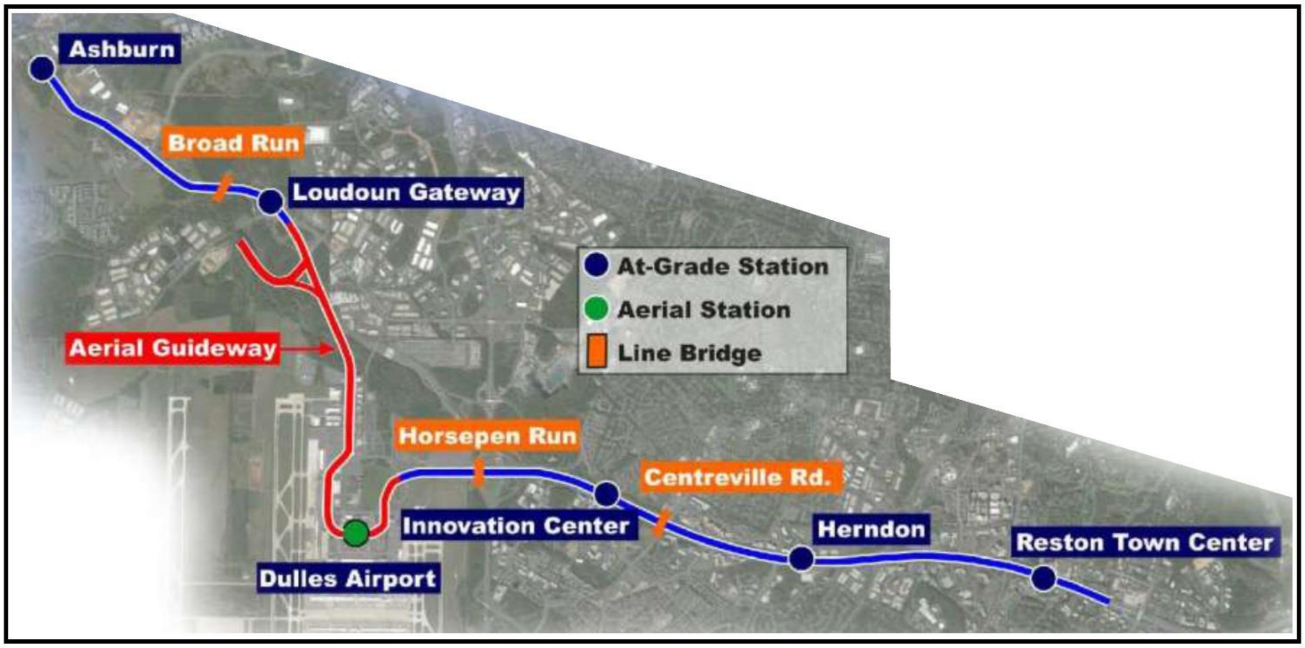

Figure 1: Phase 2 Alignment of Dulles Corridor Metrorail Project

Project Overview

On May 14, 2013 MWAA awarded Capital Rail Constructors (CRC) the design-build contract for Phase 2 of the Dulles Corridor Metrorail Project for a winning bid of $1.178 billion. Phase 2 will have six stations at Reston Town Center, Herndon, Innovation Center, Dulles Airport, Route 606 (Loudoun Gateway) and Route 772 in Ashburn. Notice to proceed was given on July 9, 2013.

The train guideway is located at grade in the median of the Dulles International Airport Access Highway (DIAAH) from the terminus of Phase 1 until it reaches Dulles Airport. At that point it transitions to aerial guideway (i.e. on structure) for 2.5 miles through the airport and then back to grade in the median of the Dulles Greenway.

In addition to the aerial guideway, there are three steel bridges grade crossings carrying the guideway over Centreville Road, Horsepen Run and Broad Run. These bridges are steel girder structures with lengths of 150 feet, 130 feet and 430 feet, respectively, each with its own unique requirements and configuration.

As part of the RFP, MWAA provided Preliminary Engineering (PE) drawings which had been developed prior to putting the project out to bid. The PE drawings presented a possible solution to meeting the project technical requirements. In response to the RFP, the Design-Build team proposed its own unique design which differed in some aspects from the PE concepts. A particular challenge to the Design-Build team was to obtain buy-in from the various stakeholders on final design concepts which departed from the PE drawings. To address specific technical challenges and arrive at a cost-effective solution that satisfied project requirements, the structure types chosen in the final design of the bridges over Centreville Road and Horsepen Run varied significantly from the PE designs.

At Centreville Road and Horsepen Run, proposed steel thru-girders provide the required vertical clearance over the road or stream while reducing the elevation of the track profile compared to the PE design. This resulted in significant savings for the retaining walls of the at-grade approaches to the bridges. It also eliminated a pier in the median of Centreville Road that would have had to been added at a future date when Centreville Road is widened. The third bridge is a conventional skewed three-span plate girder with composite deck slab founded on drilled shafts in the Broad Run floodplain.

Design Requirements

General Rapid Transit Vehicle Clearances to Fixed Features

The configuration of each bridge is defined to meet general operational requirements of WMATA. The width of the structures is defined by three clearance requirements:

- Vehicle dynamic clearance envelopes
- Maintenance clearance in the track bed, and
- Safety walk clearances to provide for safe maintenance access and emergency egress.

The design vehicle dynamic outline (clearance envelope) is defined by WMATA based on the transit car clearance envelope plus car body movements as limited by physical stops. The vehicle dynamic envelope is represented in Figure 2.

The clearance under the track is limited to allow future ballast maintenance. These restrictions have a critical influence on the structural configuration of the thru-girder bridges, especially. The deck girder bridge has direct rail fixation, which eliminates any concerns about ballast maintenance.

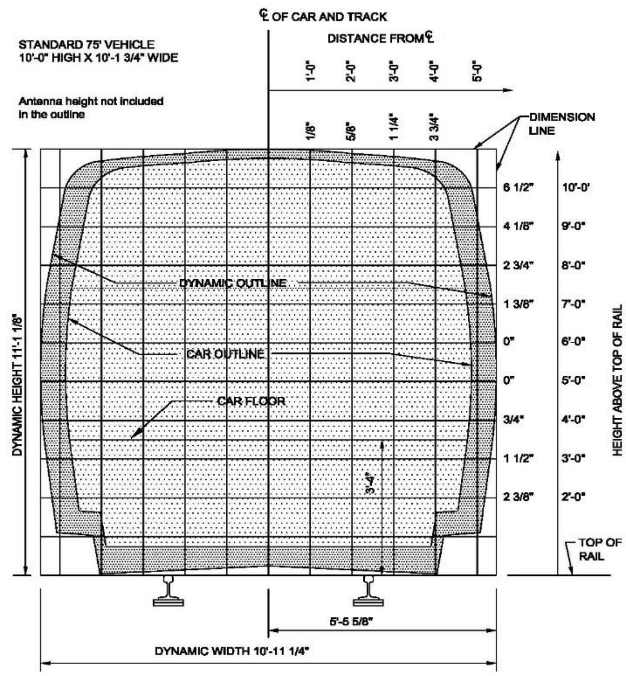

Figure 2: Vehicle Dynamic Envelope (WMATA Design Criteria)

There are two specific limitations on the walkway that is provided alongside every track. The purpose of this walkway is to provide safe maintenance access and to provide for emergency egress from the train in the event of an emergency. The requirements for safe maintenance access are provided by WMATA and require an envelope which is 24" wide and 80" tall and is fully clear of the vehicle dynamic envelope. The requirement for emergency egress comes from the National Fire Protection Association (NFPA) 130 – Standard for Fixed Guideway Transit and Passenger Rail

Systems. The means of egress along the guideway is defined as shown in Figure 3, but is measured to the car outline, since vehicles would not be operating during an emergency evacuation.

Finally, WMATA requires that each track be supported by an independent superstructure. This allows any structure to be taken out of service for maintenance, repair or replacement while not affecting operations on the parallel track.

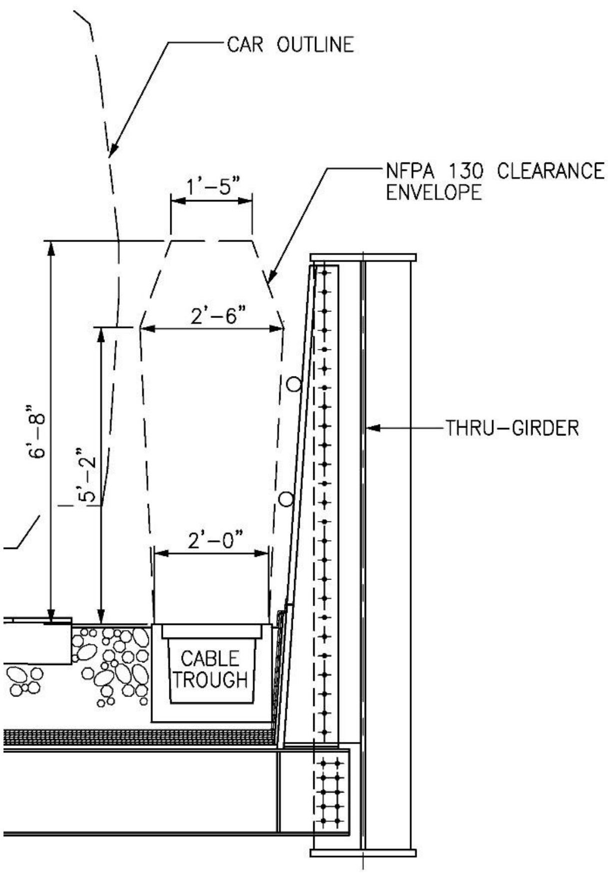

Figure 3: NFPA 130 Egress Clearance

Vibration

To prevent dynamic interaction between the transit structure and the vehicle (i.e. resonance) and to limit dynamic impact, the WMATA has placed limits on the natural frequency of the first mode of vertical vibration of the superstructure spans. For a simple span, the natural frequency shall not be less than 2.5 hertz and for continuous spans the natural frequency shall not be less than 3 hertz. This limitation is the controlling factor in the depth of superstructure sections used for both the thru-girder spans as well as the continuous deck girder spans. The result is the necessity of stiffer structures to avoid the undesirable natural frequencies of the structure.

Stray Current

The Silver Line uses an electrified train with direct current third rail power systems. There is a significant risk that improper grounding of the power system or impedance loss over time can result in current being induced in the structural steel or reinforcing steel of a concrete deck slab. This induced or "stray" current can result in galvanic corrosion of the reinforcing. Therefore, a system of protection is provided whereby the steel is bonded together with a provision to monitor the induced current. If, in the future, the stray current is observed, provisions are made to prevent corrosion.

Furthermore, for a steel girder bridge, unlike a concrete girder bridge where the reinforcing is embedded in the concrete, there is a safety risk from an induced current, if a person became the connection between ground and an electrically charged structure. Therefore, all exposed steel is bonded together and connected by cable to protective ground rods located off the structure that provide safety while not allowing an induced current.

Rails Structure Interaction

Transit structures supporting tracks with continuously welded rails are subject to induced loads due to thermal changes. Since there are no joints in the rail, a continuously welded rail is not free to expand and contract in the longitudinal direction due to changes in temperature, however, the rail will tend to expand radially when placed on a curve. When the rails are fixed directly to the deck of a transit structure (i.e. not on ties and rock ballast), the structure will restrain this radial expansion. The resulting radial force can induce controlling forces on guideway structures and must be accommodated in the design. Furthermore, a structure with continuously welded rail in direct fixation must account for the possibility that a rail may break somewhere along the length of the bridge during the service life of the structure. The stresses in the rail are maximum at the bridge expansion joints and are most critical under extreme cold temperatures. When a rail breaks, it is free to contract in the longitudinal direction. It is necessary to restrain this contraction to prevent a large gap at the break location which could induce a derailment of the train. The contraction is limited by the use of limited slip rail fasteners that provide some restraint to the free slippage of the rail. However, this restraint induces forces in the structure which could cause damage to the piers and foundations without proper consideration.

Utilities

Each of the transit structures considered here support the electrical distribution lines that supply power to the substations provided along the guideway to provide power for the trains. These 34.5 kV AC current powerlines are supported in 8” diameter conduits along the girders. The general public must be protected from the shock hazard presented by these electrical lines, so the lines are encased in fiberglass conduits where exposed above ground. As well, the transition from buried ductbank to exposed ductbank along girders required careful consideration to prevent damage to the electrical system due to settlement or thermal movement.

Centreville Road Bridge

A key design requirement at this site was for the Metrorail bridge to accommodate the future cross-section of Centreville Road. The adjacent highway bridges over Centreville Road feature 100 foot long single spans with pile supported abutments behind Mechanically Stabilized Earth (MSE) walls. Rather than matching the existing bridge lengths, the Metrorail bridge was required to span a clear opening of over 141 feet to accommodate future improvements to Centreville Road and a bike trail planned by Fairfax County. Furthermore the abutments needed to be independent of the existing MSE wall system which will ultimately be removed for the future widening of Centreville Road.

The concept presented in the Preliminary Engineering (PE) design featured a composite steel girder and concrete deck bridge over Centreville Road. The bridge was arranged as an initial three-span bridge with a center span of 102 feet and a total length of 179 feet 6 inches. Initial pile supported piers would be located just behind the existing MSE walls. In order to accommodate the future road widening, the bridge would have been designed to be ultimately converted to a two-span bridge through the addition of a center pier and removal of the initial piers. This unusual configuration as shown in Figure 4 was suggested as a means to span both the present and future cross sections of Centreville Road while meeting vertical clearance and structure depth constraints.

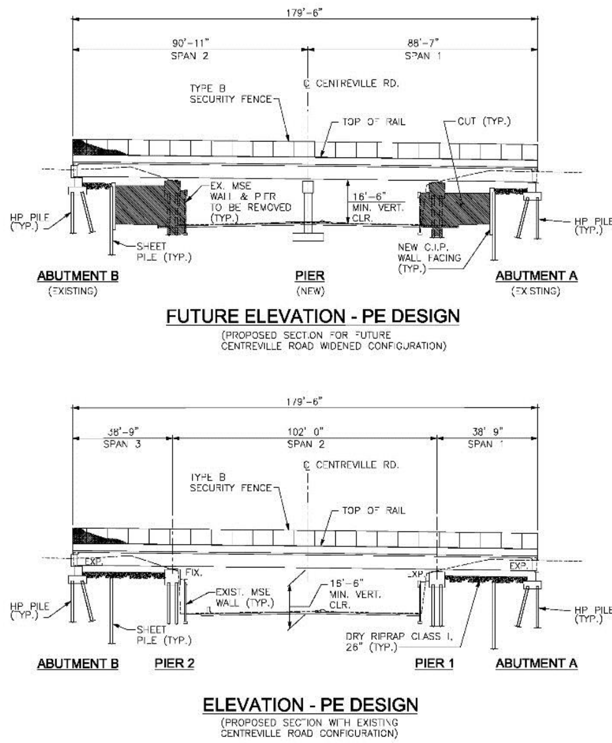

Figure 4: PE concept for Centreville Road Bridge.

As an alternative to the PE concept, the Design-Build team proposed to cross Centreville Road with a single span of 150 feet, which will not require any future modifications to the superstructure for the roadway widening. The abutments are founded on secant pile walls, which will also support the future excavation when the existing MSE walls are ultimately removed. Rather than a steel girder with composite concrete deck as shown in the PE design, a thru-girder section is utilized. The thru-girder solution affords the structure depth needed to satisfy vibration criteria, while also providing the required vertical clearance without raising the rail profile. The final design span configuration is depicted in Figure 5. This layout offers several advantages over the PE concept, including higher vertical clearance and elimination of the center pier which affords greater flexibility in accommodating the future roadway widening.

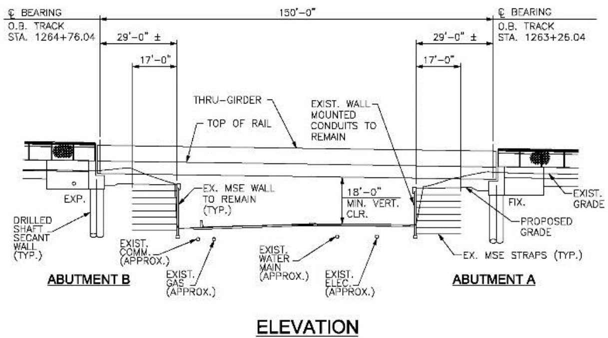

Figure 5: Centreville Road Bridge final design span configuration.

Development of the final design was coordinated with multiple stakeholders: WMATA, Virginia Department of Transportation (VDOT), MWAA, and Fairfax County. The RFP Statement of Work required that the bridge accommodate a future cross-section of Centreville Road which has yet to be designed. The Design-Build team worked with VDOT and Fairfax County to develop a conceptual roadway section for the future widening in order to determine the required opening under the bridge. Another important consideration to these parties was that the Metrorail bridge be designed such that future roadway improvements not impact rail operations. Ultimate widening of Centreville Road will require replacement of the adjacent bridges carrying the DIAAH which are located within 6 feet of the Metrorail bridge. Wing walls are cantilevered off of the secant wall abutment so that the ballasted track approaching the bridge will not be impacted by future excavation for the replacement DIAAH bridges.

The final cross-section of the bridge was established after extensive coordination with WMATA. When a thru-girder solution was first proposed, WMATA indicated a preference for a concrete deck to address concerns over corrosion of steel deck plates. The pros and cons of ballasted versus direct fixation track were considered. WMATA ultimately agreed on a ballasted steel deck with provisions made to mitigate corrosion concerns.

Horizontal dimensions of the cross-section were selected to satisfy WMATA clearance requirements while accommodating geometric constraints of the bridge location. It was initially proposed to separate the two structures for the outbound and inbound tracks by only a few inches between the center girder flanges. However this distance was expanded in the final design to fit a maintenance walkway in response to WMATA concerns over access for girder inspection.

The bridge typical section is illustrated in Figure 6. The thru-girders have a web depth of 123 inches which was governed by WMATA natural frequency requirements. The structure depth below top-of-rail is 4 foot 7 inches (requiring just 30 inches of structure below the ballast), significantly less than would have been needed for composite deck girder bridge. The reduced structural depth was the primary factor in selecting this structure type, as it allowed for the track profile to be lowered, reducing the height of retaining walls approaching the bridge.

Each track runs between a pair of thru-girders spaced at 16 feet 6 inches on center. Floor beams are spaced at 4 foot centers with a knee brace on every other beam. The floor beams support a 7/8 inch steel deck plate which carries the ballast and rail ties. In addition to accommodating the dynamic envelope of the rail car, the bridge section also provides for an emergency egress safety walk. The outside girder on the outbound side supports four conduits for the 34.5 kV power distribution system.

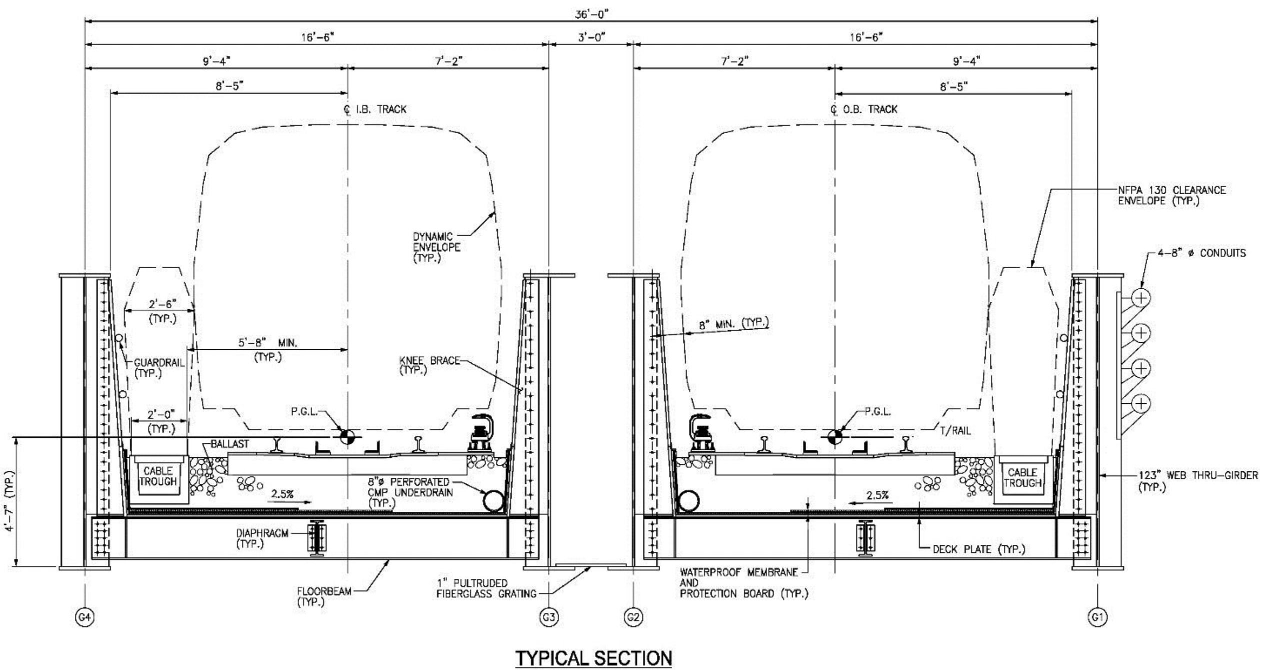

Figure 6: Typical section of Centreville Road Bridge

Floor beam and knee brace connections to the thru-girders are field bolted. Floor beams are perpendicular to the thru-girders except at the end where they align with the 12.67 degree abutment skew. The deck plate is field welded to the floor beams and made continuous by full penetration groove welds. Design of most elements were controlled by vibration and deflection requirements rather than strength requirements. The low stress levels resulting from these considerations also minimized fatigue stresses. Figure 7 shows the completed steel framing of the thru-girder bridges and the adjacent highway bridges over Centreville Road.

The bridge was designed to include several considerations toward long-term maintenance and inspection. The deck plate thickness was oversized to account for potential future section loss, and is sealed against corrosion by a spray-applied elastomeric waterproofing membrane. The membrane is protected by multiple layers of asphaltic panels which are stepped to direct water toward the ballast underdrain. A fiberglass grating is provided in the 3 foot wide space between the center girders to form a walkway for inspection and maintenance. Jacking points are incorporated at the abutments to accommodate future bearing replacement

Figure 7: Completed steel framing.

Horsepen Run Bridge

Similar to Centreville Road, the bridge over Horsepen Run was originally conceived with plate girders and composite concrete deck in the PE plans. The adjacent highway bridges have three simple spans with a center span of 60 feet and two side spans of 35 foot 5 inches each. The PE plans showed the same span lengths for the Metrorail bridge. Once the Design-Build team developed the thru-girder concept for Centreville Road, it was decided to use the same structural type at Horsepen Run. A thru-girder bridge at Horsepen Run allows for the stream to be crossed with a single span of 130 feet 10 inches and eliminates the need for any piers. Over 5 feet of freeboard is provided over the 100 year flood elevation. Figure 8 depicts the final design configuration for the bridge over Horsepen Run.

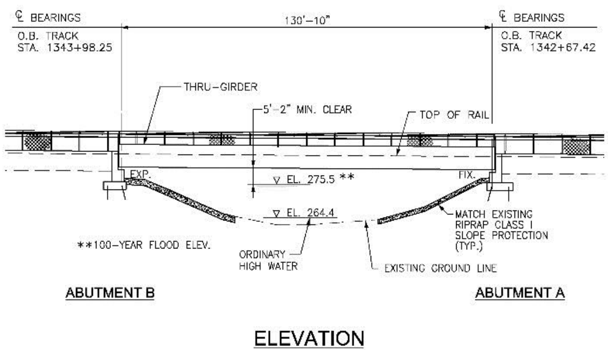

Figure 8: Horsepen Run Bridge span configuration.

The thru-girder bridge cross section used at Horsepen Run is nearly identical to Centreville Road except the web depth was reduced to 96 inches for the shorter span length. Floor beam and deck plate designs are the same as at Centreville Road. At Horsepen Run the inbound and outbound tracks are spaced further apart with over 6 feet between the center girders, so no maintenance walkway was provided here. The outside girder on the inbound side carries six power conduits. The typical section is shown in Figure 9.

The abutments are supported on steel H-piles. Existing pile-supported walls between the adjacent DIAAH bridges were demolished to construct the new abutments. New H-piles were driven between the existing piles, which were cut off and abandoned in place below the new abutments. Piles were driven in predrilled holes to achieve the required embedment in rock for scour consideration.

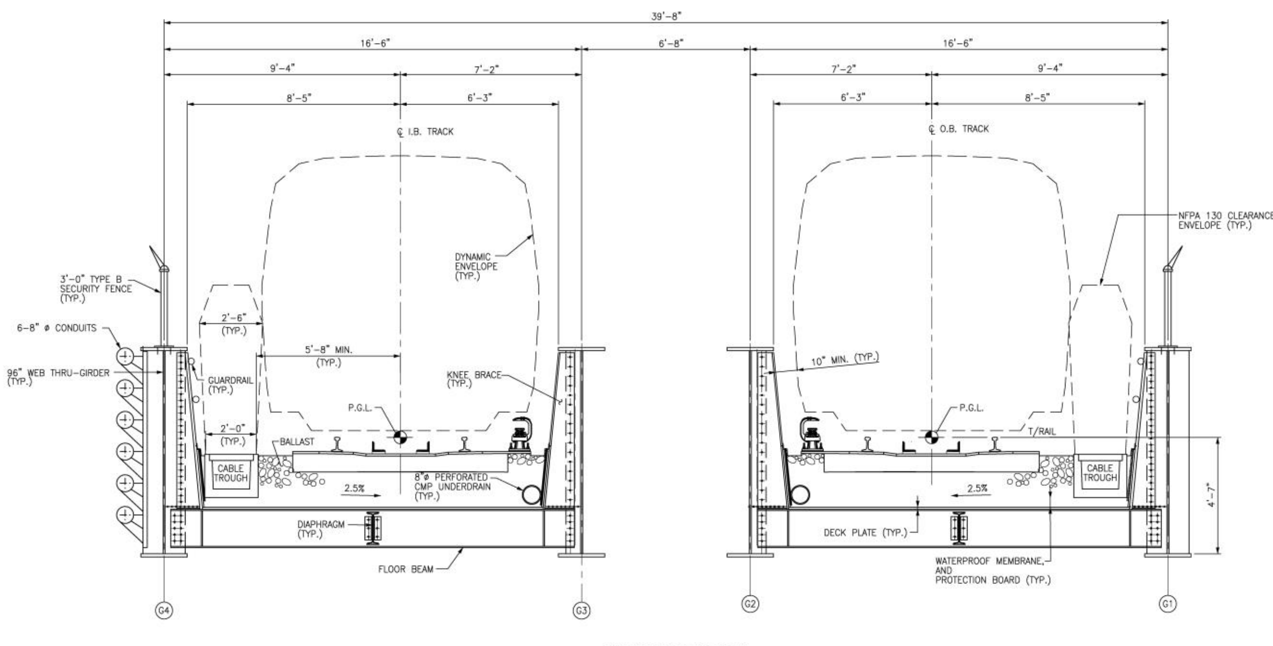

Figure 9: Typical section of Horsepen Run Bridge

Figures 10 and 11 show girder erection during construction of the Horsepen Run Bridge. As shown in Figure 10, girders were delivered by truck on the adjacent highway bridge, and lifted into place by cranes sitting behind each abutment. As seen in Figure 11, construction activity remains entirely outside the stream banks. The girders were then braced temporarily while the knee braces and floor beams were erected. A similar erection scheme was used at Centreville Road.

Figure 10: Girder delivery from adjacent bridge.

Figure 11: Girder erection over Horsepen Run.

Figure 12 illustrates the Horsepen Run Bridge during deck plate placement. Each deck plate panel spans two bays of floor beams. The plates are spliced for continuity by full penetration groove welds above every other floor beam. Side plates are fillet welded to the deck plates, forming a trough for containing the ballast and tracks.

Figure 12: Placement of deck plates.

Broad Run Bridge

The Metrorail bridge over Broad Run was constructed in the tight space between two existing highway bridges carrying the Dulles Greenway. To satisfy hydraulic requirements it was necessary to align the new piers with the adjacent existing piers and match the center span length of nearly 180 feet. Spanning this distance with a ballasted bridge deck would have required excessively deep girders to meet vibration criteria, so a direct fixation composite concrete deck was used. WMATA requires special approval for spans over 150 feet, so design of this structure drew extra scrutiny to ensure that the longer span satisfied all design criteria.

Similar to the adjacent Greenway bridges, the Metrorail bridges consist of three-span continuous steel plate girders with composite concrete deck slab. The span layout is 125’ – 180’ – 125’. The wall piers are skewed about 42 degrees to match the adjacent piers. However skewed abutments are not permitted by WMATA for direct fixation bridges. The abutments are required to be perpendicular to the track centerlines to accommodate the approach slab transition from ballasted approaches to direct fixation bridge deck. Skewed approach slabs are prohibited by WMATA in order to ensure uniform stiffness below the ballasted ties in the transition. As a result the abutments for the inbound and outbound tracks are stepped in plan to remain outside the hydraulic opening of the existing bridges. The span layout is depicted in Figure 13.

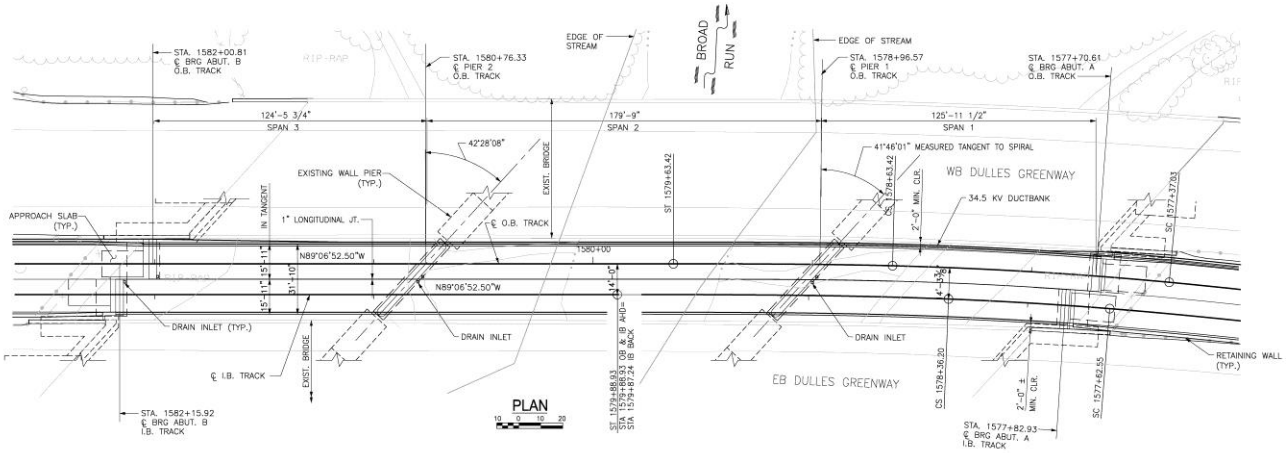

Figure 13: Span layout of Broad Run Bridge

The clear space between the Greenway bridges was only 36 feet 8 inches, leaving slightly over 2 feet of clearance on either side of the Metrorail bridge. Governed by vibration criteria, each track is supported by three girders with 111 inch deep webs spaced at 5 foot 6 inches on center. As with the thru-girder bridges, the Broad Run Bridge also carries a cable trough and safety walk outside each track, and four power conduits are supported on the fascia girder on the outbound side. The typical section is shown in Figure 14.

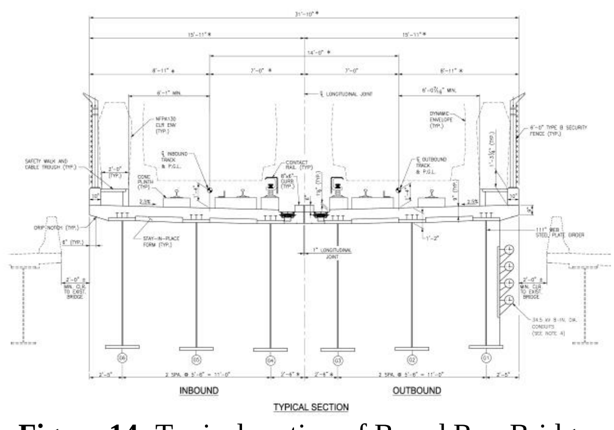

Figure 14: Typical section of Broad Run Bridge.

To accommodate the alignment of the existing Greenway bridges as well as the track alignment, the bridge is tangent for two spans and curved in one end span. Both inbound and outbound tracks feature a spiral transition in this area. Rather than fabricating the plate girders to a spiral curve, a series of compound curves was developed to approximate the track alignment. As a result there is a slight variation in deck width and overhang in the curved span. The three girders for each track are concentric within each curve segment to maintain a constant diaphragm width. The pier diaphragms and end diaphragms were detailed with jacking points and were designed to support the structure during future bearing replacement operations. Figure 15 shows a cross section of the girders during construction.

Figure 15: Broad Run girders during construction.

Each wall pier is founded on a single line of five drilled shafts socketed into bedrock. The abutment foundations are supported on groupings of drilled shafts that were spaced to clear battered piles from the adjacent Greenway bridge abutments. The shafts were designed for a full scour condition which considered all surrounding soil removed down to bedrock. Abutment seat elevations were set to keep the bearings above the 100-year flood elevation, providing the girders with over 2 feet of freeboard above the 100 –year water surface elevation.

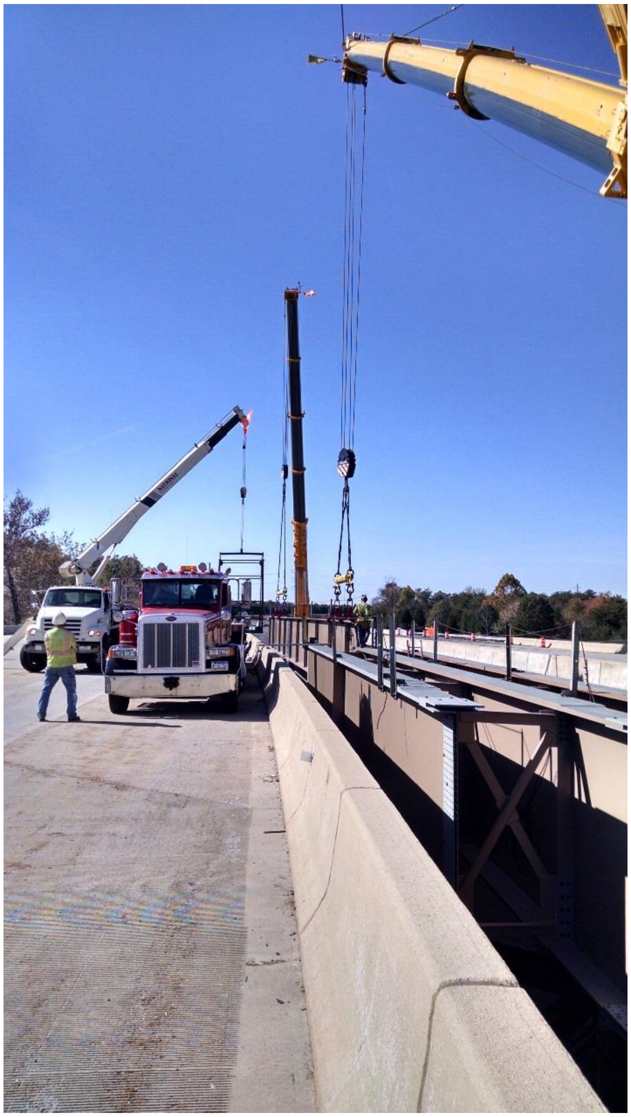

Figure 16: Broad Run girder erection.

A significant load case for design of the piers was the rail break condition. The effect of the direct fixation rail fasteners throughout the three spans restraining a broken rail concentrates high longitudinal loading on the fixed pier. These rail-structure interaction forces governed the design of the pier foundations.

The limited space available between the Greenway bridges presented challenges in erecting the girders. It was determined that the adjacent bridges could not support the loading from a crane to erect the girders, while locating a crane outside the Greenway would require excessive boom length. The erection scheme ultimately selected was to construct the bridge in stages. First the piers were constructed, the girder sections were delivered by truck on the adjacent bridge, and the center span girders were erected using cranes positioned between the Greenway bridges on either side of the stream. Then the cranes were removed from the floodplain, the abutments constructed, and the end span girders erected by cranes located behind the abutments. Figure 16 depicts a girder section being lifted into position from a truck on the Greenway bridge.

After completion of steel erection, the composite concrete deck was placed, curbs and security fence installed, followed by construction of trackwork and cable troughs. Figure 17 presents the finished deck prior to installation of the concrete plinths for direct rail fixation.

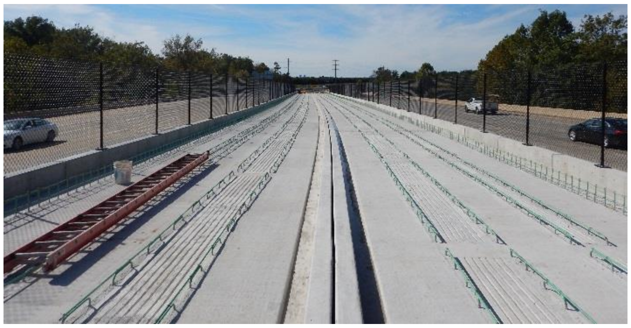

Figure 17: Finished concrete deck.

Conclusion

The Dulles Corridor Metrorail Project presented opportunities to develop innovative structural steel solutions to satisfy design requirements. The geometric constraints of the Centreville Road crossing combined with the need to accommodate future road widening lead to the selection of a thru-girder system. The shallower structure depth below the rail afforded by a thru-girder bridge allowed Centreville Road to be crossed by a single span without requiring tall retaining walls in the approaches. This structural system was repeated at Horsepen Run where it resulted in the elimination of piers in the floodplain. At Broad Run, a more conventional structure type was used but the long spans and tight clearances of the adjacent highway bridges resulted in a need for a unique erection scheme.

These design innovations were made possible by the design-build contract arrangement in which the engineer and contractor collaborated to create and design cost-effective and constructible solutions to the project requirements. Obtaining acceptance of the alternate solutions by the owner and third party stakeholders required extensive coordination to ensure that the concerns of all parties were addressed. The end result of these efforts is an extended Metrorail system that will benefit commuters and Dulles Airport travelers for years to come.

References

1. WMATA Manual of Design Criteria for Maintaining and Continued Operation of Facilities and Systems, Release 9. Washington Metropolitan Area Transit Authority, 2008.