Columbia River Crossing Project
Bridge Review Panel Final Report

February 3, 2011

Chair/Contact: Thomas R. Warne, PE • Tom Warne & Associates
9874 S Spruce Grove Way • South Jordan, UT 84095
twarne@tomwarne.com • 801.302.8300

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Executive Summary

The Columbia River Crossing (CRC) project is an important initiative intended to replace aging bridges that currently carry I-5 across the river between the cities of Portland and Vancouver. The formal environmental process as defined by the National Environmental Policy Act (NEPA) has proceeded to the point of publishing a Draft Environmental Impact Statement (DEIS) and work is proceeding towards a Record of Decision (ROD), which indicates formal federal approval of the environmental document and authorizes the state transportation agencies to proceed with design and construction based on funding availability.

The new Columbia River crossing represents the most dramatic river structure in the northwest and may be one of the last major crossings ever to be built along the West Coast. It will serve as an important transportation connection between Oregon and Washington and a gateway to Portland and Vancouver. Its significance cannot be overstated as it will meet the immediate and future needs of the growing and progressive area communities for many generations to come.

A number of issues remain unresolved; the most problematic concerns the current open-web box girder bridge design still in development. These concerns originated in the community and were echoed by the Independent Review Panel (IRP) report submitted to Governors Gregoire and Kulongoski in July 2010. Consequently, a Bridge Review Panel (BRP) was formed by the executives of the respective state DOTs. This 16 member panel was comprised of national and international bridge experts, plus key representatives from federal, state and local partner transportation agencies. The mission of the BRP was to examine the current design and potential bridge types given current project constraints and including scenarios where constraints are relaxed or modified. Issues such as meeting current environmental project commitments, sound technical and engineering approaches, aesthetic statements and cost effectiveness were also key considerations.

The current open-web box girder design stems from an evolutionary process that occurred over many years. A number of constraints have controlled the characteristics of this alternative. They include navigation, environmental, aviation, local and regional access, safety and security, geologic considerations, architectural, and historic and protected properties. In an attempt to satisfy the many disparate constraints, the CRC project team developed the open-web box girder. Last year the IRP found that the open-web box girder has technical, cost and constructability risks, rendering it an impractical and costly alternative. The BRP was given license to reevaluate various project constraints and seek alternative solutions for the new crossing.

The Bridge Review Panel met three times between November 2010 and January 2011, and conducted the rest of the evaluations via email and teleconferences. The initial meeting on November 3, 2010 included a public session for presentation to the BRP of project specific information. Individual members of the panel performed substantial engineering analysis and other work during this period of time.

While substantive improvements to the current open-web box girder design were suggested by the BRP, technical and engineering issues with this alternative could not be overcome. Therefore, the BRP developed three new bridge types: cable-stayed, tied arch and composite deck truss. The cable-stayed design offers both a pleasing aesthetic statement and a cost effective engineering solution. The tied arch bridge alternative is also viable for the same reasons but at a higher cost. The composite deck truss is the least costly alternative and also provides a sound engineering solution. The cost estimates included in this report are preliminary in nature but accurate for this level of planning. They have been normalized to the open-web box girder and are relevant for comparative purposes.

All three bridge types proposed by the panel are more cost effective than the open-web box girder design and provide viable engineering solutions for the new crossing. The tied arch and cable-stayed alternatives have less "in-water" impacts than either the current open-web box girder or composite deck truss and provide a more meaningful aesthetic statement. The composite deck truss offers less "in-water impact" than the open-web box girder and similar aesthetic value. Both the tied arch and cable-stayed designs would require resolving aviation issues relating to Pearson Field, but these will not be insurmountable. The panel recognizes that a public and technical review process will now proceed to finalize a selection of the preferred bridge type.

The panel found that replacing the North Portland Harbor Bridge would be a cost-effective strategy, as would adopting a straight or tangent alignment downstream from the current bridges. The currently planned curved alignment is longer, unnecessarily limits bridge type options, increases the technical issues with the new bridge and has greater impacts on the viewshed of the surrounding area. The general layout of the interchanges and ramps for the corridor were also reviewed. The panel concluded that improvements to the functionality of the overall roadway network in the project limits should address urban design issues. The use of a collector/distributor system was found to be unworkable, but reducing and simplifying the number of interchanges would significantly improve both functionality and cost.

Any major civil project includes detractors, although concerns and issues surrounding the CRC project seem higher than normal, particularly for aesthetics and cost of the current design. The BRP has reviewed options to address these concerns early in the process so corrective action can be taken to avoid later delays.

Recommendations

Based on the research and information previously referenced, the Bridge Review Panel offers the following primary recommendations:

- **Recommendation 1: Discontinue any further design or planning work on the open-web box girder bridge alternative.**
- **Recommendation 2: Select a new bridge type from among three feasible alternatives: cable-stayed, tied arch and composite deck truss.**
- **Recommendation 3: Proceed with further analysis and public review of recommended alternatives in order to select a preferred bridge type.**
- **Recommendation 4: Work with the Federal Aviation Administration to resolve airspace issues with Pearson Field relating to either the cable-stayed or tied arch bridge designs.**
- **Recommendation 5: Develop a tangent (straight) alignment for the main river crossing downstream of the existing bridges.**
- **Recommendation 6: Replace the North Portland Harbor Bridge.**

Secondary Recommendations / Opportunities for Improvement

- **Review all interchanges, ramps and other geometric features to simplify the overall corridor design for substantial cost savings and to improve safety and corridor operations.**
- **Review the potential impacts to the project description and technical studies for the environmental document and develop a work plan to maintain a realistic target date for the Record of Decision.**
- **Provide uniform seismic performance levels for the North Portland Harbor Bridge and Columbia River Bridge.**
- **Establish performance-based project specific criteria for all primary and secondary members upon selection of the final bridge type crossing the Columbia River.**

Introduction

Background

The Columbia River Crossing (CRC) project is an ambitious and complex transportation initiative that has been under development for many years. The current preferred structural solution that is included in the Draft Environmental Impact Statement (DEIS) is an open-web box girder design[1]. Questions have been raised concerning some of the technical/structural elements of this proposed bridge. In addition, the local community has not embraced the aesthetic qualities of the open-web box girder design. Several interest groups have focused on the unique opportunity to solve a transportation problem and, at the same time, make an aesthetic statement about bridging the two communities of Portland, Oregon and Vancouver, Washington.

Last April, Governors Gregoire and Kulongoski, of Washington and Oregon respectively, appointed an Independent Review Panel (IRP) to review the project. The IRP provided 30 recommendations in a final report presented in July 2010. One of those recommendations was for the CRC to reconsider the open-web box girder as the structural solution to the crossing. It was for this reason that the Bridge Review Panel (BRP) was established.

Bridge Review Panel (BRP)

The BRP was composed of sixteen (16) members with national and international experience in designing, managing and constructing large bridge projects around the world, including individuals representing the Federal Highway Administration (FHWA), Federal Transit Administration (FTA), and from the local transit agencies, C-Tran and TriMet. The panel was chaired by Thomas R. Warne of Tom Warne and Associates, who was also the chair of the Independent Review Panel that met between April and July of 2010. Panel members included:

- Thomas R. Warne, PE, Chair

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[1] An open web boxed girder consists of top and bottom concrete slabs connected by open webs consisting of steel or concrete struts.

- Scott A. Ashford, PhD, PE, Head of the School of Civil and Construction Engineering at Oregon State University
- Benjamin Beerman, PE, Senior Bridge Engineer, Federal Highway Administration Resource Center
- John Buchheit, PE, Project Management Oversight Consultant for Federal Transit Administration
- David Goodyear, PE, SE, PEng, Chief Bridge Engineer, T.Y. Lin International
- Siegfried Hopf, Dipl.-Ing., Chief Bridge Engineer, Leonhardt, Andrae, and Partners
- Bruce Johnson, PE, SE, State Bridge Engineer, Oregon Department of Transportation
- Jugesh Kapur, PE, SE, State Bridge Engineer, Washington State Department of Transportation
- Wesley King, High Capacity Transit Project Manager, C-TRAN
- Calvin Lee, PE, Senior Bridge Engineer, TriMet
- John McAvoy, PE, Major Project Manager, FHWA Oregon Division
- Mary Lou Ralls, PE, Principal Bridge Engineer, Ralls Newman, LLC
- Joseph Showers, PE, Business Group Technical Manager / Bridge Design and Construction, CH2M Hill
- Steven L. Stroh, PE, Deputy Director of Surface Transportation, Major Bridges, URS Corporation
- Steve Thoman, PE, SE, Principal Bridge Engineer, Stephen J. Thoman Consulting, Inc.
- Theodore P. Zoli, III, PE, Technical Director Bridge Practice, HNTB Corporation

Purpose

The purpose of the BRP was to evaluate river bridge types and configurations for the Columbia River Crossing project. The BRP was charged with bringing their best thoughts to this process so that the optimal bridge solution might be achieved. For the purpose of this panel, the optimal solution was defined as a bridge that:

- Provides a sound structural and constructible bridge solution.
- Achieves an acceptable design/aesthetic statement.
- Meets the environmental requirements/constraints for the project.
- Is cost effective.

Objectives

When the BRP was constituted in October 2010 it was given the following objectives by the executives of the respective departments of transportation:

- Given the constraints that have governed the project, evaluate and discuss all reasonable bridge types that can meet these constraints (twin-bridge, aviation, river navigation, environmental, cultural/historical, and maintenance of traffic, to name a few).
- If the panel can push or modify the constraints on the river crossing, is there a potential solution that develops a more efficient structural system that has less perceived risk and higher aesthetic opportunity?
- Gather comments, input, and discussion regarding the cost, risk, constructability, and aesthetic opportunities for all potential bridge types from objectives 1 and 2.

These objectives provided license to the BRP that allowed it to explore solutions that have not been available to the CRC project team through the development of their preliminary bridge alternatives. Figure 1 is a Venn diagram that is reflective of the process to date. Each circle represents a constraint that has been imposed on the project through the planning and development process. These include those already mentioned such as aviation and navigation issues and environmental requirements. For illustrative purposes only three constraints are shown when in reality there are many, many more. It should be noted that the solution emerging from the Venn diagram representing these many constraints falls in the very small area where all of the circles intersect. The design team's canvas for bridge type opportunities has been severely limited by the project constraints.

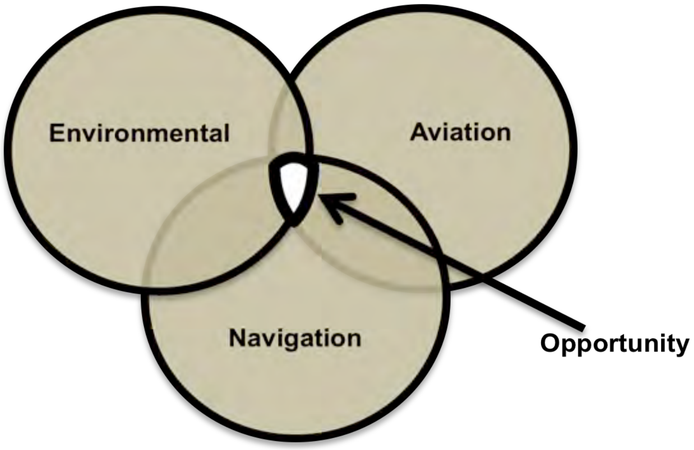

Figure 1 – CRC Constraints Limit Window of Opportunity

The BRP was given license to push back on some of the circles—to examine what might be possible if one or more constraints were modified. It is from this frame of reference that the BRP has performed their work and developed the recommendations that are included in this report. The BRP also came upon several "indirect" recommendations that were outside of the original scope in the context of betterment of the overall CRC project.

Approach

The format and approach of the BRP was left to the chair and panel members. The BRP believed that their work should be independent and objective from the CRC project office. However, the panel also recognized the importance of receiving additional information as the work progressed from subject matter experts who are familiar with the challenges and constraints associated with this project on a daily basis. To accomplish this, the panel held a kickoff meeting that was open to the public, followed by a series of panel work-sessions and interim research and analysis. At critical times, CRC staff and other resources were requested to attend portions of the panel workshops in order to provide input to the panel. Members of the bi-state Urban Design Advisory Group (UDAG) that have provided CRC with perspectives on architecture and aesthetic design were key resources for the BRP throughout this process. The panel meeting and workshop dates and subjects that were covered at each of them are presented in Table 1 below.

Table 1 – BRP Workshop Topics

Panel Meeting / Workshop	Topics Addressed
November 3, 2010 - am Open meeting	CRC Staff Project Overview; including bridge design efforts to date, current bridge design, and constraints. Alternative for consideration, presented by Kevin Peterson.
November 3 pm - November 4, 2010 Panel workshop	Discussion of challenges and constraints. Discussion of current alternative: open-box web girder design, and of alternative presented by Kevin Peterson. Preliminary identification of feasible bridge type characteristics. Identification of possible bridge solutions for further analysis.
December 15 - 16, 2010 Panel workshop	Discussion of collector distributor approach. Considerations related for a more tangent alignment over the river to allow for a greater range of bridge types and structural efficiency. Considerations related to replacing the North Portland Harbor Bridge. Discussion and comparison of possible bridge types.

Panel Meeting / Workshop	Topics Addressed
January 18 - 19, 2011 Panel workshop	Finalization of panel recommendations regarding bridge type and other topics addressed. Risk and constructability considerations related to alternatives considered.

Understand Current Proposed Alternative (Open-Web Box Girder)

The BRP began its work by reviewing relevant project information to become familiar with the project background and current status. Much of this information was provided by the CRC. The panel additionally benefitted from the experience and diverse perspectives of several members who have been working with the CRC for many years, including FHWA and local transit agencies. In addition, Tom Warne and Mary Lou Ralls were able to provide information from the recent Independent Review Panel (IRP) on which they served.

The IRP found that:

> "The current river crossing structure type is unique and presents risk to both the cost and the schedule of the CRC. Since the publication of the DEIS the Locally Preferred Alternative (LPA) has been modified considerably. Most significant is the change in structure type for the main bridges across the Columbia River. This change from a closed box segmental design to the open-web Stacked Transit/ Highway Bridge (STHB) approach is substantial. It reflects a departure from a standard structure type used across the nation to one that has never been built anywhere in the world, requiring extensive testing and engineering to determine viability".[2]

The IRP recommended that the bridge type selection for the river crossing be revisited.

Identify Challenges Associated with the Open-Web Box Girder

The BRP identified several key challenges associated with the proposed open-web design. These are described in the following pages.

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[2] Reference: I-5 Columbia River Crossing Project Independent Review Panel Final Report, July 27, 2010.

Operational Reliability

As defined in the Columbia River Bridge Technical Screening Study Final Report dated December 2008, "operational reliability is an assessment of risk associated with bridge type characteristics and how they may affect operations in emergency scenarios such as accidents, fires, and explosions."

It is the consensus of the BRP that a physical separation of transit and highway modes, such as a three-bridge configuration, provides a greater degree of redundancy in the system, with corresponding higher level of operational reliability. However, the BRP took into consideration that a shared highway-transit facility would be necessary for funding competitiveness with the Federal Transit Administration (FTA), and would minimize the footprint of such a major crossing. In addition, the bridge details on the main river crossing bridge can be further optimized to limit impacts of fires and explosions.

Structural Complexity

As defined in the Columbia River Bridge Technical Screening Study Final Report dated December 2008[3], "structural complexity refers to the relative difficulty and familiarity of the design and construction of the bridge. Unusual bridge types and/or configurations typically require a greater level of detail and therefore have a higher degree of structural complexity."

The proposed open-web box girder design is unique. It consists of top and bottom concrete slabs that are connected by vertical webs. Each web consists of a solid concrete wall at the top and bottom, with steel diagonal tubes in the middle. It is called an "open-web" because of the steel tubes located in the middle part of the web. The ends of each steel diagonal tube are connected to steel members that are embedded in the top and bottom concrete web walls.

The BRP observes that other major bridges with two levels of traffic have been designed with full-depth steel webs, but not with webs that are a combination of solid concrete walls and steel diagonals. The stiff-concrete-and-flexible-steel-tube composite webs create material deformation compatibility concerns, and combined with the many discrete steel-to-concrete

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[3] "Columbia River Bridge Technical Screening Study", Columbia River Crossing, December 2008

web connections, result in significant design and construction complexities. As a result, large scale testing to verify performance of the unique open-web box girder design would be required.

Maintainability

As defined in the Columbia River Bridge Technical Screening Study Final Report dated December 2008, "maintainability is an assessment of potential operation and maintenance costs over the life of the bridge. Considerations include inspection access, effort required for inspection, maintenance of additional systems (ventilation, lighting, etc.), potential for repair and/or rehabilitation, and the effects of these activities on operations. Bridges that are simple, common, or familiar should fare better in this category."

The BRP observes that the current open-web box girder design creates areas that would be inaccessible for inspection. In addition, the many discrete steel-to-concrete web connections would require extensive inspection time and effort, and are potential locations for concrete cracking that would increase maintenance requirements when compared with the more conventional box girder systems.

Aesthetics

The issue of aesthetics is one that is a challenge for any major bridge crossing and is judged in the "eye of the beholder." The BRP has observed that the current open-web box girder does not enjoy wide public support for its aesthetic qualities nor does it make a statement for the region or for either Portland or Vancouver. The challenge facing the CRC team is to advance an option that offers aesthetic value, as determined by the communities, while still achieving the cost objectives of the project.

Cost Uncertainty

The design and construction complexities of the unique open-web box girder design have significant cost and risk implications. To date, these have not been fully addressed and represent a risk to the agencies and to the project as whole. In addition, the testing to verify expected performance of the unique design will require additional time and cost, and in the end could result in the need for extensive design and construction modifications. The increased inspection requirements and potential maintenance issues will also increase costs over the service life of the structure.

Review Project Constraints

The CRC was faced with a challenge to develop a solution that met the needs of many diverse and sometimes competing interests. The constraints included:

- The Federal Highway Administration “strongly advised against” placing the transit facility inside the closed web of a concrete segmental bridge.
- Restrictions in bridge design height to meet Federal Aviation Administration (FAA) airspace regulations for both Portland International Airport (PDX) and Pearson Field in Vancouver.
- Navigational restrictions (both vertical and horizontal) to meet Coast Guard regulations and to accommodate navigational issues with barge and other vessel movements around the bridge.
- Federal and state regulations in regard to safety and security issues.
- In-water construction work restrictions due to environmental concerns and endangered species regulations.
- Project boundary limits due to Historic Reserve and National Park lands that limit alignment alternatives.
- Freight access requirements throughout the construction period.
- Geological constraints including liquefying soils.
- National Environmental Policy Act (NEPA) mitigation requirements.
- The Federal Transit Administration (FTA) rating is insufficient unless transit is on a shared facility. Without an acceptable rating, FTA cannot commit funding. Without that funding, the project would not be viable.
- Public sentiment - The public has expressed continued opposition to concrete segmental bridges like the Glen Jackson and trusses like the Marquam Bridge.

These interests led to multiple and often competing design constraints, as is depicted in Figure 1.

In order for the BRP to examine what might be possible if one or more constraints were modified, the panel started by exploring each constraint, how it was derived, the impacts of that constraint on the current design, and the potential benefits to the project if that constraint was modified. Through this process, the panel identified several constraints that appeared to provide the opportunity for some flexibility. These "potentially flexible" constraints include:

Table 2 – "Potentially Flexible" Constraints

"Potentially Flexible" Constraints	Explanation
Airspace.	Above-deck options could be less intrusive than the existing lift span. FAA Part 77 encroachment for Pearson Field can be minimized. Airspace flexibility exists at the south end and improvements can be made to existing encroachment. It is not apparent that an airspace design exception for Pearson Field has been pursued with FAA.
Navigation clearance.	The current navigation vertical clearance of 95 feet might be reexamined in concert with expected river traffic.
Navigation channel location.	A wider navigation channel reduces the potential for vessel impact.
Minimized footprint for in-water impacts	The Biological Opinion (BO) and DEIS are based on limited surface impacts in the river.
Horizontal alignment.	Tangent alignments simplify both design and construction, and allow more structure types. Additional bridge design options and significant cost savings can be obtained by straightening the alignment to the extent possible.
Staged Construction.	Staged construction does not appear to have been adequately addressed to date, and the potential for staging construction can be significantly impacted by the structure type. Phased construction can also provide options for limited budgets.

Identify Bridge Type Alternatives

The BRP ultimately identified five bridge types for the main river crossing to be further analyzed by the panel. These bridge types are listed in the table below.

Table 3 – BRP Identified Bridge Type Alternatives

Bridge Type	Description of Bridge Type
Open-Web Box Girder (current design)	The current design comprised of top and bottom concrete slab flange sections connected with a vertical combined concrete and steel tube system. See Figures 39 and 40 for cross-section views.
Enhanced Open-Web Box Girder	This was based on the current open-web design but with structural improvements to make it more inspectable and to address some of the technical engineering concerns.
Composite Deck Truss	The composite truss provides for a double composite deck system connected with vertical structural steel frames and steel chords. See Figures 26 and 27 for cross-section views.
Cable-stayed	Three towers with cables extending to a longitudinal spine truss (transit on lower level and bikes/pedestrians on upper level of spine truss) transversely support the load of the roadway sections. All modes of transportation supported from one bridge. See Figure 5 for cross-section view.
Tied Arch	A tied arch comprised of three arches with cables extending to a longitudinal spine truss (transit on lower level and multi-use path on upper level of spine truss) transversely support the load of the roadway sections. All modes of transportation supported from one bridge. See Figure 16 for cross-section view.

Conduct Bridge Type Assessment

To facilitate evaluation of these alternatives, the panel considered the following criteria:

- **Cost** - maintains or improves the current cost estimate and/or brings greater certainty to the final cost of the bridge.
- **Operations** - operational aspects provide for efficient traffic flow under varying levels of service and timeframes into the future.
- **Technical/Engineering** - provides a solution that relies on proven application of bridge principles and technology that limits or eliminates the need for additional study or research analysis.
- **Aesthetics** - provides a signature bridge solution that may be embraced by the community as a whole and provides a visual enhancement to the local environment.

- **Environmental** - adheres to or improves on environmental commitments already embodied in the DEIS.
- **Navigation** - provides for, or improves upon, the navigational clearances and channel accommodations envisioned in the current agreement with the US Coast Guard.
- **Aviation** - complies with the FAA requirements for PDX and Pearson Field or minimizes Part 77 encroachments for Pearson Field to less than those associated with the current structure.
- **Constructability** - employs known construction methods, minimizes extraordinary means and methods and provides for cost effective processes.
- **Risk** - minimizes risks in design, construction, maintenance and operations.
- **Long-Term Maintenance Needs** - long-term maintenance and safety inspection issues are minimized and no unusual means or methods are required to ensure the functionality of the individual and collective components of the bridges.

The BRP developed considerations for each bridge type alternative against the identified criteria and concluded the following:

- The baseline, current open-web box girder design, is not a viable option due to the complexities of design and construction. With the many potential risks associated with this unusual bridge type, it is prudent to adopt other, more proven bridge types having aesthetic qualities that are more appropriate to this location and that are cost effective.
- While the enhanced open-web box girder option marginally improves some of the problems associated with the open-web box girder, it retains key features of the original design that still make it less desirable and more costly than other bridge types that were identified and so is also not a viable option.
- The composite deck truss alternative better addresses many of the technical deficiencies associated with the baseline and enhanced open-web box girder design; however, it does not address aesthetic considerations and is not an improvement over the baseline in this regard.

- The cable-stayed and tied arch alternatives appear to meet the technical and aesthetic criteria.

The panel next compared the cable-stayed and tied arch alternatives as they emerged as the strongest options if the Pearson Field air space was addressed. They were compared against one another according to the three criteria the panel deemed most important: cost, aesthetics, and technical/engineering. The panel found that while both the cable-stayed and tied arch alternatives met aesthetic criteria, the cable-stayed bridge would best address both cost and constructability criteria. This comparison is summarized in Table 4 below.

Table 4 – Comparison of Cable-Stayed and Tied Arch Alternatives

Evaluation Criteria	Panel Assessment
Cost	**Cable-stayed is superior to tied arch.** Provides for a more predictable cost and is less expensive.
Aesthetics	**Cable-stayed and tied arch each provide aesthetic qualities.**
Technical / Engineering	**Cable-stayed is superior to tied arch.** Cable-stayed provides better constructability, good performance history and better seismic performance.

Develop Bridge Type Recommendations

With respect to the Columbia River Crossing bridge type recommendation, the BRP reached the following conclusions. The bridge type considerations were limited to the integrated bridge solutions that carry the transit on a lower deck of a combined double-deck structure.

- A truss bridge represents a proven and economical bridge type solution for the project conditions, although public comments to date have been negative to this type of solution.
- An open-web box girder bridge type as proposed by CRC represents an attempt to improve on a truss arrangement, but in fact results in a bridge system that creates unnecessary structural design and construction complications, and does not provide significant aesthetic advantages over a truss.

- A double composite truss bridge type represents an option that is visually similar to the open-web box girder design, but is a proven and cost effective bridge type. If the lowest cost solution is desired for the project, then this structure type would be the likely winner.
- The extradosed prestressed bridge is a relatively new bridge type that can be economical in the span range of 400-600 feet. Since 1994 there have been more that 30 of this bridge type constructed worldwide, although there is only one in the U.S., currently under construction in Connecticut. It is noted that this bridge type is more structurally effective for narrow bridges. Also it has relatively short towers, and this combined with wide decks, twin bridges and a four or more span bridge, results in a short "squat" design appearance that is not particularly aesthetic. The BRP was not able to develop an alternative of this bridge type that could be recommended.
- A cable-stayed bridge can provide an economical and practical bridge type that can also have a striking appearance. The double deck arrangement and relatively wide cross section is a challenge for this bridge type. Initial attempts of a structural layout for a cable-stayed bridge by the BRP were less than satisfactory, but with a breakthrough of the spine-truss superstructure (discussed later in this report) a viable alternative was developed.
- Arch bridges can have the arch below or above the deck. A below deck arrangement did not fit this project well due to vessel clearance issues, and less than desirable foundation conditions. An above deck, multi-span tied arch can, however, provide a viable alternative, especially when combined with the spine truss superstructure developed for the cable-stayed alternative. It provides a similar aesthetic statement for the region as the cable-stayed alternative.

Therefore the BRP concluded that three bridge options, composite deck truss, cable-stayed and tied arch, are viable bridge types for this site and were advanced for further development.

With respect to the Columbia River Crossing bridge design, the BRP offers the following recommendations:

- **Recommendation 1: Discontinue further design or development work on the open-web box girder bridge alternative.**
- **Recommendation 2: Select a new bridge type from among the three feasible alternatives-cable-stayed, tied arch and composite deck truss.**
- **Recommendation 3: Proceed with further analysis and public review of recommended alternatives in order to select a preferred bridge type.**
- **Recommendation 4: Work with the FAA to resolve airspace issues with Pearson Field relating to either the cable-stayed or tied arch bridge designs.**

With respect to the Columbia River Crossing bridge design, the BRP offers the following secondary recommendation:

- **Review the potential impacts to the project description and technical studies for the environmental document and develop a work plan to maintain a realistic target date for the Record of Decision.**

Explore Additional Considerations

The panel identified several topics to investigate further, and conducted limited/base-line research and analysis in small teams during the evaluation and review process. These topics included:

- Focus on ways to reduce the risk and improve the aesthetics of the main river crossing design.
- Explore improvements to the horizontal alignment.
- Consider impacts of a change to airspace constraints.
- Consider replacement of the North Portland Harbor Bridge.
- Explore viability of a collector-distributer system.

Review of Open-Web Box Girder Design

The Independent Review Panel (IRP) Report dated July 27, 2010 included a recommendation to further consider the feasibility of the open-web box girder design proposed by the CRC Project team. This BRP was established, in part, to address that question. The BRP review of the open-web box girder design revealed that it is the product of an evolutionary process that resulted in a two-bridge configuration with highway lanes on top of each and LRT and bicycle/pedestrian facilities on the lower level of the downstream and upstream structures respectively.

The panel spent considerable time examining the open-web box girder design from information provided by the project team and also used independent analysis to assess the viability of this concept. This review found that substantial issues remain unresolved regarding the design of the open-web box girder and the constructability of this concept.

Design concerns include shear deformation, a decrease in flexural efficiency, and issues with shear flow between the concrete and steel members. In addition, the panel has concerns with the differential thermal expansion that would occur with the concrete and steel webs as well as problems associated with widening at the ends of the bridges.

Construction of the open-web box girder also presents problems that include the inability to pre-cast the individual segments due to erection distortion, casting sequencing for cast-in-place construction, and geometry control of the bridge while under construction. In addition, considerable risks are inherent in the pricing, procurement and potential for claims due to all of the abovementioned issues.

There are few issues with the proposed open-web section that cannot be addressed with sufficient time and money, although it is not clear that the same level of construction quality will be achieved with the proposed open-web design as is expected for more conventional box girder construction. Laboratory testing, as recommended in the earlier IRP Report, would need to extend to the point of a full demonstration project in order to address the entire range of concerns expressed by the Panel. Even this would not guarantee a resolution of the present concerns.

The BRP attempted to resolve the design and construction problems that were identified through the development of an alternative called the "enhanced" open-web box girder. These efforts were focused on those actions that could be implemented to modify the current design. The panel considered different web to upper and lower flange connections, maintaining constant web depth, inverted bottom web slabs to maintain the haunched girder look, and other improvements. Although the BRP modifications were definite improvements to the concept, ultimately, the underlying problems with the open-web box girder design could not be overcome in spite of the efforts of the BRP to do so. Hence, the recommendation is to stop advancing this concept and adopt one of the other three presented in this report. Appendix B contains more information on the panel's analysis of the open-web box girder.

Cable-Stayed Alternative

Figure 2 – Aerial View of Cable-Stayed Bridge

General Description

The cable-stayed bridge is feasible with an accommodation of aviation requirements relating to Pearson Field. The Portland International Airport (PDX) airspace, however, is not impacted. In elevation it is a four span cable-stayed bridge with a center tower and two side towers. Spans are 520, 830, 830 and 520 feet in length as shown in Figures 3 and 4.

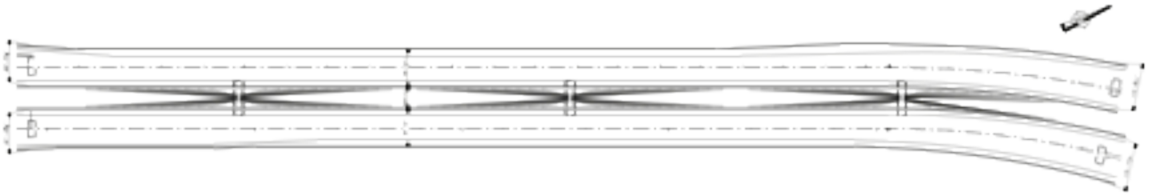

Figure 3 – Plan; Cable-Stayed Bridge

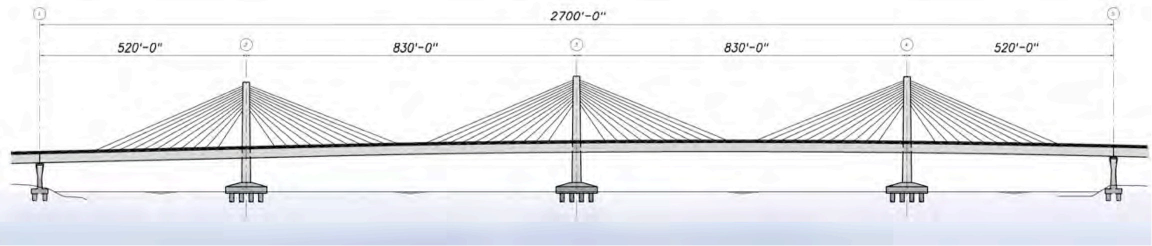

Figure 4 – Elevation; Cable-Stayed Bridge

The superstructure is a composite spine truss connected rigidly to the towers. As shown in Figure 5, the light rail transit (LRT) runs on the lower deck level through the split legs of the tower, while the pedestrian and bike lanes are arranged on an elevated promenade on the upper deck. Traffic lanes are placed east and west of the towers, supported by a longitudinal steel box girder and transverse beams.

Due to the low span-to-depth ratio of just 33 to 1, the structure will have some favorable characteristics of an extradosed bridge. Therefore the end spans can be larger than would be expected with standard cable-stayed bridges and the hold-down piers shifted apart from the last stays. The optimum ratio needs to be developed in the final design stages.

Superstructure Layout

The superstructure is shown in Figure 5. Its unique layout represents a key element of the cable-stayed bridge superstructure and is composed of the following elements:

- A core structure is made of a spine-truss with composite concrete decks at the top and bottom, supported by stay cables. The LRT runs inside this spine-truss, the pedestrian and bicycle traffic are on the elevated platform on top, and the spine truss has cantilevered decks left and right that support the roadway traffic. This typical section with the super-truss and cantilevers accommodates the variable widths necessary for ramp tie-ins near the approaches. The width of the roadway deck is greater than most cable-stayed bridges, but within the design parameters for this bridge type.
- Two outer steel boxes provide a considerable increase to the torsional stability. Should more torsional stiffness be required, bracing between the bottom strut elements can be inserted, which will almost double the area for torsion rigidity.

- Transverse trusses connect the inner and outer boxes and transfer loads from the deck into the stay cables. They are spaced at 30 feet. The concrete decks at the top and bottom are supported by steel girders spaced at 15 feet and could be replaced in the future.
- All structural steel is assumed to be HPS70.
- Cables are connected to anchor boxes next to the inner steel webs and follow basically the inclination of the tower legs; two planes are provided transversely.
- The inner steel webs are composed of a simple warren truss without vertical elements. The flanges of the webs are proposed as boxes, which can be filled in compression zones by high-strength self-compacting concrete, if required.
- The deck is transversely post tensioned, in recognition of the relatively wide deck.
- The deck can be detailed to be replicable by delaying the closure placement of the deck sections on the cantilevers. This is an important feature for assuring a long service life.

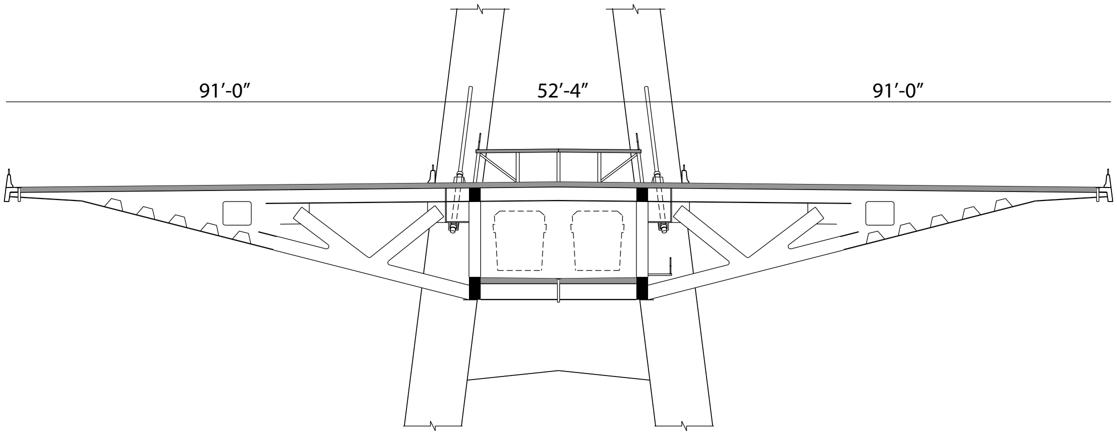

Figure 5 – Typical Section; Cable-Stayed Bridge

Tower Layout

The tower is an A-Type and runs through the deck, straddling the spine-truss so that the roadways can be arranged freely left and right (Figure 6). The height of the towers would be set just below the control surface for PDX airspace. The legs are made of solid concrete and the anchorages are mostly placed on top, where both legs are already connected.

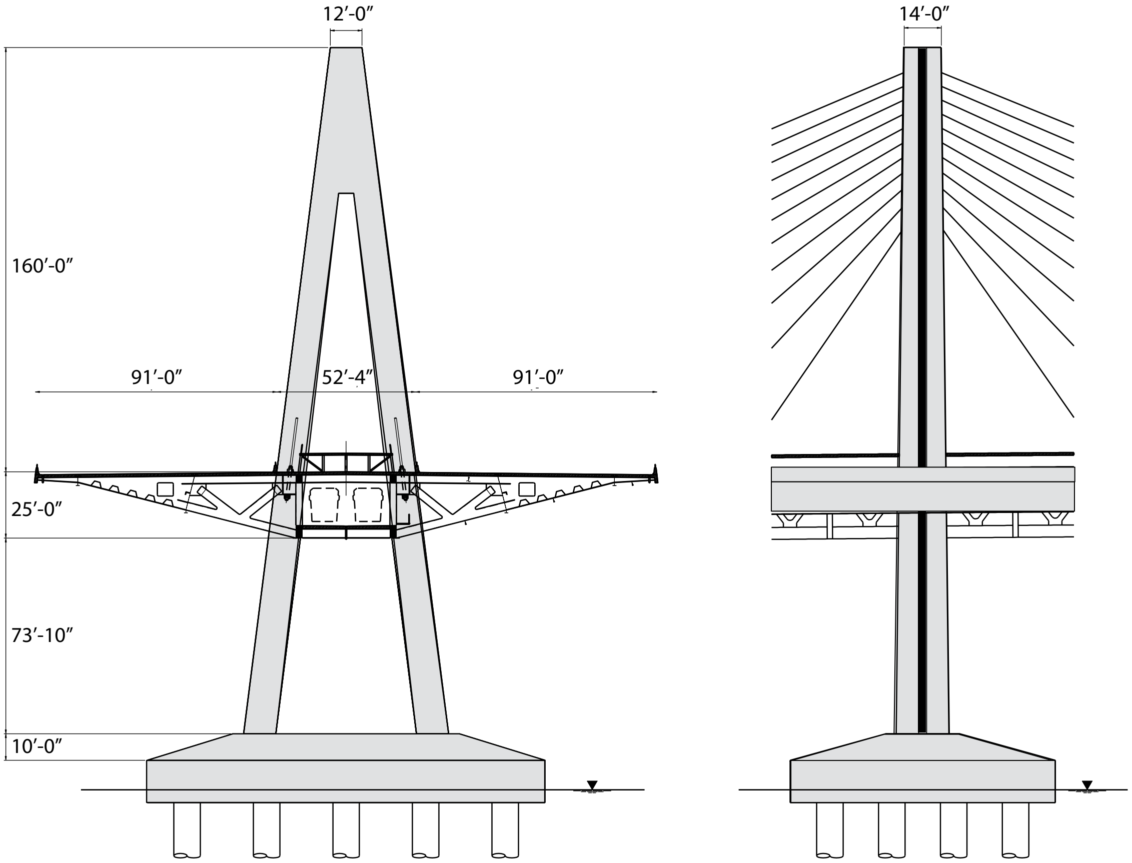

Figure 6 – Tower Elevations; Cable-Stayed Bridge

The anticipated foundations are water level footings supported by large diameter (currently estimated at 10 feet) drilled piles that are founded into the Troutdale formation.

The cable-stayed alternative has one foundation for each of the three towers, for a total of three foundations in the Columbia River. The current open-web box girder alternative has 12 foundations in the river, so there is a net reduction of nine in-water foundations. However, the individual foundations for the cable-stayed bridge are larger than those for the open-web box design and the net surface area of the foundations in the water are about the same (approximately 45,000 square feet).

Erection

The anticipated erection of the cable-stayed bridge will be done by proven methods used on many previous bridges. The towers would be erected by jump forming to their full height, serviced by a tower crane. Should the head be made completely of structural steel, which is a valuable option to be considered, it would be preferable to lift it in place by a floating crane.

The bridge superstructure would be erected by balanced cantilevering in two directions from the tower. The spine-truss would be cantilevered in each direction from the tower either in large prefabricated sections (lifted from the water by floating cranes), or by smaller piece-by-piece construction, and then supported by stay cables. Both schemes have previously been successfully used to erect other cable-stayed bridges. The cantilevered roadway box sections and attaching truss works would then be erected from the spine-truss. This repetitive procedure would continue from each tower until closure is achieved at the mid-span. Finishing works would include installation of the final riding surface, barriers, LRT rails and supporting mechanical and electrical works, and the elevated pedestrian/bicycle promenade.

The construction site "ceiling" is defined by the PDX and Pearson Field controlled airspace. Regardless of the bridge scheme, masts of cranes required for construction of towers and superstructures will project above the superstructure elevation. Since cranes and other equipment will likely be in place for extended time periods, permitting will be required with the FAA, as has been done on other projects across the country.

Aesthetics

Figure 7 – Riverbank View of Cable-Stayed Bridge

A rendering of the cable-stayed bridge is shown in Figure 7. The three concrete towers that project to approximately 280 feet above the river surface are the most distinctive visual feature of this bridge type. When viewed from a distance, these vertical elements define the crossing position within the surrounding area, and largely define the bridge's identity in the mind of the observer. This three-tower arrangement will be unique within the U.S. to the I-5 Columbia River Crossing. The towers are about 50 feet higher than the existing lift bridge towers but are to the south in less restricted airspace. The height of the towers, when combined with their scale, makes them dominant visual features in the surrounding landscape. When viewed from the roadway and shoreline areas near the bridge, the A Frame towers are simple repetitive forms that clearly express their function in supporting the bridge superstructure. The series of towers also act as reference points to define the traveler's position within the overall bridge length and also define the two major span positions relative to the overall river width. When viewed from more distant shoreline locations, the towers are perceived more in elevation view as slender elements that mark the crossing location within the overall surrounding landscape.

Another strong visual element is the 25-foot deep, continuous steel truss superstructure that extends across the entire river, with spans of up to 830 feet between the A Frame towers. The highly articulated cross section has a central steel spine truss, steel box section members cantilevered from the spine truss, and struts to support the box sections. As shown from the river bank (Figure 7), the repetitive truss member arrangement is perceived as a nearly horizontal inclined surface from vantage points close to the alignment, and slightly less opaque when viewed from more distant oblique ground vantage points. Given the crossing length, and orientation of the bridge relative to the shorelines, all vantage points will offer an angled view of the bridge. In addition, the cross section arrangement obscures a large portion of the truss fascia. As a result, the overall impression of the superstructure from many perspectives will be highly articulated and relatively opaque. Selection of an appropriate paint color may play a major role in the perception of bridge mass and relationship to the surrounding landscape. This articulated superstructure may also provide some interesting options for aesthetic lighting, with internal lighting radiating from within the structure.

From the perspective of structure massing, the above deck portions of the bridge will appear to be relatively light due to the minimal number of elements and their relative slenderness. In contrast, the wide deck width relative to the tower base width and north-south orientation of the bridge axis will place the substructure largely in shadow and below deck tower legs will be viewed in silhouette. Perceptions of the bridge at night would be greatly enhanced by lighting the tower legs and stay system.

Figure 8 – Roadway View of Cable Stayed Bridge

The stays are slender tensile elements that clearly express their function of supporting the superstructure from the towers. When viewed by travelers crossing the bridge on a path nearly parallel to the planes of stays (Figure 8), the stays can be perceived as a warped surface generated by a series of nearly parallel lines. From vantage points along the shoreline and close to the alignment, the stays will be perceived as individual and sometimes overlapping linear elements that have a complex geometric relationship. In contrast, when viewed from more distant shoreline locations, individual stays will not be perceptible and stays appear as relatively transparent surfaces that slightly obscure the distant landscape. Colored stays can be provided by using a colored, co-extruded sheathing on the cables.

Figure 9 – Multi-Use Path View of Cable Stayed Bridge

From the pedestrian's perspective (Figure 9), the trail location between the stay planes and tower legs has a dynamic influence on the perceptions of the cable-stayed bridge. Located directly above the lower level transit tracks and above the highway traffic deck level, the trail will provide a unique vantage point for looking out over the Columbia River viewshed and achieve a degree of physical separation from the adjacent high-speed traffic. Edge barriers for the trail do not need to resist high-speed traffic and could be open to a wide range of potential design treatments with respect to transparency and detail. It is envisioned that the experience will have some similarities to the Brooklyn Bridge pedestrian promenade. Similarly, the pedestrian and bicyclist experience of approaching and passing through the towers alongside of the stays would be unique. Walkway surface treatments and railings are beyond the scope of this study, but may be significant features in the user experience. Those shown are for illustrative purposes only.

The cable-stayed bridge is representative of contemporary bridge technology. No similar bridges currently exist within the immediate region (although the TriMet Willamette River Transit Bridge is a cable stay bridge concept, to begin construction in 2011). As a result, this bridge type would be iconic and perceived as a landmark by virtue of its basic form and scale. This is highly compatible with the stated objective of building a bridge that would be appropriate for crossing the Columbia River, a natural resource with deep meaning for regional history and identity.

Figure 10 – Aerial View of Cable-Stayed Bridge

Figure 11 – Riverbank View of Cable-Stayed Bridge

Figure 12 – Multi-Use Path View of Cable-Stayed Bridge

Tied Arch Alternative

Figure 13 – Aeriel View of Tied Arch Bridge

General Description

The tied arch alternative would be a relatively unique presentation, readily identified with the setting on the Columbia River. There are few similar structures, and none with the framing and deck section offered here.

The tied arch option is a moderate span, through structure that is designed to minimize piers in the river as well as provide for a signature structure across the Columbia. The general plan and elevation are shown in Figures 14 and 15. Like the cable-stayed alternative, the tied arch alternative penetrates the space previously reserved for Pearson Field, but not used under present operations. The tied arch does not encroach on PDX airspace, leaving a 35-foot cushion below that ceiling.

The main tied arch structure is framed with structural steel tubes filled with high strength concrete. This composite system allows for a smaller cross section than a steel only section, and should have some advantages for both initial erection and life cycle maintenance (there will be no interior to inspect). The arch is deck tied, springing from concrete piers that flow to a common foundation for successive spans. The current profile shows three equal arch spans, although further refinement may result in a larger central span with two shorter flanking spans for both operational and aesthetic reasons. The design presented here has vertical cables. A networked cable arrangement (cables placed in a crosshatched pattern) is also possible and should be considered as the design is further developed. Networking cables improves the strength and stiffness of the arch and can offer another visual dimension. The cross section and general lane layout follows that of the cable-stayed alternative, with both light rail and pedestrian promenade down the center of the cross section as shown in Figure 16.

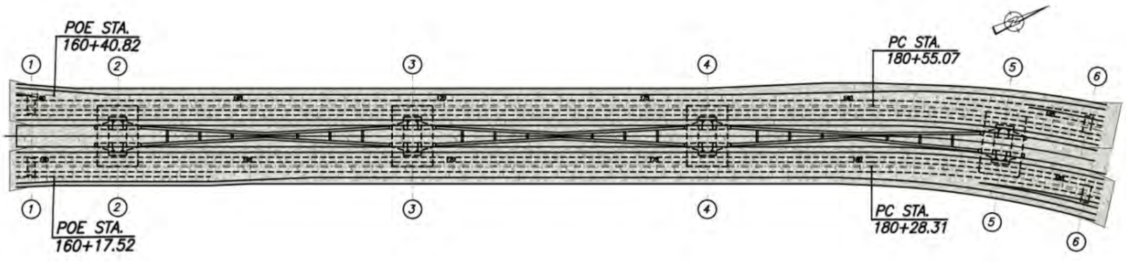

Figure 14 – Plan; Tied Arch Bridge

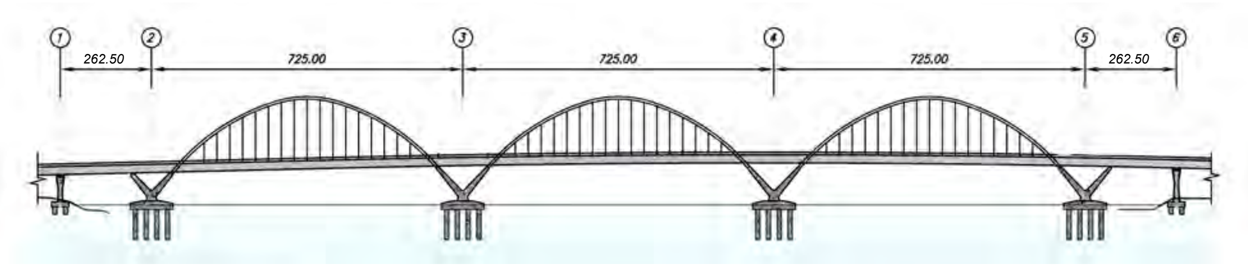

Figure 15 – Elevation; Tied Arch Bridge

Superstructure Layout

The superstructure section is similar to that of the cable-stayed alternative, consisting of a full width roadway framing system, cantilevered off the central truss that serves as a spine for the roadway. In contrast to the cable-stayed section, which is largely in compression from the stay cable, the spine truss serves as a deck tie for the arches, and so is in tension throughout. All structural steel is assumed to be HPS70 quality.

The main purpose for the deck tie is to eliminate thrust loads on the foundation during erection and to minimize the thrust loading during service conditions. The roadway sections that are cantilevered from the spine truss will frame the roadway deck transversely, and will be post tensioned as a transverse composite. The cross section shown in Figure 16 provides for full lanes in each direction about the center arch framing. The single support reduces the number of pier columns in the water from the open-web alternative. The original 12 pier columns are reduced to four piers, albeit with larger footings and Y-leg piers. At the conceptual level the overall footprint in square feet would be approximately the same as the open-web box girder; however, further design will refine this value.

The attributes of the tied arch alternative include the following features:

- Clean, transparent steel arch ribs above deck structure.
- Y-leg piers, expressing the flow of arch compression down to the footings.
- Spine truss arch tie, with transversely cantilevered deck sections.
- Elevated multi-use path promenade.
- Integrated transit corridor within the spine truss, utilizing the structural core for the major loads associated with rail service.

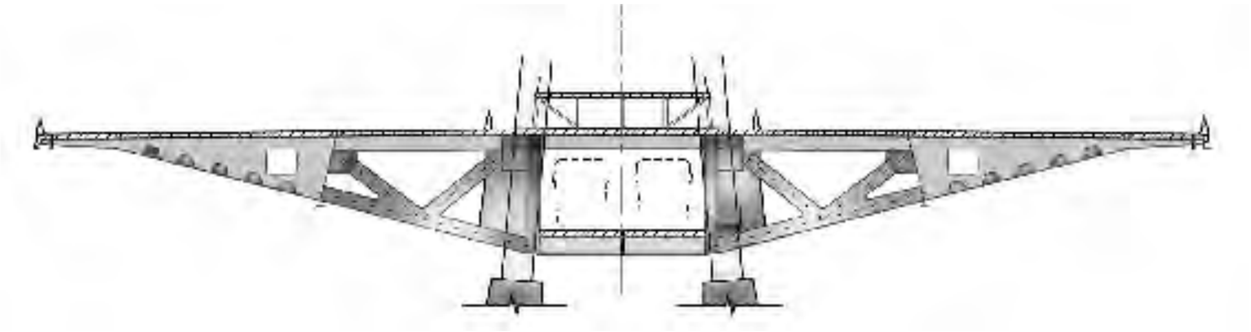

Figure 16 – Typical Section; Tied Arch Bridge

The steel framed composite deck truss is modular, with a repetition of the truss elements 30 feet along stations, with intermediate deck beams depending on the deck slab design. The central arch frame provides a canopy for pedestrians crossing the river and a beacon for those vehicles crossing the Columbia River by auto.

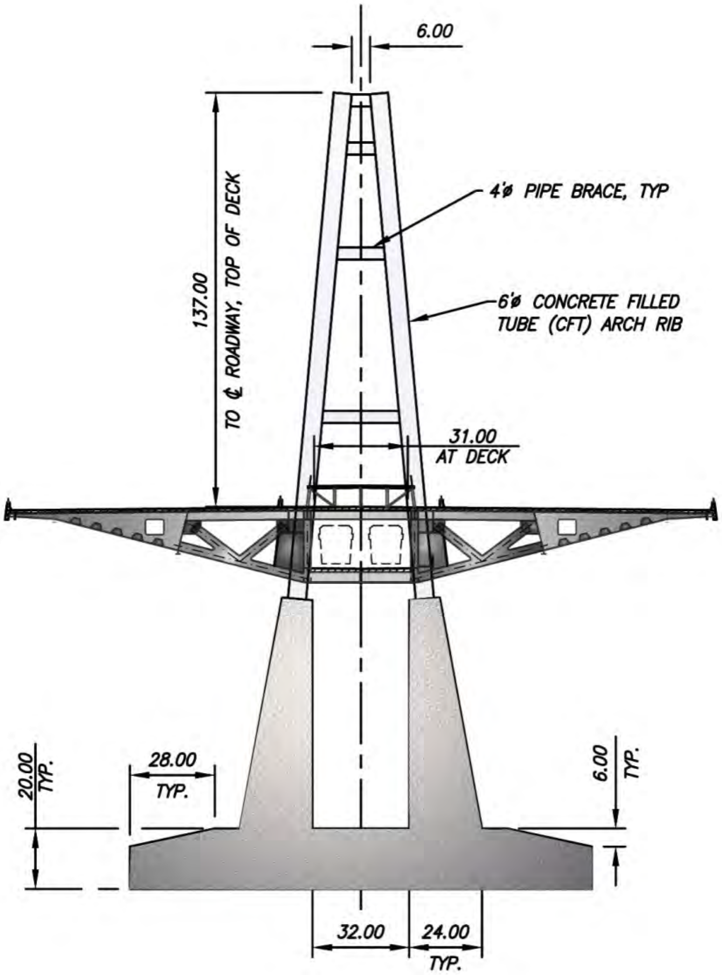

Figure 17 – Pier Elevation; Tied Arch Bridge

Foundations

The foundation is comprised of 10-foot diameter drilled piles supporting a single footing. Y-leg piers are tapered above the footing to match the springing of the arch ribs, providing a smooth line from foundation to the arch, and a clear flow of forces down into the foundation. The A-frame structure of the arches provides an openness (Figure 17) allowing light to penetrate for pedestrian and transit.

Erection

The 600-foot clear span length for the steel arch is larger than for the composite deck truss, which may lead to the use of two in-span temporary bents during spine truss erection. Following completion of the falsework-supported truss, additional falsework bents can be placed on top of the spine truss to temporarily support the arch rib sections. Once arch rib erection is completed for a span, hangers are installed and stressed, and the arch thrust is resisted by the spine truss acting as a tie member between the tops of the supporting delta pier members. The temporary in-water bents are then removed and the load transmitted directly to the delta piers.

Alternatively, the arch and spine truss may be pre-assembled and floated into place. The Y-leg piers and spine truss tie would be erected and stabilized prior to executing the lift of the tied arch section as a unit.

The feasibility of either erection method, as well as others that have not been identified, will need to be evaluated in more detail during preliminary design should the arch alternative be selected as the final bridge scheme.

Aesthetics

Figure 18 – Riverbank View of Tied Arch Bridge

The steel arch ribs that project to nearly 250 feet above the river surface are the most distinctive visual feature of this bridge type (Figure 18). When viewed from a distance, these arch members define the bridge identity while providing a rhythm to the overall bridge composition and dominant visual forms within the surrounding landscape. The series of arch ribs also act as reference points to define the traveler's position within the overall bridge length and also define the three major span positions relative to the overall river width. When viewed from more distant shoreline locations (Figure 18), the arch ribs are perceived more in elevation view as slender classical elements that mark the crossing location.

Steel arch ribs are shown as composite steel tube sections, but could also be closed sections with a rectangular, trapezoidal or other more articulated cross section. They are inclined in a basket-handle arrangement that minimizes the need for lateral bracing between the arch ribs, minimizes the number of above deck structural members, and provides a unique visual identity.

The 25-foot deep, continuous steel truss superstructure extends across the entire river, with spans of 725 feet between the concrete delta frame piers. The cross section arrangement of the superstructure is virtually identical to that of the superstructure shown for the cable-stayed bridge, and the overall impression of the superstructure when viewed from many perspectives will clearly communicate the function of forms.

Visually, the above deck portions of the bridge will be relatively light due to the minimal number of elements and their relative slenderness. In contrast, the wide deck width relative to the tower base width and north-south orientation of the bridge axis will place the substructure largely in shadow and below deck tower legs will be viewed in silhouette.

Figure 19 – Mulit-Use Path View of Tied Arch Bridge

Hangers connecting the superstructure with the arch ribs can either be bridge strand or stays, similar to those used for the cable-stayed bridge scheme. The hangers will be perceived as an inclined planar surface by directly adjacent trail users and motorists, and a similar perception will be gained when viewed from vantage points along the shoreline and close to the alignment (Figure 19). In contrast, when viewed from more distant shoreline locations, individual hangers will be virtually imperceptible.

The trail user's experience will be similar to that of the cable-stayed bridge. The elevated, centrally located trail location will provide a unique vantage point for looking out over the Columbia River viewshed. One significant difference will be the presence of a continuous arch rib directly above the trail as opposed to the separated tower positions of a cable-stayed bridge. The height of the arch above the observer will vary as one crosses the bridge, which results in a unique experience as one passes through a series of three arches (Figure 19).

The tied arch bridge also is very compatible with the stated objective of creating a bridge that is appropriate for consideration at this special site. As with the cable-stayed bridge, the basic form and scale of the arch scheme would make this a landmark bridge. However, arch bridges also have another level of meaning given the historic construction of arch bridges in the surrounding area designed by Conde McCullough and others. Unlike the cable-stayed bridge, the arch combines traditional forms with a highly contemporary interpretation of an arch bridge form to result in an iconic structure. The arch form will also be clearly distinguishable at large distances from the site, which would result in this bridge becoming a major element of the surrounding area visual context. All of these features make this bridge very appropriate for consideration at this special site.

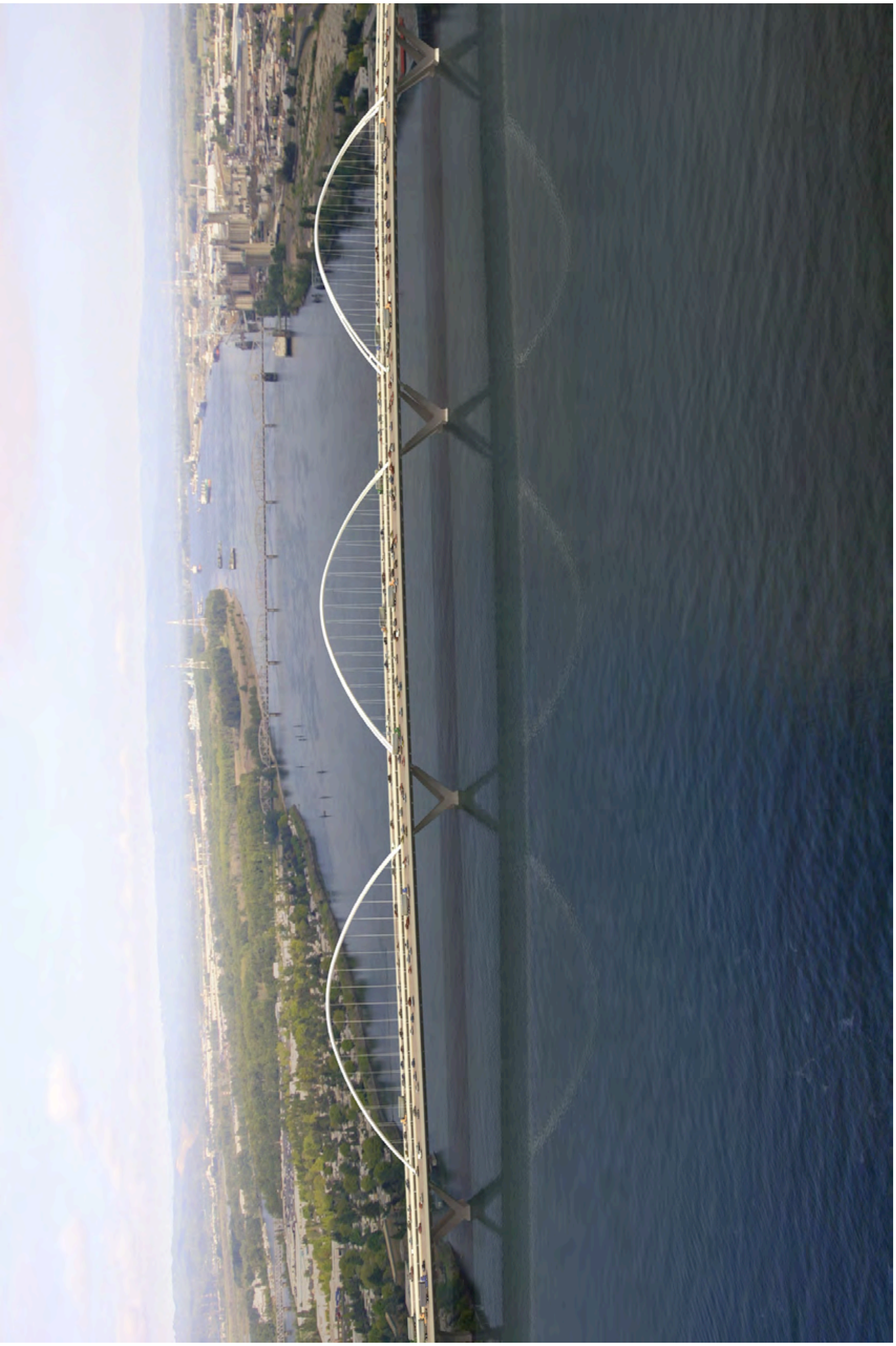

Figure 20 – Aerial View of Tied Arch Bridge

Figure 21 – Riverbank View of Tied Arch Bridge

Figure 22 – Multi-Use Path View of Tied Arch Bridge

Composite Deck Truss

Figure 23 – Aerial View of Composite Deck Truss Bridge

General Description

The composite deck truss provides an alternative to the open-web box girder option and meets all of the current project constraints, is similar in appearance, and can be constructed at lower cost and with less risk than any other recommended alternative. It is based on the general layout of the open-web box girder option. It has both north and southbound roadway traffic on top and LRT and pedestrian/bike lanes on the bottom deck. Each one is in a separate box, similar to the open-web box girder option. However this option avoids the technical limitations of the open-web box girder design, and is a "proven" structure configuration.

The superstructure is split into two independent elements, a southbound and a northbound box structure. Each box is supported by a single pier. The span lengths are 350 - 500 - 500 - 500 - 500 – 350 feet, leading to a total length of 2,700 feet (see Figure 24). The transition of the main bridge to the approaches is proposed to be located just on shore. The piers arranged at these points need to be slightly wider to accommodate the expansion joint and the widening of the deck, which is illustrated in Figure 25.

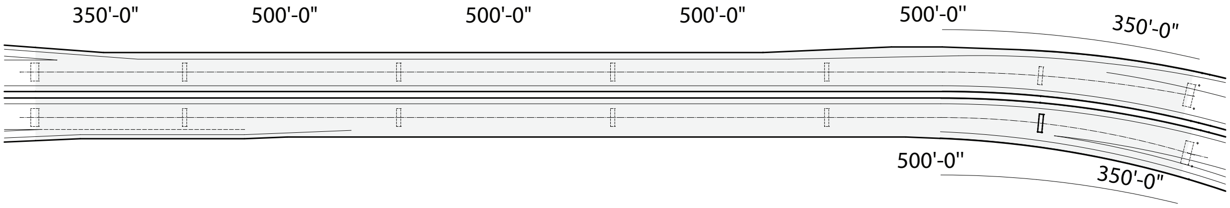

Figure 24 – Plan; Composite Deck Truss

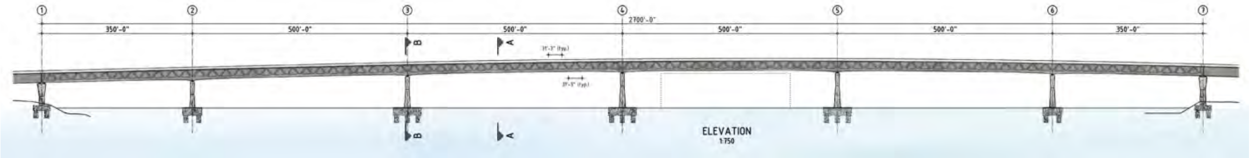

Figure 25 – Elevation; Composite Deck Truss

Superstructure Layout

The superstructure is composed of the following:

- Steel frames in the transverse direction spaced at about 15 feet. The frames act within the box as Vierendel elements.
- Two longitudinal, slightly inclined webs with Warren type trusses and no vertical elements. The joints are spaced at 31feet, 3 inches apart and need to be carefully shaped to enhance the elegance of the truss. Inclination of the diagonals is constant along the structure (about 45°). See Figure 29. The top and bottom chord of the trusses are boxes. If necessary (in compression zones) they can be filled with concrete. They support the transverse frames, with every 2nd frame located directly at the joints. The depth of the bottom chord increases from 5 feet to 8 feet, 5 inches towards the piers and provide a slight haunch. See Figures 26 and 27. If desired this haunch could be increased to about 8 feet.

- A 12-inch thick top deck made of precast concrete elements, suitable for three layers of longitudinal rebar (likely required over the piers). Joints are preferably arranged directly above the top flanges of the transverse steel girders and the longitudinal top cords of the web truss. These steel elements are provided with shear studs to create a continuous composite action. This design could allow for deck replacement.
- A bottom plate composed of a steel plate (about ½ inch thick) and a cast in place (CIP) concrete deck. The plate is stiffened to allow casting of the concrete without additional formwork and is provided with shear studs to achieve the composite action. The thickness of the concrete varies between one foot in the mid-span and about three feet towards the piers.
- All structural steel is assumed to be HPS70 quality.
- A fascia is proposed at the end of the cantilevers, made of precast elements, integrated with the barriers.
- Railings are placed on top of the barriers and between the truss elements on the bottom paths.

The typical superstructure arrangement is shown in Figures 26 and 27. At both ends of the bridge the structure widens to accommodate the ramps. This can be done by increasing the cantilever of the transverse girders. Should this cantilever become too long, the width of the box can be increased without changing their inclinations, as shown in Figure 28.

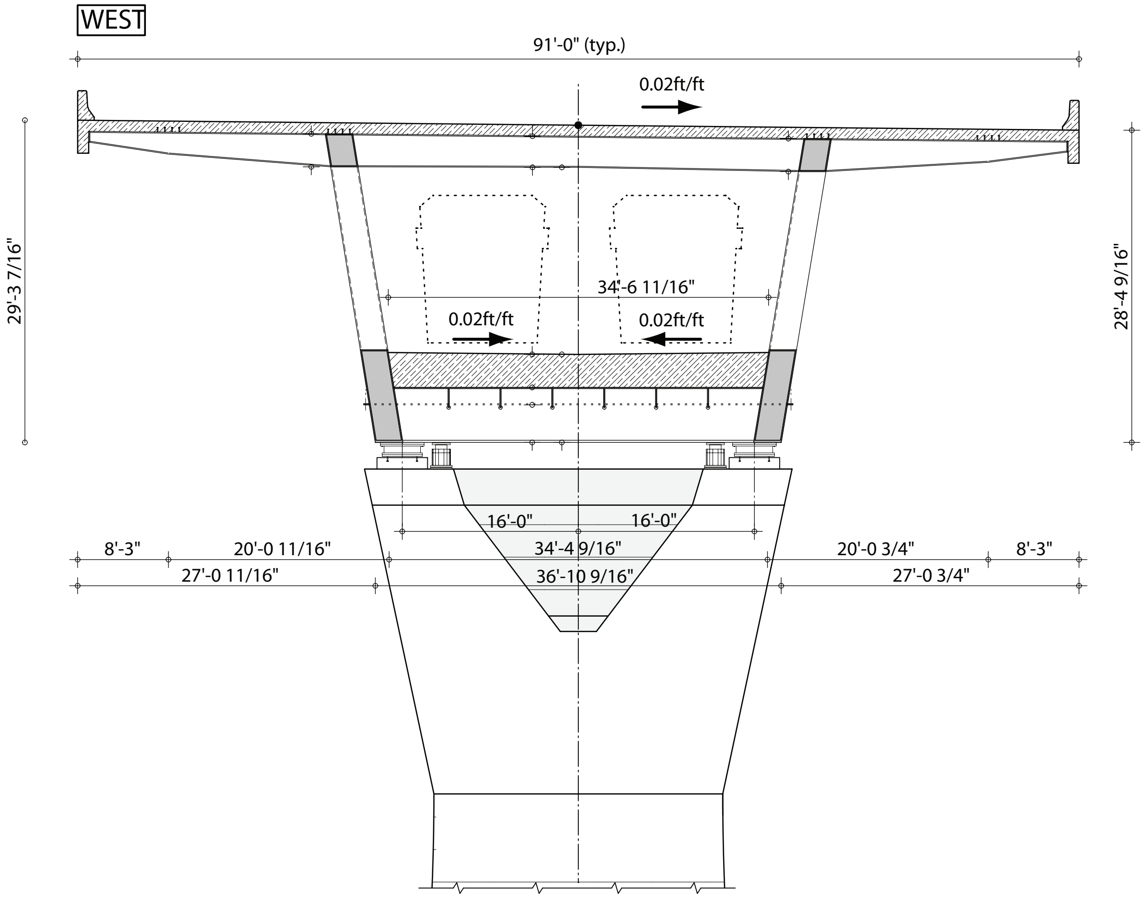

Figure 26 – Standard Section at Pier; Composite Deck Truss

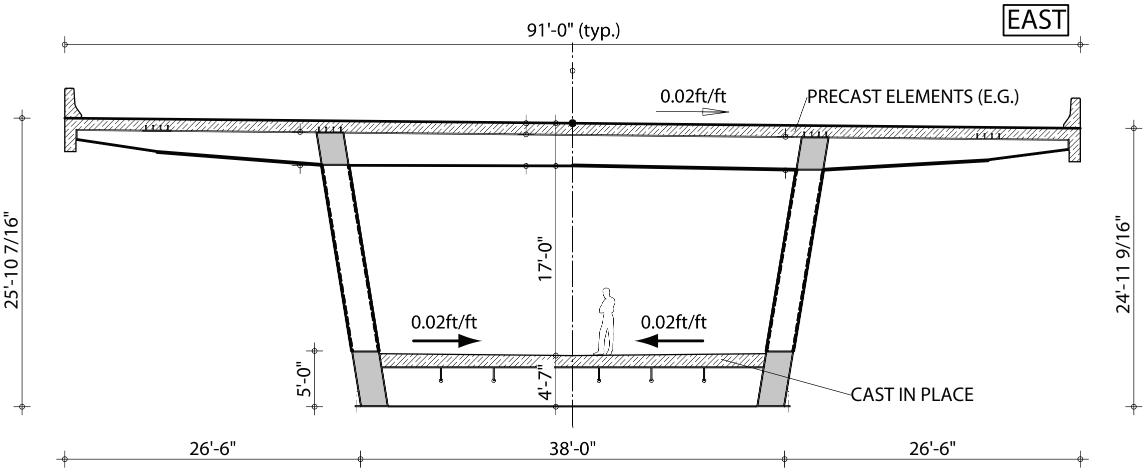

Figure 27 – Standard Section at Midspan; Composite Deck Truss

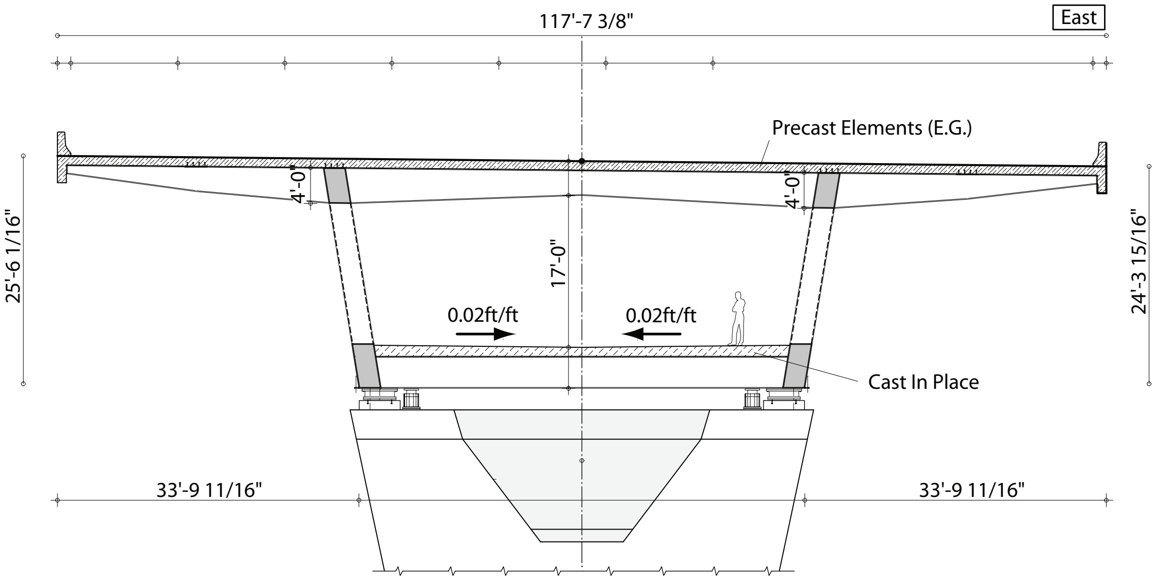

Figure 28 – Section with Maximum Width; Composite Deck Truss

Pier Layout and Articulation

One pier is arranged under each box. The pier head is subject to final aesthetic development. Depending on the seismic loads, piers will be designed as ductile structures or in the elastic range. Generally, the piers for this alternative can be similar to those of the open-web box girder alternative, but they are reduced in size, since the weight of the superstructure is less.

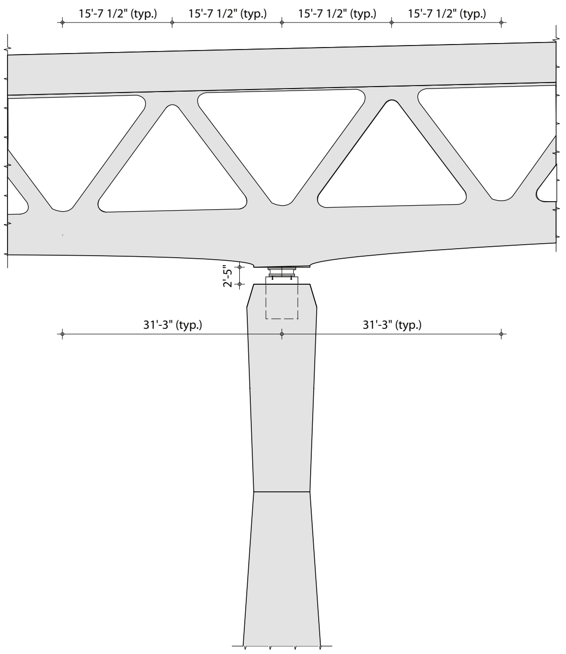

Figure 29 – Elevation at Piers; Composite Deck Truss

Typically, one guided bearing and one multidirectional moving bearing is provided on top of each pier as shown in Figure 29. The three piers in the center will be provided with longitudinal fixed bearings. Should the lateral seismic forces become too large for the guided bearings, transverse support can be provided by shear keys.

Further reduction of lateral loads, compared to the reductions achieved by reducing the dead weight, can be achieved by provision of isolating bearings.

Foundation

The anticipated foundations are water level footings supported by large diameter drilled piles that are founded into the Troutdale formation, similar to the open-web box girder. The number of foundations is reduced by one. This and the size reduction due to reductions in dead weight result in approximately 25% less in the water-line surface area relative to the current open-web box girder design.

Erection

The main span lengths for the composite deck truss scheme are 500 feet, which results in a span to depth ratio of 20 and may allow for a free cantilever erection until the mid-span closure is reached. It may be necessary to utilize temporary bents to provide for stability during truss erection, placed on the pilecap or in the water. This would be subject to an investigation into their effect on navigation and marine issues.

One promising approach would be to erect the complete steel element in one segment between panel points, which would make the segments approximately 31 feet, 3 inches long. The segments would be bolted to the previous erected structure and the concrete slab placed immediately following the steel erection. The CIP bottom slab would be placed over the full soffit width. The deck slab could be erected as a precast element, which is erected using the same derrick which was used for erecting the steel truss segments. It is estimated that each segment weight will vary between 110 and 140 tons depending on the location within the bridge length.

Incremental launching would only be possible for an alignment with constant curves in plan and elevation; therefore the north end would need a different erection method. It requires a constant depth of the girder, so the haunch would not be practical. For both reasons the incremental launching is not considered as an entirely feasible erection method for the entire span for this alternative.

Aesthetics

Figure 30 – Riverbank View of Composite Deck Truss

Similar to the current open web design the deck type bridge has far different visual features when compared to the cable-stayed and arch bridge alternatives. There are no above deck elements that define the experience of the stationary viewer at ground level, the motorist and pedestrians; however, this structure provides unobstructed views at the deck level. See Figure 30. In addition, the deck type bridge has no feature that defines its position within the distant landscape, or provides the bridge with a unique identity. Clearly, this is more of a "utilitarian" design, and should be detailed to provide a simple, clean structural system that is unobtrusive and blends, as much as possible, into the landscape.

The below deck piers are the only vertical bridge elements. The two lines of piers supporting the twin superstructures are relatively slender. However, since there are ten piers, oblique views may perceive the piers as visual obstructions to cross-river views. Articulated or sculpted pier forms, similar to those shown for the open-web box girder, are appropriate for consideration in developing a sense of identity for this major bridge. Since the new piers will extend above the river surface to nearly the upper elevations of the existing bridge trusses, they will be visible from more vantage points than the existing solid wall concrete piers. However, the primary viewpoints will be limited to the shoreline areas.

The primary visual element will be the 25-foot deep, continuous steel truss superstructure that extends across the entire river, with spans of 500 feet. In contrast to the cable-stayed and arch bridges, the superstructures for the twin composite steel trusses are relatively simple and unarticulated. Given the crossing length, orientation of the bridge relative to the shorelines, and multiple planes of trusses, there are no land based vantage points from which the truss bridge can be seen in a classical elevation view- see Figure 30. The overall impression of the superstructure from many perspectives will be somewhat opaque. As with the two other bridge types, selection of an appropriate paint color may play a major role in the perception of bridge mass and relationship to the surrounding landscape.

Figure 31 – Composite Deck Truss Rendering, View from Multi-Use Path

From the perspective of light, the wide deck width overhangs and north-south orientation of the bridge axis will place each superstructure and substructure largely in shadow. Lighting of the below deck trail area may be a design consideration.

The trail user's perspective would be far different than on the other two bridge types. The trail is located in the under deck area of one of the bridge superstructures. While this will provide a large degree of physical separation from traffic at the deck level and protection from the elements for those on the long crossing, this will be somewhat offset by the lack of natural light - see Figure 31. A significant advantage of the below deck crossing for bicycles and pedestrians will be the reduced noise from the roadway traffic that will be present for both the cable-stayed and tied arch alternatives. Views up the river will be relatively unobstructed, while down-river views would be somewhat more obstructed by the truss diagonals on the opposite bridge that carries traffic. The repetitive structural system, long bridge length, and lack of visual cues to mark ones location on the crossing may result in a tunnel perception. While entry and exit portals of the trail are not addressed, appropriate consideration should be given to their design.

Figure 32 – Composite Deck Truss Rendering, Driver Perspective

Figure 32 reflects the driver's perspective while crossing the composite deck truss bridge. It is like many other bridges in the country that provide significant functionality while being largely void of anything remarkable about the traveling experience.

The composite deck truss bridge is representative of a bridge type that has historically been utilized in the area and is largely without a special identity in the mind of most observers. As with the arch bridge, this is a contemporary interpretation of a traditional bridge type. However, limitations imposed by the basic structural form and project constraints limit the range of potential modifications of this bridge type. In addition, since deck type bridges represent by far the majority of our contemporary bridge inventory, they are inconspicuous and largely lack an identity. While the monumental scale of the project does provide for a degree of significance, it would be very difficult to develop a composite deck truss or any other girder bridge to a form that could readily be perceived as having a similar signature appearance to the cable-stayed and arch alternatives. As a result, it is difficult to present any truss bridge as an architectural solution that would be appropriate for this special crossing of the Columbia River. Ultimately, the composite deck truss closely resembles the open-web in appearance and form.

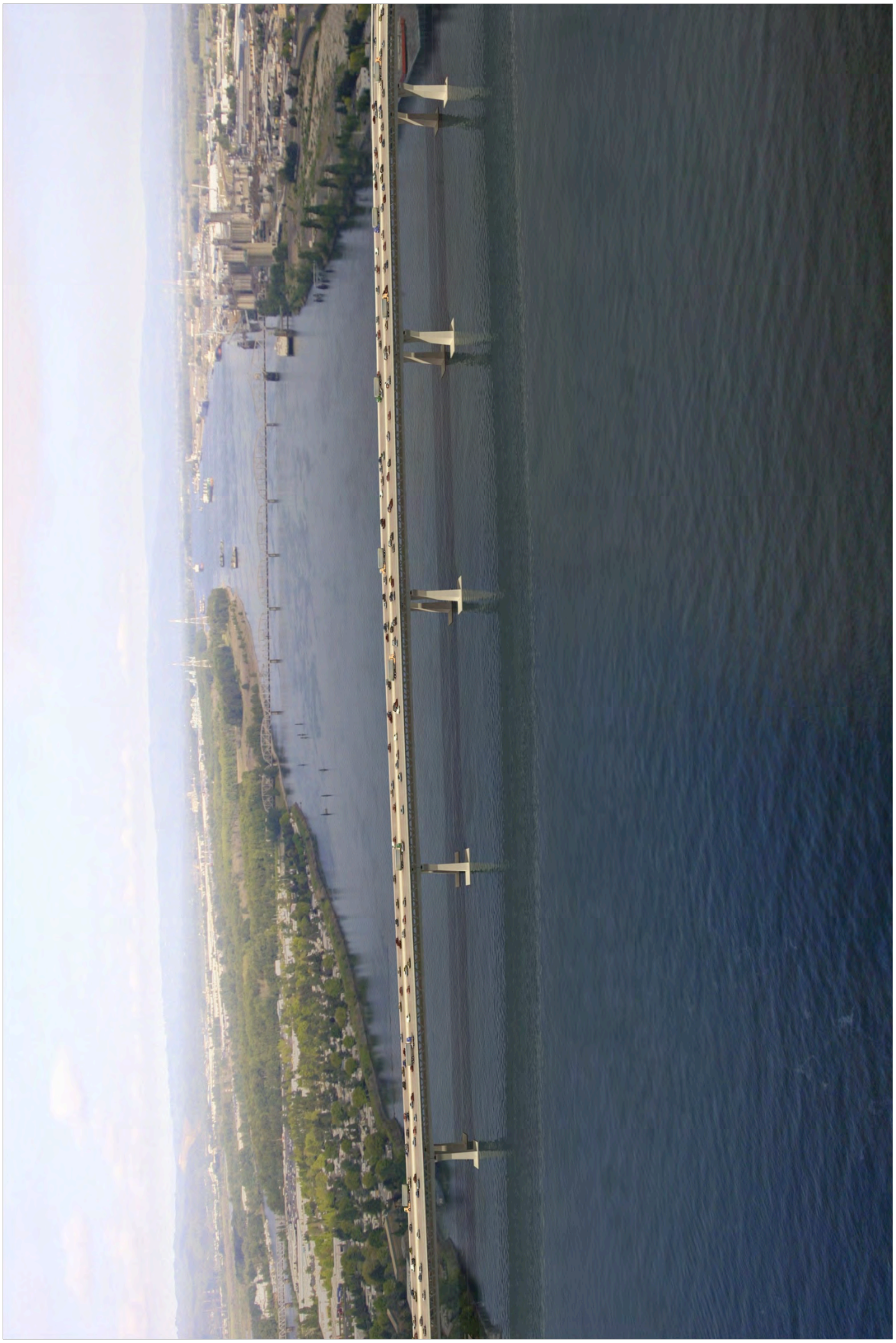

Figure 33 – Aerial View of Composite Deck Truss Bridge

Figure 34 – Riverbank View of Composite Deck Truss Bridge

Figure 35 – Multi-Use Path View of Composite Deck Truss Bridge

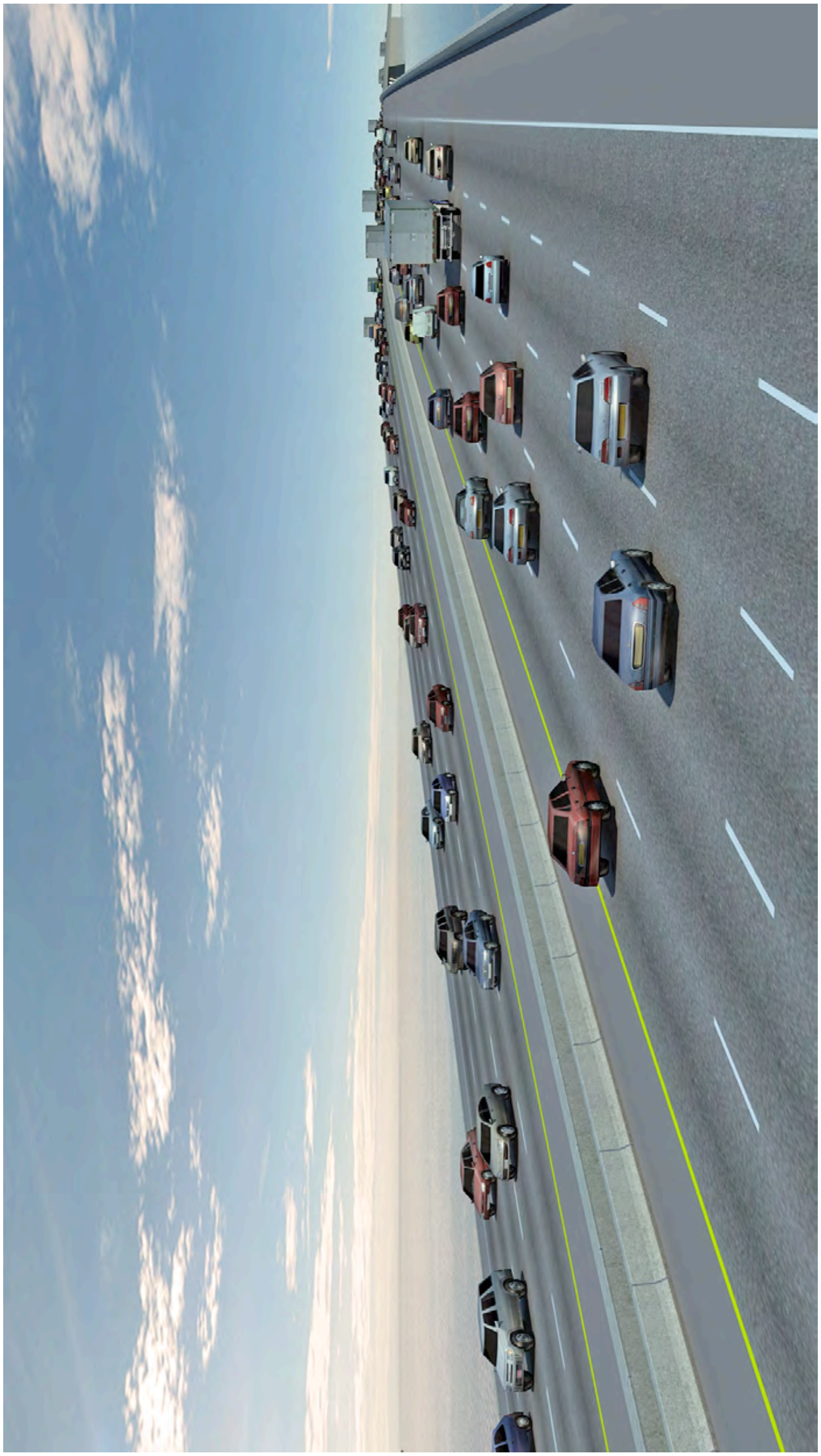

Figure 36 – Roadway View of Composite Deck Truss Bridge

Cost Estimates

The cost estimate for the open-web box girder option that has been developed by CRC is based on partially developed design and material quantities. The bridge cost was developed based on a "contractor-style" estimate that built costs up from permanent material cost, construction material cost, labor cost, construction equipment cost, transportation cost, etc. These costs were adjusted by indirect costs, burden costs and mark up. They were further adjusted to include escalation, bond costs, builders risk insurance and other pricing contingencies, and subjected to WSDOT's CEVP (cost estimate validation process) to include project fees, risk and contingencies.

In contrast to the methods used by CRC for the project estimate, the cost estimates for the three alternative bridge options developed by the BRP are based on experience within the panel considering member sizing and quantities from other similarly built projects. It is also based upon estimated member sizing and quantity calculations for the given width and spans required for this site. For the purposes of decision-making in a more practical and normalized manner for all the alternatives under consideration, an "engineer-type" estimate is used that identifies the major material quantities that significantly contribute to the overall bridge costs with additional considerations to project contingencies. For consistency with the assumptions and methods used by the panel, a new cost estimate was prepared for the open-web box girder option that is based on an "engineer-type" cost estimate approach, similar to the three options proposed by this panel. This estimate uses quantities taken from the existing open-web box girder design, combined with similar unit prices used for the other three options.

The estimates presented here are considered appropriate for identifying the potential costs for the Columbia River Bridge in a comparative and normalized manner as noted above. These costs should be further developed and validated in the ongoing Type, Size, and Location (TS&L) development of the project. However, it is the Bridge Review Panel's assessment that the unit price based cost comparison for all the options is a more meaningful assessment of relative costs at this early stage of development, both for the current open-web box girder design and for the conceptual designs developed by the panel based on experience and reference to other projects.

Other basis of estimate used in this study include the following:

- Estimates were developed based on 2010 unit prices to represent the relational costs for the structure types presented solely for comparison purposes only. No escalation to construction year is included.
- The costs presented are for the 2,700 foot river crossing structure for all the alternatives, and do not include the end transition piers.
- Design costs are included as a contingency percentage of the bridge type costs which, for comparison purposes, reflects the degree of effort needed for the given bridge type complexity.
- A mobilization cost of 10% was included on all options.
- A design contingency of 10% was included for the composite deck truss, tied arch and cable-stayed options. This contingency was increased to 15% for the open-web box girder, recognizing the panel assessment that some design research will be ultimately necessary to develop an acceptable design.
- A construction contingency of 20% was included for all options.
- The estimates have not been assessed through WSDOT's CEVP.

The cost spreadsheets developed for this study are included in Appendix C, and the cost summary is as follows:

Table 5 – Summary of Estimated Costs for Bridge Types

Bridge Option	Cost	Cost Index	Square Foot Cost
Open-Web Box Girder	$ 440,000,000	1.00	$ 849
Tied Arch	430,000,000	0.98	680
Cable-Stayed	400,000,000	0.91	632
Composite Truss	340,000,000	0.77	656

Note: Square foot cost for cable-stayed and tied arch are based on 632,700 square feet of deck area and the composite deck truss and open-web box girder are based on 518,300 square feet. The difference accrues from configuration changes between the bridge options for the roadway, transit and pedestrian/bicycle ways.

A few comments are appropriate on this comparison. The composite deck truss option is shown to cost about 23% less than the open-web box girder. A significant portion of this difference is in the more efficient section and optimization of the material used in the superstructure. The composite deck truss is a more structurally efficient system from a material viewpoint. In addition the composite deck truss can be constructed more efficiently and with less risk; and it is important to note that the cost estimate does not attempt to capture these additional benefits (costs are based on material alone). The steel composite superstructure will be lighter than the open-web box girder resulting in smaller foundations, which can become a significant contributor to the project costs and delivery given the complexities associated with in-water construction.

Additional Considerations Impacting Bridge Type Recommendations

Aviation

The Columbia River Crossing Project lies in proximity to the Portland International Airport (PDX) and Pearson Field. Each one provides aviation service to the communities of Portland and Vancouver respectively and the region as a whole. The interrelationship between the main span of the project and the operations of both of these aviation assets is an important factor in determining the optimal solution for crossing the river.

Figure 37 – Pearson Field with Current and Future Towers

Note that the approach and departure route for 10L passes over the top of the western end of Pearson Field and those of that 10R pass just south of the mid-point of the I-5 bridge crossing. In addition, the lift towers for the current Columbia River Crossing are in approximate alignment with the end of the runway at Pearson Field.

For many years the two facilities have had to operate safely together and those using Pearson have modified the western departures to not only avoid the lift towers of the current Columbia River Crossing bridges but also the approach for 10L for PDX. In order to do so departures to the west from Pearson Field remain to the north of the northern bank of the Columbia River and turn further to the north towards Lake Vancouver. If aircraft approach from the west they enter the pattern north of Pearson Field and fly over Vancouver making a series of left turns until they line up with the runway. At all times this pattern keeps them north of the river, away from the landing pattern for PDX's 10L and north of the Columbia River bridges.

A number of FAA regulations govern the restrictions relating to obstructions that are in proximity to aviation facilities like PDX and Pearson Field. One of these is Federal Regulation 49 CFR Part 77, which establishes standards and notification requirements for objects affecting navigable airspace. It is used to chart new man-made or natural objects which might impact safe operations of aviation facilities. It guides decision-making relating to the height and lateral distance structures can be in relation to aircraft routing. Currently, under the strict interpretation of Part 77, the lift towers for the existing bridges are an encroachment into the available Pearson Field airspace. However, both the bridges and Pearson Field pre-date the establishment of Part 77 and a "grandfathering" action has occurred to allow this situation to exist (see Figure 37).

In considering new crossing alternatives for the Columbia River the panel sought to reconcile the goals and objectives given to the panel with constraints imposed by Part 77 and other FAA regulations. Both Pearson Field and PDX were examined separately to ensure proper consideration for each as described in this section.

While a number of the aspects of the flight operations need to be considered for safety at PDX the one criterion that governs many of the decisions relating to the new Columbia River Crossing is the One Engine Inoperative (OEI) elevation at the bridge itself. In the case of 10R which crosses just south of the middle of the bridge the OEI elevation varies from

280 to 284 feet depending on the specific alignment of the bridge. Thus, any structure extending above the deck of the new bridge, whether as a structural element such as a tower, or lighting or a sign structure should not protrude above that elevation. Taking into account navigation requirements for clearances below the bridge and the depth of the bridge structure itself this OEI elevation allows for a structure with a nominal height of approximately 160 feet above the bridge deck which is within the parameters of typical tied arch and cable-stayed bridges.

Among the other factors impacting PDX that bridge designers will need to consider is any lighting of the bridge itself and potential confusion that might occur for pilots of approaching aircraft at night. Another would be the radar impacts or interference that might result from stay cables or other features of a bridge. Each of these would have to be addressed in the engineering design process and would require appropriate reviews and approvals from the Federal Aviation Administration. While not trivial in nature, these types of approvals are achievable with proper documentation, engineering and coordination with the FAA so they do not represent insurmountable barriers.

As noted earlier, the current situation at Pearson Field requires special operations for those departing to and approaching from the west to avoid the approach pattern for 10L. It is anticipated that these limitations imposed by PDX on Pearson Field operations to the west will not change, regardless of the bridge type selected for the new crossing.

The conceptual design for each of the bridge types holds as one of the principal criteria the need to provide a navigation channel under the new crossing that does not require a lift span of any kind. The current proposed clearance is 95 feet based on historical river traffic. With this characteristic for the new bridge the removal of the current lift towers becomes possible and a new lift span structure unnecessary. With the removal of the lift towers the theoretical obstruction concerns they impose on Pearson Field operations is no longer an issue.

As noted earlier the new bridge will have the possibility of at least some vertical superstructure above the roadway surface either in the form of roadway lighting or signage or towers/arches. They range in height from approximately 20 feet to the possibility of a cable stay tower of 160 feet. Given that Pearson Field operations are already restricted to the north shoreline of the Columbia River by agreement with PDX and the cable-stayed tower and arch rib are well to the south of this shoreline, there will be substantial improvements to the operational safety of Pearson Field as compared to the existing bridge with its vertical lift towers (see Figure 37).

Navigation

One area that the BRP reviewed during its assessment of bridge types was the issue of navigation. Currently the Columbia River Crossing Bridges provide access up and down river for large navigation traffic by opening the two lift spans, allowing the maximum vertical height of 179 feet. These lifts or openings for river traffic occur infrequently but often enough to make these operations disruptive to traffic on I-5. Current time restrictions discourage such events from taking place during hours of peak traffic flow across the river but that is not always possible.

One of the objectives of the CRC has been to remove the need for lift spans by constructing a bridge with a higher clearance than exists today. During the preliminary work performed by the CRC in this regard they have done several things. First, they inventoried the river traffic and determined the number of vessels requiring the opening of the bridge. This inventory is included in their report entitled, "Navigation Technical Report, 2008." It concluded that the majority of the traffic passing under the bridge could do so with a bridge height above the water of 95 feet. Through discussions with the US Coast Guard this became the standard against which the CRC project designers advanced the engineering for the replacement bridges.

The panel examined the navigational clearance stemming from the process described in the referenced report and determined that this was one constraint that might be challenged in the process of considering new bridge types. However, as the BRP advanced their bridge alternatives it was found that such a challenge was unnecessary and that all of the proposed new bridge types could accommodate the already negotiated clearance of 95 feet.

A second navigational issue has to do with the channel alignment for river traffic. Currently vessels traverse the existing Columbia River Crossing by passing beneath the northern most opening whether or not they require a lift span operation. Sometimes however, they traverse a more southerly pathway under the bridge. The disadvantage of this more southerly route is that this traffic must line up with the railroad bridge to the west, which requires a sharper turn in the river channel between the two bridges (Figure 38).

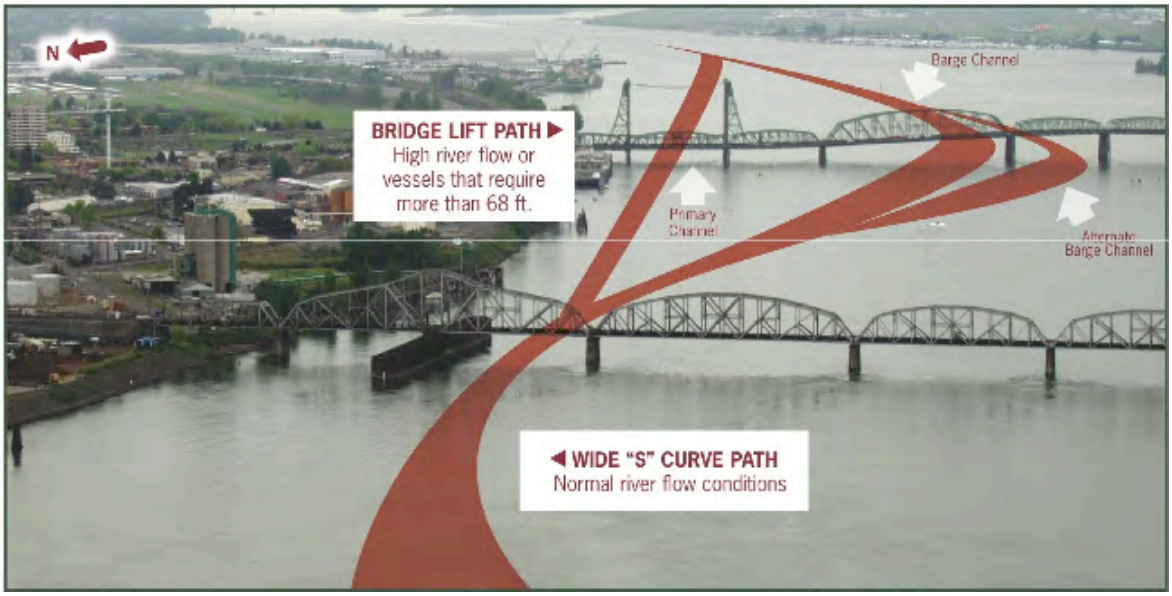

Figure 38 – Existing Navigation Channels

The panel recognized these river movements and reviewed the vessel operations in connection with the bridge types reviewed. At this time the pier openings remain either the same or are enlarged by the designs being provided by the panel. No issues exist that would negate or impact the current agreement with the US Coast Guard regarding navigational commitments for the new Columbia River Crossing bridge.

In-Water Impacts

The value of the Columbia River in the area of the I-5 bridges from a marine standpoint is indisputable. The CRC environmental process has endeavored to identify and address all of the relevant concerns with both temporary construction activity in the river and how the permanent footings might influence marine resources.

It was not within the scope of the panel to conduct a full analysis of the in-water issues such as has been done by the CRC team over the last several years. Nevertheless, a relationship exists between the total number of piers in the water and the gross square footage of in-water structures and their impact on the marine resources in the river. For summary purposes Table 6 presents a summary of the relative in-water impacts for all four alternatives.

Table 6 – Summary of Estimated In-Water Impacts for Bridge Alternatives

Bridge Type	**Total Piers in Water**	**Total Number of Piles**	**Total Plan Area of Piles (sq. ft.)**	**Total Plan Area of Footings (sq. ft.)**
Open-web box girder	12	88	6,910	58,500
Cable Stay	3	84	6,597	52,500
Arch	4	96	7,540	60,000
Composite Deck Truss	10	66	5,184	44,000

More detailed information about the in-water impacts for each bridge alternative discussed here is available in Appendix D.

Risk

One of the tasks given to the BRP was to consider the relative risks associated with the bridge alternatives under consideration. In doing so, the desire was to provide a sense of the relative risks associated with each one and offer decision-makers the ability to weigh risks against cost and other factors that would eventually factor into the choice of the preferred alternative.

The state DOTs have found success in the use of the Cost Estimate Validation Process (CEVP) tool developed a number of years ago. The CEVP process weighs risks, assigns probabilities and costs and produces a deliberate picture of the risk character for a given project or element. The BRP did not conduct a CEVP analysis for any of the bridge types presented in this report. Nevertheless, a comparative risk analysis was accomplished by the panel based on its extensive national and international experience with major bridge projects, which provides an initial picture of the relative risks associated with the different bridge types considered in this report.

The BRP identified fifteen risk factors for consideration. Each one was assessed against all four bridge types described in this report: composite deck truss, tied arch, cable-stayed and the current design, the open-web box girder. By including the open-web box girder, the comparison provides decision-makers a contrasting picture of how that design compares against the others proposed by the panel.

In addition to the fifteen factors the BRP chose to rank risk on a scale from one to four with one being a low risk and four being the highest risk. In some cases the relative risks between bridge types were the same so not all factors have four different numbers.

The risk factors and their ratings are found in Table 7. Although the BRP deems cost, aesthetics, and technical/engineering criteria to be most important, no effort was made by the panel to weight the risk factors against one another. Thus, a simple addition of the numerical values in each column would not necessarily provide a quantitative picture of the risks for the four bridge types. That said, some conclusions can be drawn from the information found in Table 7.

Table 7 – Comparative Risk Ratings

Risk Factor / Risk Ranking[4]	**Comp. Deck Truss**	**Tied Arch**	**Cable-Stayed**	**Open-Web Boxed Girder**
Cost (bid cost variance from forecast cost)	1	3	2	4
Schedule (design)	1	2	2	4
Schedule (construction)	1	2	1	4
Design (greater level of effort anticipated)	1	3	2	4
Procurement (number of bidders)	2	3	3	3
Construction (claims, etc.)	1	3	2	4
Public Support (aesthetics)	4	1	1	4
Long-Term Maintenance (higher than anticipated)	2	2	2	4
Seismic (predicted behavior)	2	3	1	4
Environmental (problems with in-water construction)	2	1	1	3
Environmental (risk of delay of ROD)	1	2	2	1
Legal challenge to the ROD	3	2	2	4
Operational reliability (risk of facility closure)	2	3	3	2
Successful modification of existing constraints (risk of aviation modification going forward)	1	2	2	1
Impact to Sustainability (risk of obsolescence)	2	2	2	2

What conclusions can be drawn from this risk information? It is clear that the option offering the highest risk in the most areas is the open-web box girder. In fact, of the four options under consideration it is by far the most risky in almost all areas considered by the BRP. While there isn't sufficient information to assign a quantitative value to this risk, it is clear that cost, schedule and other implications would result were the project to continue with this alternative. The other three bridge types offer varying levels of risk amongst one another depending on the factor involved.

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[4] 1 = Lower risk, 4 = Highest Risk

Once the new preferred bridge type is selected the project staff will need to perform a more robust risks assessment to secure the quantitative information necessary to go forward with the project.

Additional Findings and Recommendations

Alignment Considerations for the Columbia River Crossing

For long span bridges, particularly for river crossings, there are advantages to a tangent (straight) alignment as compared to an alignment that is curved in plan. The curved alignment proposed by the CRC team is more consistent with concrete segmental box construction given its torsional stiffness and strength to resist loads associated with curvature combined with the adaptable geometry of this construction method. The use of an open-web box girder configuration, as proposed by the CRC team, is not as amenable to in-plan curvature, given the variable geometry of the webs, deflection controls during construction, and the avoidance of pier diaphragms between webs to allow for under-deck mass-transit and pedestrian/bicycle paths. With these issues in mind, the BRP sought to examine the possibilities and benefits of a tangent alignment.

The primary advantages of a straighter alignment are:

- It minimizes the overall length of the bridge over water. There are inherent difficulties to construct bridges that require water-based construction equipment and in-water foundations. Any reduction in bridge length over water provides advantages in terms of construction cost and schedule.
- In-plan curvature results in some forces that are related to the degree of curvature and must be resisted by the structural system; these forces are *in addition* to all other design forces. If an opportunity exists to avoid designing for these additional forces then it makes sense to do so.
- A curved alignment limits or eliminates certain bridge types from consideration. Arch and cable stayed alternatives are more practical for tangent alignments.
- The geometry for a bridge curved in plan is significantly more complex. Inner and outer radii are different thereby eliminating repetitive details and symmetry. This is not only in plan but also in section where a cross-slope (and cross-slope transitions) must be incorporated. Given the width of the Columbia River Crossing, the geometry impacts of in-plan curvature and cross-slope add substantially to cost and complexity.

Given these advantages, the goal of the BRP was to develop a straight (tangent) alignment that focused on the Columbia River crossing portion of the project; this effort was in concert with developing more signature bridge alternatives, which incorporate longer spans, less in-water foundations, and offer an above deck superstructure.

Upstream Alignment

The BRP considered both upstream and downstream alignments for the replacement I-5 structure over the Columbia River. An upstream alignment was defined as a new structure to the east (upstream) of the existing I-5 crossing and the downstream alignment was defined as a new structure to the west (downstream) of the existing I-5 crossing. Due to logistical, maintenance of traffic, construction duration and other concerns, an alignment that replaced the existing I-5 crossing in-place was not analyzed.

The Columbia River Crossing project team had dropped consideration of an upstream alignment in October 2007 due to environmental, design and constructability factors. During its deliberations, the BRP reviewed the CRC's October 2007 decision, contemplated the benefits and limitations of an upstream alignment for the replacement bridge and concluded this is a firm project constraint.

Benefits

Alignment – Visually, an upstream tangent alignment from the northern bank of the Columbia River in Vancouver to the south bank of the river on Hayden Island seems to be a natural course for a replacement bridge. It is the shortest distance across the river and could be constructed adjacent to and off-line of the existing bridge.

Bridge Type – An upstream alignment, on a tangent section would allow for a variety of different bridge types. While concrete or steel box girders can be easily designed for curved or tangent alignments, cable supported bridges such as suspension, cable-stayed, or extradosed bridges are more efficient in reducing the number of substructure units, which is require for this site location given the high costs and efforts that are needed to perform in-water construction.

Limitations

Section 4(f) – The Department of Transportation Act of 1966 included a special provision, Section 4(f), which stipulated that the Federal Highway Administration (FHWA) and other USDOT agencies cannot approve the use of land from publicly owned parks, recreational areas, wildlife and waterfowl refuges, or public and private historical sites unless the following conditions apply:

- There is no feasible and prudent alternative to the use of land.
- The action includes all possible planning to minimize harm to the property resulting from use.

Planners had previously concurred that there was no feasible and prudent alternative to the replacement of the existing I-5 crossing that would avoid all impacts to cultural resources. Therefore, planners had to pursue reasonable and prudent actions to minimize harm to any Section 4(f) property.

Historic, prehistoric and geologic evidence suggests that the Washington side of the river, both upstream and downstream of the existing crossing, has a potential for containing cultural resources. The presence of the Hudson's Bay Company in the 1800's has resulted in substantial historic archeological resources as well as known and likely burials locations of both Europeans and Native Americans. The proposed downstream alignment would disturb an area that has seen a number of previous disturbances and a variety of other uses throughout the years ranging from a municipal dock in the 1880's, to a shipyard during World War I, to its current use as a hotel, dock and warehouse. The proposed upstream alignment, on the other hand, has a much higher potential for encountering cultural resources. The Fort Vancouver Historic Reserve is located on the upstream side of I-5. Additionally, historic record and past discoveries indicate that there is a higher potential for finding burials on the upstream alignment. And finally, oral history places a potential cultural site either in the water or on the near shore where the upstream alignment would be located.

Constructability

From a constructability standpoint, the upstream alignment presents more challenges than does the downstream alignment. First and foremost, the project would have to minimize the impact to Pearson Field air space by moving the new bridge as close as possible to the existing bridge. This would result in several more phases of construction (construct NB bridge, move NB & SB traffic, demo existing NB, construct SB, etc.) than would be necessary in a downstream alignment. The phased construction of the upstream alignment could add 2 years or more to the construction schedule.

Time

The longer time frame required for the upstream alignment extends in-water work and has the potential for greater impacts to listed endangered or threatened species and wildlife habitat. River vessels, especially less maneuverable commercial barges, have much more exposure to construction equipment in the river with the upstream alignment.

The additional time required to construct an upstream alignment could also pose financial hardships upon the project. Longer construction schedules on multi-billion dollar projects cause an increased potential to weather related delays and the contracting community will increase their bids to account for idle equipment costs, labor rate fluctuations, and unused material payment costs. These risks eventually result in added cost to the project either in the initial bid or in the form of change order requests.

The upstream alignment would have a greater potential to impact Section 4(f) properties and violate Section 4(f) of the DOT Act of 1966 in that it would not include all possible planning to minimize harm to the property resulting from use. Additionally, an upstream alignment would result in a significantly longer construction schedule, impacting endangered and threatened species and add additional cost.

Upstream & Downstream Tangent Alignment

A tangent alignment upstream of the existing bridge, in a two level configuration, has been suggested in order to limit impacts to the City of Vancouver waterfront and urban fabric. This concept is predicated on an under/over configuration for vehicular traffic and a separation between main-line and local traffic, with mass transit and pedestrians placed on the outside of the lower levels. Given the limited right-of way available upstream of the existing bridge, such an under-over configuration is necessary to minimize footprint. However, as will be described briefly below, this arrangement is impractical.

For an upstream alignment, right-of-way limitations in Vancouver are problematic given the close proximity of 4(f) properties. Additionally, aviation impacts to Pearson Field airspace, are exacerbated with an upstream alignment particularly given the potential for bridges which incorporate above-deck superstructure elements such as cable-stayed bridge towers or arches.

To minimize footprint, a two level vehicular traffic configuration results in mainline (express) traffic on the upper level and arterial (local) traffic on the lower level. This has many negatives, including:

- An increased number of access requirements are necessary for interchanges that are already substandard in terms of spacing.
- There is limited interconnectivity between mainline and arterial, which is problematic given the mix of arterial and mainline traffic demands.
- Light rail and pedestrian traffic (presumptively located at the fascia) are in conflict with ramp movements.
- Access ramp movements require outrigger bents, particularly at the Columbia River shoreline with negative cost, environmental, and seismic performance impacts.

A more detailed discussion of these issues is provided in Appendix E.

Fortunately, there are a number of downstream alignments that are feasible, and with assistance from the CRC design team, a recommended tangent downstream alignment has been developed and is presented herein (see Figure 39 below).

Figure 39 – Tangent Downstream Alignment

This downstream alignment limits 4(f) property impacts, offers the most flexibility for construction staging, and provides sufficient footprint to overcome the negative impacts of an upper level mainline/lower level arterial vehicular traffic configuration.

Further refinements to this alignment are appropriate in final design, whereby curvature and ramp lengths that encroach on the river portion of the crossing are minimized to the extent possible. The potential for an alignment which does not parallel the existing bridge, is also worthy of consideration, particularly to minimize the footprint of the proposed bridge at the Vancouver waterfront and the elimination of curvature to the portion of the span over the Columbia River.

With respect to the horizontal alignment and location along the river, the BRP offers the following recommendation:

- **Recommendation 5: Develop a straight/tangent alignment downstream of the existing bridges for the selected bridge alternative.** A modified tangent alignment section is the basis for the conceptual alternatives developed by the BRP.

Straight Alignments and the Influence of the North Portland Harbor Bridge

The original plan was to replace the North Portland Harbor Bridge (NPHB) along with other improvements in the corridor. However, in a recent effort by the CRC team to reduce the overall cost of the project a decision was made to rehabilitate the existing bridge in lieu of replacement. The curved alignment proposed for the river crossing begins in proximity of the NPHB, curves westerly and then turns east towards the Vancouver touchdown near SR 14.

Reasons given for this curved and longer alignment included providing more space between the new and existing bridges for construction purposes and improved roadway geometrics. The BRP considered all of the information provided about the NPHB and determined that too much space had been allocated between the old and new bridges for construction and that significant improvements could be made to the alignment as I-5 crosses Hayden Island.

As the BRP revisited the decision-making behind re-use of NPHB, it is clear that its replacement offers a number of advantages that include:

- Improvement to the overall highway geometry for the Columbia River Crossing and elimination of an S-curve for the mainline alignment.
- Elimination of a number of separate structures that must cross North Portland Harbor to accommodate interchange movements for Hayden Island and Marine Drive, which can be better integrated into a new NPHB.
- A reduced footprint on Hayden Island associated with the interchange.

Given the incremental cost of replacing versus retrofitting the NPHB described in the North Portland Harbor Bridge Replacement section of this report, together with these advantages, replacement of NPHB is recommended by the panel. That said, this is an independent decision from a tangent alignment or any of the three bridge types offered for consideration in this report.

Substandard Interchange Spacing and Project Impacts

In the project corridor, seven interchanges in less than five miles results in interchange spacing that does not meet state or federal minimum requirements of one mile for interstates in urban areas. In some circumstances, interchange spacing is half the minimum required. It is not unusual in urban areas to have substandard interchange spacing. However, it is unprecedented that *all seven* interchanges on a project corridor have less than minimum spacing. Not only are safety and operations an issue, more than 70 percent of the project budget is associated with these interchanges.

Minimum interchange spacing is necessary for operational efficiency and user safety. Substandard interchange spacing in the project corridor can be expected to negatively impact both. Interchanges adjacent to the Columbia River and North Portland Harbor also increase environmental impacts and detract from the visual quality of the shoreline and the character of a signature bridge.

It is the view of the panel that some consolidation of the interchanges on the project corridor is warranted. This consolidation would have the following direct benefits to the project:

- Improved safety and operations.
- Significant reduction in capital costs.
- Reduced environmental impacts.
- Enhanced viewsheds along the Columbia River.
- Improved opportunities for a signature span, from budgetary, logistical, and performance perspectives.

With respect to interchange spacing, the panel offers the following secondary recommendation:

- **Review all interchanges, ramps and other geometric features to simplify the overall corridor design for substantial cost savings and to improve safety and corridor operations.**

North Portland Harbor Bridge Replacement

The assessment of a straight or tangent alignment for I-5 as it crosses the Columbia River resulted in a number of other project related issues being exposed to analysis. One of those was the NPHB as it spans the slough from the mainland to Hayden Island. During the project planning process the CRC team considered and eventually adopted a strategy to replace the bridge. More recently, in an effort to reduce the overall cost of the project, the staff eliminated the NPHB from the scope. As it stands now, the existing bridge would receive some rehabilitation work but remain largely as it is when the corridor is reconstructed.

As one of the related impacts of straightening out the alignment of I-5 as it crosses Hayden Island the BRP considered constructing a new NPHB as part of this study. Replacement of the NPHB provides several advantages to the overall project with respect to the proposed tangent alignment for the river crossing:

- It results in a mainline alignment with current and uniform seismic resistance for the entire river crossing.
- It provides the opportunity to use a portion of the existing NPHB for local access.
- It eliminates the need for an “S” curve to match in with the existing NPHB alignment.
- It maximizes the opportunity for consistent aesthetic treatment throughout the project.

The summary of the BRP’s analysis and review of the rationale for replacing the NPHB can be found in Appendix F.

With respect to the NPHB, the BRP offers the following recommendation:

- **Recommendation 6: Replace the North Portland Harbor Bridge.**

Structural Design Criteria Review

Efforts have been made to provide design criteria[5] that will facilitate achieving WSDOT's and ODOT's structural performance goals over the 150-year design life for the new bridge. It is anticipated that this design criteria will require modifications as the preliminary design work progresses leading to a final bridge type. The codes cited are applicable and analysis methods and techniques used will be state-of-the-art for bridge type structures recommended for further development.

Members of the BRP reviewed the draft structural design criteria and concur with the general seismic performance levels at the safety and functional seismic events. However, with respect to structural design criteria, the BRP offers the following secondary recommendations:

- **Provide uniform seismic performance levels for the North Portland Harbor Bridge and the Columbia River Bridge.**
- **Establish performance based project specific criteria for all primary and secondary members upon selection of the final bridge type crossing the Columbia River.**

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[5] "CRC Structural Design Criteria for the River Crossing", CRC, Revision b, July 31, 2008.

Conclusions and Recommendations

The Columbia River Crossing (CRC) project is at an important juncture. A number of critical issues remain unresolved, preventing the conclusion of the environmental process and the start of construction. The Independent Review Panel (IRP) report from July 2010 recommended 30 actions on the part of the CRC team to advance the project forward. Among the recommendations was the need to look carefully at the open-web box girder concept currently being advanced. This BRP study of potential bridge types was the outcome of the IRP recommendations. This report documented the findings of the panel and the conclusions and recommendations from the BRP's work, which are summarized in this section.

The panel examined the current open-web box girder bridge design, exploring alternatives that would render it as a more viable option in terms of engineering attributes and constructability. Risks associated with this design were also considered. The BRP found that significant design, construction, serviceability, cost uncertainties, and long-term performance issues arising from this concept were of such a magnitude that further design and consideration of the girder bridge as a viable alternative is not prudent. Changing course in the near future would save engineering costs associated with continued development of this design. The overall project budget would improve due to lower probabilities of delaying the start of construction and lower potential for contractor claims during construction.

The BRP went further and sought to determine if the open-web box girder design could be improved to make it viable. In doing so the panel considered different web connections to the upper and lower flanges, maintaining constant web depth, inverted the bottom web slabs to improve structural efficiency, and other improvements. The panel called this the "enhanced" open web. After considerable effort to resolve many of the original problems that remained from the current open-web box girder design, the panel rejected this as a feasible alternative for many of the reasons already noted.

One of the designs developed by the BRP was a cable-stayed bridge with a multi-level through section that provides for both vehicular, light rail transit and bike and pedestrian traffic. A cable-stayed bridge is a very efficient structural approach to a crossing like this and offers many benefits from a cost, aesthetics, constructability and performance standpoint.

Another option developed by the panel was a tied arch consisting of three arches, also with a multi-level through section that provides for both vehicular, light rail transit and bike and pedestrian traffic. A tied arch bridge offers an aesthetically pleasing appearance, significant clear spans over the water similar to the cable-stayed bridge, and an efficient structural approach.

The composite deck truss was the third bridge type considered by the panel. It represents a traditional design with a good performance history and low initial capital cost. While similar in appearance to the untrained eye to the open-web box girder design, the composite deck truss offers connections between the web and chord members that are easily constructed, with a proven long-term serviceability record. Building of the composite deck truss and subsequent construction of the upper and lower concrete decks are straightforward. Each of these three designs was carried through the evaluation process by the BRP.

All three designs advanced by the BRP through the review process accommodate the navigation requirements already in place. The cable-stayed and tied arch options have significantly fewer piers in the water. The composite deck truss and cable-stayed options offer less "in-water" impacts in the Columbia River considering size of pile footings, while the tied arch would have greater "in-water" impacts relative to the open-web girder design. Other environmental issues such as the 4(f) and Section 106 concerns on the northeast corner of the bridge site are held to the same standard for all three alternatives as the current CRC design.

The impacts to aviation were considered by the panel for both Portland International Airport (PDX) and Pearson Field. While some design and construction coordination will be required with PDX for any of the three proposed designs, no significant issues exist. The arch and cable-stayed alternatives will improve the current flight operations at Pearson Field relative to the existing bridge, but will require further approvals from the FAA for the new conditions imposed by their presence.

The panel examined other attributes of the three new alternatives in comparison to the open-web box girder design. While construction methods will differ somewhat between these three types, unlike the current open-web design each one has known and proven practices and the construction industry is familiar with their use.

The BRP developed high-level comparative cost estimates for the composite deck truss, arch and cable-stayed options. The estimates are based on very preliminary engineering but also the significant experience of the BRP on many large bridges. In addition, the panel reviewed the cost information for the open-web box girder and normalized this information for comparison purposes. In 2010 dollars the cost (excluding risk cost) for each alternative would be:

Table 8 – Comparative Cost Estimates

Bridge Alternative	Cost
Open-Web Box Girder	$ 440,000,000
Composite Deck Truss	340,000,000
Tied Arch	430,000,000
Cable-Stayed	400,000,000

Each of the three proposed options offers a more cost-effective approach to the new crossing than the currently considered open-web box girder design.

The BRP considered aesthetics as a component of their analysis. Both the cable-stayed and arch options provide aesthetic statements that seem to be in keeping with the expectations of those in the region. In contrast, the composite truss and the open-web box girder do not appear to provide aesthetics commensurate with the site.

The current design includes a wide curved alignment for the bridge that extends a considerable distance downstream of the current bridges. The panel examined in detail the opportunities associated with straightening out the alignment and bringing the new bridge closer to the existing bridges. In doing so the panel found that savings accrue to the project and this new straight alignment improves the roadway geometrics on Hayden Island and in Vancouver. It also reduces visual impacts on the City of Vancouver.

The BRP found the current geometry of the alignment to be problematic and even considered whether a collector-distributor (C/D) system could be used to improve the congested nature of the interchanges and ramps found throughout the corridor. While the C/D concept was not found to be viable due to issues with ramp movements both on and off the new bridge and in the corridor, the panel does feel strongly that much work remains to be done to improve the ramps and interchanges throughout the project and that simplification of these elements will bring about a better and more functional solution. In fact, the panel is struck by the fact that most states are working to remove congested interchanges and ramps rather than building their way towards such a condition: as is occurring here. In addition, the volume of interchange access is not in harmony with state or Federal guidelines. The BRP recommends further study to address interchange geometrics and operations. In addition, the whole corridor would benefit from a more comprehensive urban design review.

With the review of the alignment and movement towards a more tangent river crossing the panel also examined in detail the North Portland Harbor Bridge. Consideration was given to keeping the existing bridge and making seismic enhancements consistent with the design criteria. This was compared to the cost and benefits of a new bridge. Ultimately, the panel found that a new bridge, consistent with the original project conceptual design, was a sound approach and that the cost of this option would be in keeping with the project budget. Overall, the panel found that the cable-stayed, tied arch, and composite deck truss alternatives honor the current environmental and budget constraints of the project.

Cost savings will accrue from the recommendations presented in this report if any of the three structures are built in lieu of the current open-web design and significant savings and operational functionality will follow if the North Portland Harbor Bridge is replaced. The panel believes that additional savings are available with the reduction and simplification of access ramps and interchanges.

Recommendations

Based on the foregoing, the Bridge Review Panel makes the following recommendations:

- **Recommendation 1: Discontinue any further design or planning work on the open-web box girder bridge alternative.**
- **Recommendation 2: Select a new bridge type from among the three feasible alternatives: cable-stayed, tied arch and composite deck truss.**
- **Recommendation 3: Proceed with further analysis and public review in order to select a preferred alternative bridge type.**
- **Recommendation 4: Work with the FAA to resolve airspace issues with Pearson Field relating to either the cable-stayed or tied arch bridge designs.**
- **Recommendation 5: Develop a tangent (straight) alignment for the main river crossing downstream of the existing bridges, and**
- **Recommendation 6: Replace the North Portland Harbor Bridge.**

Secondary Recommendations / Opportunities for Improvement

- **Review all interchanges, ramps and other geometric features to simplify the overall corridor design to achieve significant cost savings and improve safety and corridor operations.**
- **Review the potential impacts to the project description and technical studies for the environmental document and develop a work plan to maintain a realistic target date for the Record of Decision.**
- **Provide uniform performance levels for the North Portland Harbor Bridge and Columbia River Bridge.**
- **Establish performance based project specific criteria for all primary and secondary members upon selection of the final bridge type crossing the Columbia River.**

Appendix A – Panel Member Bios

Chair, Thomas R. Warne, PE, Tom Warne and Associates, Inc.

Mr. Warne was appointed by the governors of Oregon and Washington to serve as the chair of the CRC Independent Review Panel during the summer of 2010. He has over 30 years of experience funding and delivering light rail and highway infrastructure projects. For the past nine years he has worked as a consultant assisting public agencies and private companies. Clients include the Federal Highway Administration, American Association of State Highway and Transportation Officials (AASHTO), metropolitan planning/regional transportation organizations and authorities, departments of transportation and contractors. Mr. Warne is known for his work on complex projects and programs. His projects include light rail systems, significant design-build efforts, major bridges, strategic planning, partnering facilitation, process improvement initiatives, and more. Mr. Warne was one of the early leaders in starting Context Sensitive Design in the late 1990s and this was one of his emphasis areas as President of AASHTO. For the past seven years, he has been the transportation advisor to Daybreak, a smart growth development in Salt Lake County. Other projects include the Woodrow Wilson Bridge, the 35 W Bridge Replacement in Minneapolis and University Light Rail in Utah. While serving as the Executive Director of the Utah Department of Transportation, he was responsible for delivering the $1.325 billion I-15 Reconstruction project three months ahead of schedule and more than $30 million under budget. He has an M.S. in Civil Engineering from Arizona State University and a B.S. in Civil Engineering from Brigham Young University.

Scott A. Ashford, PhD, PE, Oregon State University

Dr. Ashford has over 25 years experience in the design and performance of bridge foundations. He served on the faculty in the Department of Structural Engineering at the University of California, San Diego, for 11 years and is currently Head of the School of Civil and Construction Engineering at Oregon State University. He is an internationally known expert in the design and construction of bridge foundations subjected to liquefaction and lateral spreading. His work in private industry prior to joining academia focused on bridge foundations, and he has served on several technical advisory and review panels. He earned his BS in Civil Engineering from Oregon State University, and his MS and PhD in Geotechnical Engineering at the University of California, Berkeley. He is currently the Chair of Oregon's Statewide Transportation Improvement Plan (STIP) Stakeholder Committee.

Relevant Project Experience:

- I-210/I-215 Technical Advisory Panel (California)
- San Francisco Oakland Bay Bridge (California)
- Cooper River Bridge (South Carolina)

Benjamin Beerman, PE, Federal Highway Administration

Mr. Beerman is currently a Senior Structural Engineer with the Federal Highway Administration. He brings over 14 years of experience in bridge design, repair, and rehabilitation of both highway and rail structures located throughout the mid-Atlantic region. He has been involved in numerous bridge design and rehab projects, including a networked tied arch (the largest in the world), three cable stay structures, and many steel trusses (fixed and moveable – for both highway and rail). Mr. Beerman began his career at the Louisiana Department of Transportation while attending graduate school at Louisiana State University. He went on to join Modjeski and Masters in New Orleans then later transferred to help establish their Charleston, WV office. He later worked at the HDR rail group based out of Jacksonville, FL, and Ralph Whitehead and Associates (currently STV) in Richmond, VA.

John A. Buchheit, PE, DBIA, Federal Transit Administration

Mr. Buchheit has over 24 years experience leading highway; bridge; and design-build projects. He is a certified professional with the Design Build Institute of America [DBIA] and is also a lead participant in the Project Delivery Subcommittee of the ARTBA Bridge Policy and Promotion Council. He has served as the Structures Manager for numerous complex projects including SR 836 Extension Design-Build for the Miami-Dade Expressway Authority [$148 M] and the Lackawanna Valley Industrial Highway Reconstruction for the Pennsylvania Department of Transportation [$610 M]. Mr. Buchheit has also performed consultation for Owners on development of procurement and bridging documents for alternative delivery contracts including the RailRunner Transit Project from Albuquerque to Santa Fe for the New Mexico Department of Highways. He has provided support to the FTA on the Columbia River Crossing Project working for the Project Management Oversight Consultant [PMOC] furnishing technical consultation and review of bridge documents and the Grantee's Project Management Plan. Mr. Buchheit is a Vice President with Gannett Fleming, Inc. and currently serves as a Regional Manager in the firm's southeast region. He is a senior member of Gannett Fleming's Design-Build Leadership Team and has also held the position of National Practice Manager for Bridge operations.

David Goodyear, PE, SE, PEng, Chief Bridge Engineer, T.Y. Lin International

During his thirty-five year career, Mr. Goodyear has developed engineering solutions to challenging issues involving concrete, steel, segmental, and cable-stayed bridge design. He is nationally recognized as a premier bridge engineer with the ability to deliver innovative, constructible design products. Mr. Goodyear has worked with public agencies and contractors across the nation, on small rural projects as well as large urban projects with a focus on concrete bridges, segmental and cable-stayed bridge design, foundation engineering, and waterfront structures.

His experience ranges from preparing analysis reports and feasibility studies to developing final PS&E documents and providing quality control, construction engineering, and value engineering services. His background working with multi-disciplined teams and public participation is extensive, and he is completely familiar with Local Agency and AASHTO standards, guidelines, and procedures. Mr. Goodyear served on the PTI Ad-Hoc Committee writing the Concrete Segmental Bridge Guide Spec, has supported AASHTO T-10 on behalf of ASBI, and is the current chairman of the PTI Committee on Cable-stayed Bridges.

Relevant Project Experience:

- Port Mann (British Columbia)
- Hoover Dam Bypass (Arizona – Nevada)
- Crooked River Gorge (Oregon)

Siegfried Hopf, Dipl.-Ing., Chief Bridge Engineer, Leonhardt, Adra and Partners

Mr. Hopf, based in Stuttgart, Germany, has a wide experience within bridge engineering from numerous bridge projects around the world, including some of the firm's largest cable-stayed, concrete and composite bridges. Most of these bridges are built abroad in USA, Norway, Korea, South America and Hong Kong. He spent 15 years in the USA for the concept design two major bridges. He was LAP's design manager for the Kap Shui Mun Bridge design, the Ting Kau tender design, the Stonecutter Island Bridge Design Competition in Hongkong, the Rhinebridges Ilverich and Wesel in Germany, the Stay Cable Portion of the Parana Bridge Rosario-Victoria in Argentina and 2nd Panama Canal Bridge. During his working career he was responsible for more than 20 conceptual/preliminary designs, many of them ended up to be successfully built, such as the Baytown Bridge in Houston, Texas, the Helgelands Bridge in Norway, the Kap Shui Mun Bridge in Hongkong, the Cable-stayed Bridge at Rosario-Victoria, Argentina, the Geo Geum Bridge in South Korea and the Sava River Bridge in Belgrade, Serbia.

Relevant Project Experience:

- Cable-Stayed Bridge Across the Orinoco River (Venezuela)
- Baytown Bridge (Houston, TX)
- Rhine River Highway Bridge Wesel (Germany)

Bruce Johnson, PE, SE, Oregon Department of Transportation

Mr. Johnson is the State Bridge Engineer in Oregon since September 2004. He supervises 51 people in bridge design, standards, operations, inspection, major bridge maintenance, load rating, bridge management, and preservation. Prior to that, he was the Division Bridge Engineer, for Federal Highway Administration in Oregon from October 1988 to September 2004. He worked in various positions with FHWA in Oregon, Nevada, Kansas, Colorado, Indiana, and Iowa from 1975-1988.

Mr. Johnson is chair of AASHTO SCOBS, Technical Committee T-9 on Bridge Preservation, vice-chair of AASHTO SCOBS, Technical Committee T-20 on Tunnels, and a member of T-10, Concrete and T-3 Seismic. He is vice-chair of the TBR Committee on Bridge Management, AHD-35, and a member of TRB Committee on Bridge Aesthetics, AFF-10(2). Mr. Johnson is the vice-chair of the FHWA Expert Task Group for Bridge Preservation. He received many outstanding awards from FHWA, including an Engineering Excellence Award in 2001. He is a member of ASCE, fib, ACI, and the Underground Construction Association of the Society of Mining and Excavation.

Jugesh Kapur, PE, SE, Washington State Department of Transportation

Mr. Kapur is the State Bridge and Structures Engineer for Washington state where he provides direction, guidance, and management to the structural engineering program with the assistance of 140 individuals in the WSDOT's Bridge and Structures Office. Prior to this position he was the State Bridge Design Engineer, Design Unit Manager and also worked in the private sector for 8 years. He is a University of Washington graduate and a registered professional engineer in civil and structural engineering in Washington and Oregon.

Wesley King, High Capacity Transit Project Manager, Clark County Transit Authority (C-TRAN)

Mr. King has extensive planning and project management experience for transit and highway projects. While with the Michigan Department of Transportation he was actively involved in the rehabilitation efforts for the M-1/M-102 tri-level grade separated interchange rehabilitation, M-85 viaduct rehabilitation analysis, and the Detroit River International Crossing (DRIC) Study. All three projects included extensive public outreach utilizing context sensitive solutions. The DRIC is a multi-billion dollar project and is analyzing public/private partnerships as well as tolling options for development. The DRIC also underwent a bridge type analysis of cable-stayed vs a suspension structure. Mr. King was also assistant project manager on the Detroit Transit Options for Growth Study and was contracted to the City of Detroit's Department of Transportation. through URS Corp. before joining C-TRAN.

Calvin Lee, PE, TriMet

Mr. Lee is TriMet's bridge and structures engineer and is a registered professional engineer with over 20 years of experience. His experience includes the development, design, construction, and inspection of bridges for both highway and transit uses as well as the asset management of a public agency owned and maintained bridge inventory system. He is currently responsible for structural design and construction oversight on large scale transit capital projects. Prior to joining TriMet, Mr. Lee was the City Bridge Engineer and a Division Manager for the City of Portland's Office of Transportation.

John McAvoy, PE, Major Project Manager, FHWA Oregon Division

John McAvoy currently serves the FHWA in the Oregon Division as the Major Project Manager for the Columbia River Crossing project. He is responsible for delivering a multi-modal, multi-billion dollar, comprehensive, long-term transportation solution that addresses congestion, safety and mobility problems on I-5 between Portland, OR and Vancouver, WA. Prior to joining the Oregon staff, Mr. McAvoy served in the Rhode Island Division as the Major Project Manager overseeing the planning, permitting, design, and construction of 15 separate construction contracts making up the $600 million relocation of Interstate 195 in Providence. Mr. McAvoy joined the FHWA in 2001 as the Design Engineer in the Connecticut Division. He began his professional career as a consultant with Close, Jensen & Miller in Wethersfield, CT. before joining the staff at Purcell Associates in Glastonbury, CT in 1994. Mr. McAvoy received a bachelor's degree from the University of Connecticut in 1987 and is licensed by the State of Connecticut as a Professional Engineer. He was selected for the FHWA's highest honor in 2003 as a recipient of the Administrator's Award for Superior Achievement and was a 2008 recipient of the Secretary's Partnering for Excellence Award.

Mary Lou Ralls, PE, Ralls Newman, LLC

Ms. Ralls has more than 25 years experience, including bridge design, structural engineering, project management, and accelerated bridge construction. She was the project manager for development of the FHWA Framework for Prefabricated Bridge Elements and Systems (PBES) Decision-making and PBES Cost Study and is currently a course instructor for the National Highway Institute. Her research and expertise is nationally recognized and she has served on multiple independent review panels and advisory groups for projects in Maryland, Massachusetts, Rhode Island, and others. Ms. Ralls has received numerous awards including the Administrator's Public Service Award from FHWA, the AASHTO President's Award in

Research Category, and the Design Award for Best Bridge with Spans Greater than 135 feet, presented by the Precast/Prestressed Concrete Institute. Prior to her current position of Engineering Consultant with Ralls Newman, LLC, she directed the Bridge Division of the Texas Department of Transportation. Ms. Ralls has an M.S. in Engineering, Structures, and a B.S. in Civil Engineering with Highest Honors from the University of Texas at Austin. Ms. Ralls served on the CRC Independent Review Panel in 2010.

Joe Showers, PE, Business Group Technical Manager/Bridge Design and Construction, CH2M Hill

Mr. Showers is the Chief Bridge Engineer for CH2M Hill, and is based in the Denver corporate office. He holds a Masters Degree in Civil Engineering and a Masters Degree in Architecture from Virginia Tech and has 35 years of experience in the design of bridges and structures, including long span bridges over navigable waterways and areas with challenging foundation conditions. He is the current chairman of TRB AFF10(2) committee on Bridge Aesthetics, and past member of the Concrete Bridge Committee. His work experience includes the planning, design and construction of segmental and cable-stayed bridges, including the Folsom Bridge over the American River near Sacramento, the Golden Ears Bridge over the Fraser River near Vancouver, and the James River Bridge near Richmond. He is currently assisting the Minnesota DOT as owner's representative on the Hastings Bridge over the Mississippi River, a design build project that includes a 545 foot span composite steel and concrete, post-tensioned tied arch bridge.

Relevant Project Experience:

- Northumberland Strait Crossing (Prince Edward Island – New Brunswick)
- Golden Ears Bridge (British Columbia)
- Cooper River Bridge (South Carolina)

Steve Stroh, PE, Deputy Director of Surface Transportation, Major Bridges, URS Corporation

Mr. Stroh is the URS National Deputy Director for Surface Transportation, focusing on major bridge projects. He also serves as the manager of URS' Center of Excellence for Bridge Design in the Tampa, Florida office. He has been responsible for the development of a number of long-span and complex bridges throughout the United States and internationally, including development of the first extradosed prestressed bridge in the U.S., the Pearl Harbor Memorial Bridge in New Haven, CT. Mr. Stroh joined URS in 1983 and has 35 years of industry experience. He is a nationally recognized expert in bridge design and serves on several national committees and boards. He earned a Masters Degree in Civil Engineering from the University of South Florida. He is also a long-standing member of the faculty of the University of South Florida, teaching undergraduate and graduate courses. He is registered as a professional engineer or structural engineer in 20 states.

Relevant Project Experience:

- Pearl Harbor Memorial Bridge (Connecticut)
- Kap Shui Mun Bridge, (Hong Kong)
- Crossing of the Panama Canal at the Atlantic Side (Panama)

Steve Thoman, PE, SE, Stephen J. Thoman Consulting, Inc.

Mr. Thoman provides project management, bridge design and construction services for transportation projects throughout the United States. He is a registered structural/civil engineer in numerous States with over 33 years of experience, having earned his BS in Civil Engineering from the University of Iowa, and his MS in Structural Engineering at the University of California, Berkeley. He specializes in the programming, planning, design and construction of bridges for highway and transit systems.

Mr. Thoman has led design teams as project manager or bridge project manager for individual projects with bridge construction costs totaling more than $4B. These design projects have included complex freeway interchanges, toll ways, long-span bridge crossings, and seismic retrofit of viaducts and long span structures. Mr. Thoman is currently under contract to the Bay Area Toll Authority and the City of Los Angeles.

Relevant Project Experience:

- New Benicia-Martinez Toll Bridge (California)
- Seismic Retrofit of the Antioch, Dumbarton and Carquinez Toll Bridges Bridge (California)
- Sixth Street Viaduct (Los Angeles)

Theodore P. Zoli, III, PE, HNTB

As Technical Director of HNTB's bridge practice nationwide, Mr. Zoli has led the design of many award-winning bridges throughout the US and abroad, including the Blennerhassett Island Bridge over the Ohio River (winner of the Gustav Lindenthal Medal), the Leonard B. Zakim bridge in Boston, MA and the Bob Kerrey Pedestrian Bridge in Omaha, NE. Mr. Zoli's work has been informed by his research into bridge safety and reliability with a focus on the design of structural systems against member loss and structural behavior under unforeseen extreme events. He leads HNTB's infrastructure security practice and has developed innovative protective measures for some of our nation's largest and most important bridges. Mr. Zoli has received national recognition for his work in bridges including a Special Achievement Award by the AISC for the Bob Kerrey Pedestrian Bridge. On New Year's Eve in 2009, he was featured on NBC Nightly News with Brian Williams in a news segment entitled What Works.

In September 2009, Mr. Zoli was made a MacArthur Fellow by the John D. and Catherine T. MacArthur Foundation. This prestigious award was granted for major technological advances to protect transportation infrastructure and for his innovative designs. With the generous grant that is associated with the Fellowship, Mr. Zoli is currently working on two initiatives: a lightweight hyperbolic paraboloid modular roof based upon an adaptation of boat hull construction technology and catenary pedestrian bridges fabricated using synthetic (polyester) rope for use in remote mountainous regions.

Appendix B – Review of the Open-Web Design

Description

The Independent Review Panel (IRP) Report dated July 27, 2010 included a recommendation to further consider the feasibility of the open-web box girder design proposed by the CRC Project team. This Bridge Review Panel was established, in part, to address this question. The BRP review of the open-web box girder design focused on issues of design efficacy, constructability, and general risk elements associated with design and construction of the proposed partial open-web design as presented to the panel and described in the 2010 IRP report.

Design of the partial open-web box girder reportedly evolved through project development as a means by which light rail transit could be carried across the Columbia River with a minimum additional expense over the baseline cost for a new I-5 Columbia River Highway Crossing. What began as a more typical concrete box girder evolved into the open-web design as a means of providing light, ventilation, and an unconfined volume within the box for light rail transit. The panel has been advised that as the project has developed, elimination of a third structure for light rail and use of the stacked highway and transit structure has become a de-facto requirement for the project to move forward.

The panel review of the open-web box girder design covers three general categories. They are:

- Design Issues with Section Design
- Construction Issues
- Aesthetic Values

Design Issues with Open-Web Box Girder Bridge

The basic section and elevation is shown in Figures 40 and 41.

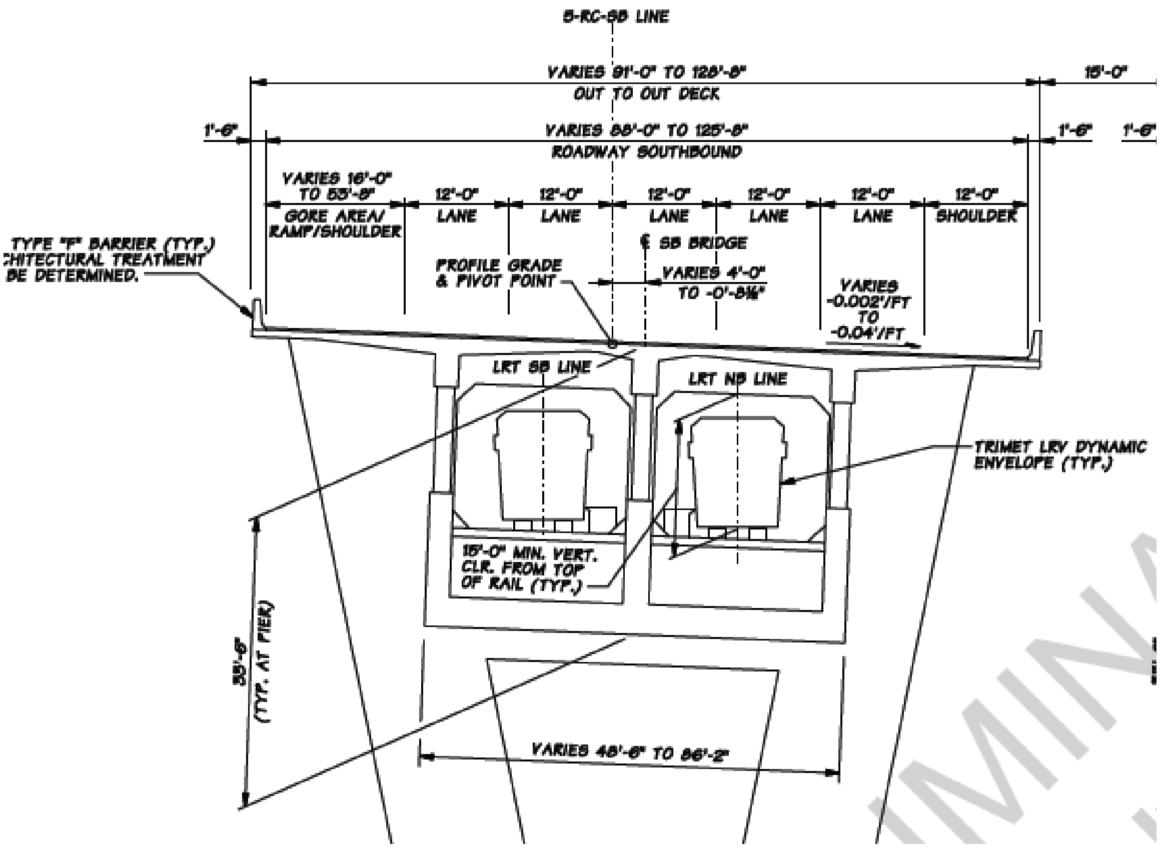

Figure 40 – Open-Web Box Girder Typical Section

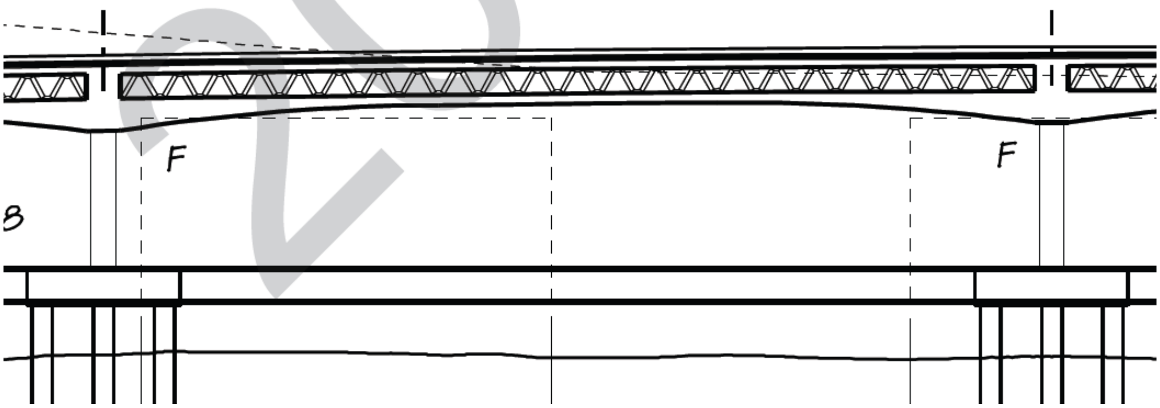

Figure 41 – Cross Section of Open-web box girder

The section was developed as a conventional variable depth concrete box girder, dissected by removing a chorded section of the box girder web and replacing that section with a steel truss. This modification of what is otherwise a standard bridge form has a number of ramifications for design and construction.

Design Issues with Section Design

Bridge beam design is based on the assumptions of the classical "Bernoulli" beam. A key element of the classical beam is that plane sections remain plane throughout the deflection of the beam. In the case of concrete box girders, this assumption is valid for practical dimensions of most concrete beam sections. In order to maintain plane sections, shear deformations over the depth of a web have to remain insignificant relative to longitudinal strains, or flanges otherwise have to be limited to top and bottom plate elements that will always define a plane section.

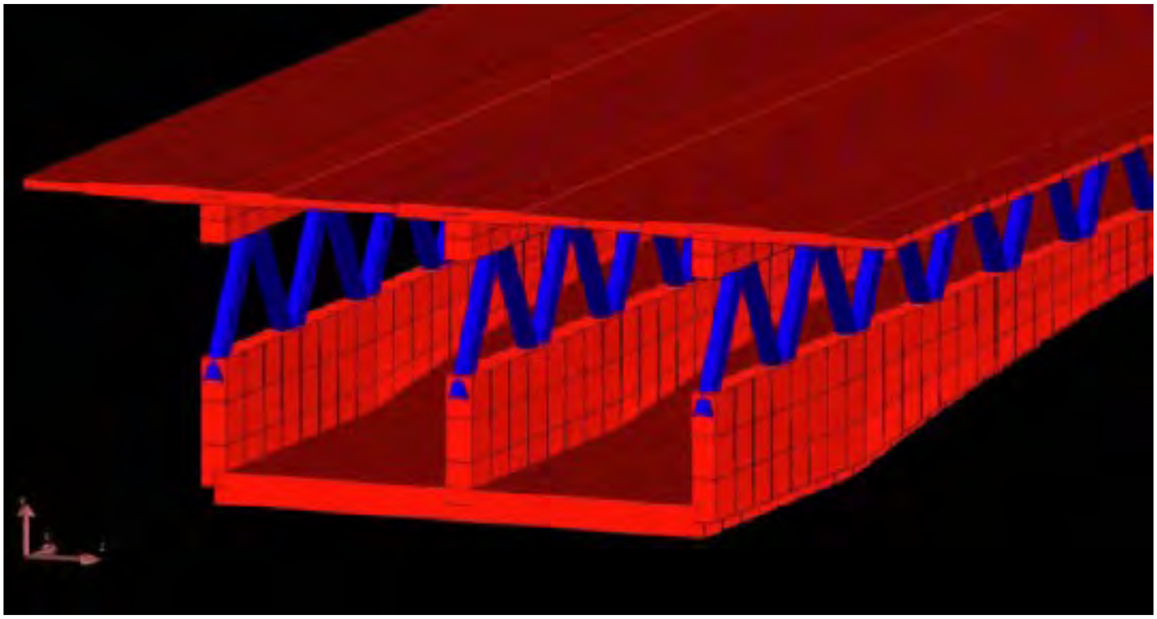

Figure 42 – Model of Open-Web Box Girder Showing Bottom Trough, Steel Truss and Top Inverted Trough

Once the core of the web is removed in the proposed open-web configuration, the section is a parallel system of three components – the bottom trough, the steel truss and the top inverted trough. The shear stiffness of these three elements differs, and the plane strain assumption is no longer valid. The result is an indeterminate cross section for bending and shear (Figure 42). This has design implications as well as construction implications (construction is discussed below).

The typical concrete box girder is post-tensioned as it is constructed in cantilever fashion from the pier. For long span box girders, cantilever construction is the only practical method to build the bridge. The demands of this method are integral to the design. In a Bernoulli beam built in cantilever, the main post-tensioning (PT) is applied to the top slab, with little or no PT applied to the bottom slab. This PT counters dead load bending in the overall box section as additional segments are constructed.

Figure 43 – Composite Truss

A short digression is appropriate here. It is important to recognize the distinction between the proposed open-web box girder that has partial concrete webs with a composite section that has only concrete flanges but steel webs. Several post-tensioned bridges have been constructed based on concrete flanges and steel webs. However all of these bridge sections have the entire web in steel, and only plate flanges in concrete, see Figure 43. Design of those bridges is based on carrying the entire shear demand in the steel web, and the bending demand in the flanges. The flanges are thereby treated as two 'nodes' in the depth of the section, and two nodes always create a straight line (a plane section). This segregation of moment and shear allows for conventional beam theory to apply even in the presence of shear deformation with the depth of the steel elements. There are no other major bridges that combine shear resistance in a series of flexible steel truss and stiff concrete web plates such as proposed for the open-web box girder.

The design consequence of the discontinuous web stiffness is that the bottom trough of the box section shown in Figure 42 will carry a proportionate share of bending and shear as a separate element in relation to the stiffness of this lower section to the entire hybrid cross section. While this can be evaluated in design, it is nonetheless a departure from classical beam behavior that has design and construction consequences. At the ultimate limit state, failure of the web system in shear will be a 'zipper' sequence rather than a single, ductile limit state. The lower web concrete section will draw a disproportionate amount of shear until it reaches its limit strength. Noting that this lower stem section supports the central steel web, once the concrete stem shear limit is reached, it is questionable as to whether addition shear capacity can be developed through the truss, and shear strength is likely to be limited by the weakest element in the chain of web components. This affect will require the concrete web section to be designed for a disproportionately high value of shear relative to a normal box girder.

While this unusual behavior can be addressed in design, once recognized, the ensuing design cannot be as efficient as a conventional web design – be it all concrete or all steel. Cost factors for design that relate the proposed section to a conventional box girder will not be a reliable forecast for material or labor requirements for the proposed section. Furthermore, designing the component sections for strength will not address the constructability issues noted below.

A related issue arises at the ends of the bridge with widening of the box. The schematics show a three-web box for the typical section. The extreme widening is not shown. In order to widen the typical box the deck depth for cantilevers must be increased beyond what would typically be considered practical. The design could incorporate ribs or struts, but neither works well with the open web box framing for the top trough. This condition is complicated further at the diaphragms, where the openings for train passage reduce the strength and rigidity in general, and particularly so for an extreme cantilever slab section.

Construction Issues with Open-Web Box Girder Bridge

The construction issues with the proposed open-web box design are perhaps more problematic than the design issues. Once recognized, the design issues may be addressed with more reinforcing and post tensioning. However, it is not clear that the construction issues can be addressed within the scale of costs contemplated for the superstructure work.

As noted above, the only practical erection scheme for a 500 foot+ concrete span is as free cantilever construction. There are two methods for this construction scheme. One is to precast short elements of the bridge for later erection, and the other is to cast each short element in place as the cantilever progresses.

Precasting is, at first glance, the logical option for the proposed open-web section. Precasting in this case might be in a long line bed to facilitate geometry control with the complication of mid-height trusses (see below for more on this item). One then expects that the geometry of the precast spans is fairly precise.

Precasting establishes an unstressed shape for the bridge beam. As the beam is erected, it is stressed through dead load, erection equipment and post-tensioning. The beam deforms through these loads and due to creep and shrinkage in the concrete elements. This is all typical for a normal concrete section. Where one has a Bernoulli beam, each face of concrete can be matched to the next as it was in the casting bed since there is no shear deformation in the section. However, for the proposed open-web design, there will be incompatible shear deformation between the height of the steel web sections and the height of the concrete trough sections. The concrete will creep and shrink, whereas the steel web members will deform only elastically with applied load. This deformation will distort the match cast face to varying degrees, complicating or destroying the fitup necessary to assemble the bridge. Local element bending of the bottom or top concrete trough sections will not line up with the planar geometry of the unstressed trough section in the piece being erected. The standard methods for shimming to correct geometry will be difficult at best, and perhaps impractical.

As spans exceed 450 feet or so, cast in place construction typically becomes more economical than precast construction. In the case of the proposed open-web section, cast in place construction would likely be necessary due to the above limitations noted for precasting. There are a number of practical limitations of cast in place construction for the proposed section.

- Web casting: A problem common to both precast and cast in place construction of the proposed section is that there is a formed surface at the top of the bottom trough section in the middle of the web height. That limitation forces the form design to be open in the midst of the web form, essentially requiring the assembly of the section as three units rather than one (referring to the above design text on other hybrid girder designs – there is no web form needed for those cases where the full depth of web is steel). The form traveler for this type of operation will be far more complex than a typical traveler (see below), and the effort required for setting the trusses, placing the lower web, and then the upper web will be considerably more expensive than for a construction of a typical box girder. The erection cycle for this type of section is likely to be three times that of a more conventional cast-in-place box girder section.
- Lower truss composite connection: The current connection from the lower concrete stem to the steel truss either requires casting up to the soffit of the connection plates, or casting the lower trough entirely, letting it cure, and then setting the truss into place. Assuming the latter has been ruled out for geometry control and schedule reasons, casting a key connection from below is a questionable practice. This is difficult enough on a slope, but even more so for a level connection plate. Special procedures and inspection will be needed to assure that there are no trapped air voids or poor consolidation under the connection. While this area could be pressure grouted, that operation will also have a considerable effect on production of a segment. A casting scheme that required curing of the lower section in order to set and grout the truss would increase curing time over a conventional box girder construction by at least 100 percent, and would also complicate geometry control owing to the likely need for lower stage post-tensioning in order to set the weight of the truss on a lower chord – it is very unlikely that a contractor would elect to erect in this fashion.
- Geometry control of the hybrid section: While cast in place assembly addresses the plane section issues noted with precasting, one is still constrained by the fabricated truss geometry from segment to segment. As geometry is corrected with form traveler setting, truss section dimensions will no longer suit the local geometry at the segment faces. The proposed steel section is a truss in name only – the proposed fabrication is a rigid frame (Figure 44). While bolted connections can allow modest shortening or lengthening of

diagonals and chords, the aspect ratio and rigid connections of the proposed truss sections may limit angular correction as construction progresses if corrections are significant (with the proposed truss connections, splices will be within the length of members, not at truss nodes). This geometry control operation is also a major consideration for the cycle of construction, since this adds a compound element of control not present for typical box girder construction.

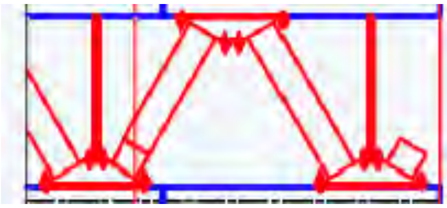

Figure 44 – Segment Web Truss

- Rail slab construction: The proposed open-web box has a variable depth soffit, but includes a second constant depth interior slab on which the light rail is supported. This slab would logically be cast as a follow-on component, since casting with the basic box section would further complicate an already complex forming scheme. However, casting at any time involves a sliver form where the rail slab intersects the box slab. Connections for the remainder of the slab will be time consuming operation, both during the second stage pour, but more importantly during the first stage cantilever placement where embeds need to be placed in the wall form. These would typically be form saver embeds. The history with these embeds typically includes a fair amount of rework which will also add to the cost of construction. The likely alternative is to make the rail slab non-structural (relative to the box section), supporting it from below instead of from the webs. This approach would add unproductive dead load, but would likely be less expensive overall.

Figure 45 – Cantilever Construction, Cast-in-Place with Form Travelers

- Equipment requirements: There are several special equipment requirements for the proposed open-web section. The most obvious is the need for deck cranes to set the truss sections. However, the most challenging special equipment is the form traveler. This traveler will need to accommodate all of the following:
  - The variable trough section of the bottom slab and stems.
  - Setting the truss in the middle of the web height.
  - Access to the top of the lower stem for finishing.
  - Setting the lid for the top stem against the upper truss connections.
  - Adjusting the top and bottom troughs separately for geometry control.
  - Providing for sufficient stiffness through the range of segment operations to avoid opening joints at the back of field sections as weight is applied during segment casting and truss setting.
- The likely solution is a heavy framed traveler that is more akin to an erection gantry frame than a typical form traveler (Figure 45). As noted above, the section will likely be cast in one pass (not 3 settings), so the overall traveler frame will need strength and stiffness for the truss section, and a separate upper slab support system that is tied in to the truss frame in order to maintain local geometry. This type of frame will present challenges for any change or correction in super-elevation, which is normally not an issue with a typical light traveler. Operation of this type of traveler will be more prone to incidents, and will be considerably more time consuming than for a traditional form

traveler operation. The quality of the as-cast product will be in question for some time, and it will be difficult to establish a casting routine from anything short of a full scale trial, the practicality of which is questionable.

- Margin for Construction Risk: Assuming traditional design-bid-build delivery with the proposed open-web design, there should be an expectation of compound risk monies in the project budget. Contractors will add risk to their margins for the complications noted herein. This risk money will be limited by bidding competition. Additional risk will inevitably accrue to the Project in the event that constructability issues related to design limitations adversely affect productivity and construction costs, since the Project will not be able to transfer design related risks through a design-bid-build construction contract. Any payments for design-related impacts to construction through change orders or claims would further increase costs over the additional margin from bid day.

Aesthetic Value

Considerations of value are fundamental to every project. Here, aesthetic value is viewed as a quotient of appealing visual presentation over cost related to that appeal. There are typically two advocacies in this discussion – those whose priority is the least cost, and those whose priority is the aesthetic presentation of the physical work. The panel believes those advocacies should be addressed, each on their merits. Input to the panel was that an open deck structure would not satisfy the aesthetic interests from the stakeholders. Budget is always an issue, and particularly so for such a large project as CRC. The panel considered these issues in the broader context of project constraints when reviewing the open-web box girder. The panel does not see that the open-web box girder brings any aesthetic statement to the new Columbia River crossing, and is, in this regard, the same as the composite deck truss.

The panel does not believe that any open deck structure of the size and character required for CRC would attract the laud of those seeking an aesthetic solution. The panel believes that both the cable-stayed and arch alternatives are worthy candidates for signature solutions that are value based. They both address the more difficult aesthetic challenge of deck width with superstructures that have attractive scale and dimension, through the use of efficient structural forms that have good value.

Recommendation

There are many reasons to not continue with the open-web box girder, both in absolute terms and relative to the options recommended by this panel. The technical issues are such that they put funding and project schedule at greater risk. There are issues with the proposed open-web section that will require significant time and money to address, and it is the opinion of this panel that the level of design and construction quality with the open-web box girder will not be as good as can be achieved with the recommended alternatives in this report. In the opinion of the panel, there is no technical or aesthetic advantage justifying the considerable risks associated with this design. Therefore, the BRP does not recommend that the project proceed with this option.

Cost Estimate

The BRP developed a cost estimate for the open-web box girder to compare its cost to the other bridge alternatives estimated by the BRP. The estimates provided have been performed at a high level and further detailed analysis will refine them to values that can be used for project programming and funding. In doing so, the panel has taken each in their basic form and analyzed their costs. This approach normalizes the estimates made for the different bridge alternatives. This cost estimate can be found in Appendix C of this report.

Given the panel's focus on value, it is clear to this panel that there are better values to be found for the operational constraints of the project than the proposed open-web box girder design. In addition, there is no apparent benefit to assuming the considerable risks associated with the open-web box girder design.

The open-web box girder design should not progress further for the following reasons:

- The comparative estimate of additional cost of construction is higher than cable-stayed and tied arch alternatives.
- There is significant construction risk associated with this type of technology.
- The open-web box girder has a higher level of post-construction "owners risk" associated with maintenance of the facility.

- There is a risk that fewer bidders will compete for this work due to the complexity and risk, adding additional margin to the bids for the job.
- Design issues and full-scale testing requirements could result in jeopardized schedule and funding.
- There is a greater potential for construction claims, project delays, and additional construction costs.
- Structural components of a system should be compatible – as proposed with the composite deck truss.
- The structure is more likely to have performance problems, including cracking or deterioration at the web truss connections that would be difficult to address over the life of the project.

Appendix C - Cost Estimates

Composite-Deck Truss

Item	QTY Total	Unit Cost	Total	Total
Superstructure				
Deck				
Structural Steel	45,320,000 Lb	$ 2.00 LB	$ 90,640,000	
Concrete (CIP)	6,240 CY	$ 1,000.00 CY	$ 6,240,000	
Concrete PC	25,000 CY	$ 1,000.00 CY	$ 25,000,000	
Reinforcing Steel	10,700,000 Lb	$ 1.20 Lb	$ 12,840,000	
Bridge Railing 42" Type F	10,800 LF	$ 80.00 FL	$ 864,000	
Pedestrian Railing	5,400 LF	$ 350.00 FL	$ 1,890,000	
Deck Subtotal			*$ 137,474,000*	
Misc. Appurtenances				
Overlay	517,700 SF	$ 7.00 SF	$ 3,623,900	
Lighting , Drainage, Elect, Access, etc.	1 LS	$ 5,000,000.00 LS	$ 5,000,000	
Misc. Appurtenances Subtotal			*$ 8,623,900*	
Superstructure Subtotal				***$ 146,097,900***
Substructure				
Piers				
Concrete	12,975 CY	$ 1,700.00 CY	$ 22,057,500	
Reinforcing Steel	3,414,000 Lb	$ 1.20 Lb	$ 4,096,800	
Prestressing Steel	- Lb	$ 4.00 Lb	$ -	
Piers Subtotal			*$ 26,154,300*	
Pier Foundations				
Footing Concrete	35,275 CY	$ 450.00 CY	$ 15,873,750	
Footing Reinforcing	8,818,759 Lb	$ 1.20 Lb	$ 10,582,511	
Drilled Shaft Steel Casing	13,041,225 Lb	$ 1.50 Lb	$ 19,561,838	
Drilled Shaft	16,013 LF	$ 1,500.00 LF	$ 24,019,500	
Pier Foundations Subtotal			*$ 70,037,598*	
Substructure Subtotal				***$ 96,191,898***
Quantities Subtotal (rounded)			***$ 242,000,000***	
Mobilization 5%			**$ 12,100,000**	
Design Contingency 10%			**$ 25,410,000**	
Main Bridge Total (rounded)				**$ 280,000,000**
Construction Contingency 20%			$ 56,000,000	
Bridge Grand Total (rounded)				**$ 340,000,000**
Bridge Grand Total (per SF)	Based on deck area of	518,300	SF	**$ 656**

Tied Arch

Item	QTY Total	Unit Cost	Total	Total
Superstructure				
Deck				
Structural Steel (Deck System)	*45,423,000* Lb	$ 2.00 Lb	$ 90,846,000	
Structural Steel (Arch Ribs)	*9,000,000* Lb	$ 3.00 Lb	$ 27,000,000	
10 ksi Concrete (Arch Infill)	*4,050* CY	$ 1,000.00 CY	$ 4,050,000	
Concrete (Slabs)	*29,700* CY	$ 1,000.00 CY	$ 29,700,000	
Reinforcing Steel	*7,425,000* Lb	$ 1.20 Lb	$ 8,910,000	
Post Tensioning	*632,700* Lb	$ 4.00 Lb	$ 2,530,800	
Bridge Railing 42" Type F	*10,800* LF	$ 80.00 FL	$ 864,000	
Pedestrian Railing	*5,400* LF	$ 350.00 FL	$ 1,890,000	
Deck Subtotal			*$ 165,790,800*	
Hanger System				
Hanger Ropes	*600,000* Lb	$ 4.00 Lb	$ 2,400,000	
Hanger System Subtotal			*$ 2,400,000*	
Misc. Appurtenances				
Overlay	*632,700* SF	$ 7.00 SF	$ 4,428,900	
Lighting , Drainage, Elect, Access, etc.	*1* LS	$ 5,000,000.00 LS	$ 5,000,000	
Misc. Appurtenances Subtotal			*$ 9,428,900*	
Superstructure Subtotal				***$ 177,619,700***
Substructure				
V-Piers				
Concrete	*31,962* CY	$ 1,700.00 CY	$ 54,335,400	
Reinforcing Steel	*6,392,400* Lb	$ 1.20 Lb	$ 7,670,880	
Prestressing Steel	*-* Lb	$ 4.00 Lb	$ -	
Structural Steel	*1,455,300* Lb	$ 2.00 Lb	$ 2,910,600	
V-Piers Subtotal			*$ 64,916,880*	
Pier Foundations				
Footing Concrete	*32,044* CY	$ 450.00 CY	$ 14,419,800	
Footing Reinforcing	*9,613,200* Lb	$ 1.20 Lb	$ 11,535,840	
Drilled Shaft Steel Casing	*13,409,000* Lb	$ 1.50 Lb	$ 20,113,500	
Drilled Shaft	*16,380* LF	$ 1,500.00 LF	$ 24,570,000	
Pier Foundations Subtotal			*$ 70,639,140*	
Substructure Subtotal				***$ 135,556,020***
Quantities Subtotal (rounded)			***$ 313,000,000***	
Mobilization 5%			**$ 15,650,000**	
Design Contingency 10%			**$ 32,865,000**	
Main Bridge Total (rounded)				**$ 362,000,000**
Construction Contingency 20%			$ 72,400,000	
Bridge Grand Total (rounded)				**$ 430,000,000**
Bridge Grand Total (per SF)	Based on deck area of	632,700	SF	**$ 680**

Cable-Stayed

Item	QTY Total	Unit Cost	Total	Total
Superstructure				
Deck				
Structural Steel	*49,900,000* Lb	$ 2.00 LB	$ 99,800,000	
Concrete (Slabs)	*29,700* CY	$ 1,000.00 CY	$ 29,700,000	
Reinforcing Steel	*7,425,000* Lb	$ 1.20 Lb	$ 8,910,000	
Post Tensioning	*949,000* Lb	$ 4.00 Lb	$ 3,796,000	
Bridge Railing 42" Type F	*10,800* LF	$ 80.00 FL	$ 864,000	
Pedestrian Railing	*5,400* LF	$ 350.00 FL	$ 1,890,000	
Deck Subtotal			*$ 144,960,000*	
Stay System				
Stay Cables	*3,197,250* Lb	$ 8.00 Lb	$ 25,578,000	
Damping Devices	*66* ea	$ 20,000.00 ea	$ 1,320,000	
Stay System Subtotal			*$ 26,898,000*	
Misc. Appurtenances				
Overlay	*632,700* SF	$ 7.00 SF	$ 4,428,900	
Lighting , Drainage, Elect, Access, etc.	*1* LS	$ 5,000,000.00 LS	$ 5,000,000	
Misc. Appurtenances Subtotal			*$ 9,428,900*	
Superstructure Subtotal				***$ 181,286,900***
Substructure				
Pylons				
Concrete	*16,860* CY	$ 1,700.00 CY	$ 28,662,000	
Reinforcing Steel	*7,081,200* Lb	$ 1.20 Lb	$ 8,497,440	
Prestressing Steel	*-* Lb	$ 4.00 Lb	$ -	
Structural Steel	*1,455,300* Lb	$ 2.00 Lb	$ 2,910,600	
Pylons Subtotal			*$ 40,070,040*	
Pylon Foundations				
Footing Concrete	*32,044* CY	$ 450.00 CY	$ 14,419,800	
Footing Reinforcing	*9,613,200* Lb	$ 1.20 Lb	$ 11,535,840	
Drilled Shaft Steel Casing	*13,409,000* Lb	$ 1.50 Lb	$ 20,113,500	
Drilled Shaft	*16,380* LF	$ 1,500.00 LF	$ 24,570,000	
Pylon Foundations Subtotal			*$ 70,639,140*	
Substructure Subtotal				***$ 110,709,180***
Quantities Subtotal (rounded)			***$ 292,000,000***	
Mobilization 5%			**$ 14,600,000**	
Design Contingency 10%			**$ 30,660,000**	
Main Bridge Total (rounded)				**$ 337,000,000**
Construction Contingency 20%			$ 67,400,000	
Bridge Grand Total (rounded)				**$ 400,000,000**
Bridge Grand Total (per SF)	Based on deck area of	632,700 SF		**$ 632**

Open-Web Box Girder

Item	QTY Total	Unit Cost	Total	Total
Superstructure				
Deck				
Structural Steel	*7,684,410* Lb	$ 2.00 LB	$ 15,368,820	
Concrete (segments 8ksi))	*81,113* CY	$ 1,600.00 CY	$ 129,780,800	
Post Tensioning (strand)	*7,429,420* Lb	$ 4.00 Lb	$ 29,717,680	
Post Tensioning (bar)	*2,576,750* Lb	$ 4.00 Lb	$ 10,307,000	
Bridge Railing 42" Type F	*10,800* LF	$ 80.00 LF	$ 864,000	
Pedestrian Railing	*5,400* LF	$ 350.00 FL	$ 1,890,000	
Deck Subtotal			*$ 187,928,300*	
Misc. Appurtenances				
Overlay	*517,711* SF	$ 7.00 SF	$ 3,623,977	
Bearings	*24* Ea	$ 20,000.00 Ea	$ 480,000	
Lighting , Drainage, Elect, Access, etc.	*1* LS	$ 5,000,000.00 LS	$ 5,000,000	
Misc. Appurtenances Subtotal			*$ 9,103,977*	
Superstructure Subtotal				***$ 197,032,277***
Substructure				
Piers				
Concrete	*11,353* CY	$ 1,700.00 CY	$ 19,300,313	
Reinforcing Steel	*2,987,250* Lb	$ 1.20 Lb	$ 3,584,700	
Prestressing Steel	*444,675* Lb	$ 4.00 Lb	$ 1,778,700	
Piers Subtotal			*$ 24,663,713*	
Pier Foundations				
Footing Concrete	*41,155* CY	$ 450.00 CY	$ 18,519,638	
Footing Reinforcing	*10,268,417* Lb	$ 1.20 Lb	$ 12,322,101	
Drilled Shaft Steel Casing	*15,214,763* Lb	$ 1.50 Lb	$ 22,822,144	
Drilled Shaft	*18,681* LF	$ 1,500.00 LF	$ 28,021,875	
Pier Foundations Subtotal			*$ 81,685,757*	
Substructure Subtotal				***$ 106,349,469***
Quantities Subtotal (rounded)			***$ 303,000,000***	
Mobilization 5%			**$ 15,150,000**	
Design Contingency 15%			**$ 47,722,500**	
Main Bridge Total (rounded)				**$ 366,000,000**
Construction Contingency 20%			$ 73,200,000	
Bridge Grand Total (rounded)				**$ 440,000,000**
Bridge Grand Total (per SF)	Based on deck area of	518,300	SF	**$ 849**

Appendix D – In-Water Impacts

Open-Web Box Girder Design

Currently, bridge designers propose two open-web box girder bridges supported by six in-water pier complexes for a total of 12 piers in the main channel of the Columbia River. The piers will be constructed using drilled piles, rather than driven piling. Each pier will consist of up to nine, 10-foot-diameter drilled piles topped by a concrete pile cap. The piers have been designed to withstand the design scour without scour protection (e.g., riprap). Each of the roadway surfaces will range from approximately 91 to 136 feet wide, with a gap of approximately 15 feet between them. The over water length of each new main-line bridge will be approximately 2,700 feet. Current designs place none of the pier complexes in shallow water (less than 20 feet deep).

Quantity of Permanent Piles

The number of permanent piles is summarized in Table 9 below. Span lengths are proposed to be approximately 465 feet.

Table 9 – Summary of Permanent Piles in the Columbia River

Location	Piles per Pier	Total Piles	Total Plan Area of Piles (sq.ft.)	Approx. Depth from Observed Lowest Water (0' CRD[6])
Piers 3-6 on northbound structure	Varies: 6-9	32	2,513	Varies: 24 to 32
Piers 3-6 on southbound structure	Varies: 6-9	32	2,513	Varies: 24 to 32
Pier 2	4	12	942	Varies: 21 to 25
Pier 7	4	12	942	Varies: 20 to 27
Total	24 to 30	88	6,910	

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[6] CRC = Columbia River Datum

Pile Caps

Pile caps will be placed on top of the drilled piles at each pier in a pier complex. The caps could be either cast-in-place or precast concrete. Table 10 below summarizes the dimensions of each pile cap and its total area.

Table 10 – Summary of Pile Caps in the Columbia River

Type	Number	Width	Length	Total Area (sq. ft.)
Piers 3-6	8	75	75	45,000
Piers 2 & 7	4	75	45	13,500
Total	12	–	–	58,500

Cable-Stayed Alternative

If the Project changes the current open-web girder bridge concept to a cable-stayed concept, designers could accommodate all travel modes (vehicle, transit, multi-use path) on one bridge. The bridge could be supported by three in-water piers. The piers would also be constructed using drilled piles. Each pier could consist of approximately 24, 10-foot-diameter drilled piles topped by a concrete pile cap. The piers would be designed to withstand the design scour without scour protection (e.g., riprap).

Quantity of Permanent Piles

The number of permanent piles is summarized in the table below. Span lengths are proposed to vary between approximately 500 feet and 800 feet.

Table 11 – Summary of Permanent Piles in the Columbia River

Location	Piles per Pier	Total Piles	Total Plan Area of Piles (sq.ft.)	Approx. Depth from Observed Lowest Water (0' CRD)
Piers 1 & 5 would be located on land	–	–	–	–
Piers 2,3 & 4 on combined north & southbound structure	28	72	5,655	Varies: 24 to 32
Total	28	84	5,655	

Pile Caps

Pile caps will be placed on top of the drilled piles at each pier. The caps could be either cast-in-place or precast concrete. The table below summarizes the dimensions of each pile cap and its total area.

Table 12 – Summary of Pile Caps in the Columbia River

Type	Number	Width	Length	Total Area (sq. ft.)
Piers 1 & 5 would be located on land	–	–	–	–
Piers 2, 3, & 4	3	100	175	52,500
Total	3	–	–	52,500

Tied Arch Alternative

If the Project chooses a tied arch concept, designers could accommodate all travel modes (vehicle, transit, multi-use path) on one bridge. Four in-water piers could support the bridge. The piers would be constructed using drilled piles, rather than driven piling. Each pier could consist of approximately 24, 10-foot-diameter drilled piles topped by a concrete pile cap. The piers would be designed to withstand the design scour without scour protection (e.g., riprap).

Quantity of Permanent Piles

The number of permanent piles is summarized in the table below. Span lengths are proposed to vary between 212 feet and 725 feet.

Table 13 – Summary of Permanent Piles in the Columbia River

Location	Piles per Pier	Total Piles	Total Plan Area of Piles (sq.ft.)	Approx. Depth from Observed Lowest Water (0' CRD)
Piers 1 & 6 would be located on land	–	–	–	–
Piers 2,3,4 & 5 on combined north & southbound structure	24	96	7,540	Varies: 24 to 32
Total	24	96	7,540	–

Pile Caps

Pile caps will be placed on top of the drilled piles at each pier. The caps could be either cast-in-place or precast concrete. The table below summarizes the dimensions of each pile cap and its total area.

Table 14 – Summary of Pile Caps in the Columbia River

Type	Number	Width	Length	Total Area (sq. ft.)
Piers 1 & 6 would be located on land	–	–	–	–
Piers 2, 3, 4, & 5	4	100	150	60,000
Total	4	–	–	60,000

Composite Deck Truss Alternative

If a double composite truss concept is chosen, designers could accommodate all travel modes (vehicle, transit, multi-use path) in a similar fashion to the open-web box girder design. The quantity, configuration, and impact of the permanent piles would be substantially less than the open-web box girder design. The quantity, configuration, and size of the pile caps would be less than that of the open-web concept.

Appendix E – Roadway Configuration - Is Mainline / Arterial Configuration Feasible for the Columbia River Crossing?

The arterial under / mainline over configuration is fundamentally incompatible with the unusual interchange density for an interstate as proposed by the project today. An urban corridor, with seven interchanges in less than five miles, all with substandard spacing (less than one mile) is no place to attempt such a design approach. This situation is exacerbated by the large proportion of local traffic, which requires both arterial and mainline access (75 percent Southbound and 68 percent Northbound). An upper mainline / lower arterial configuration will necessitate a large increase in the number of interchange connections, in an already substandard corridor.

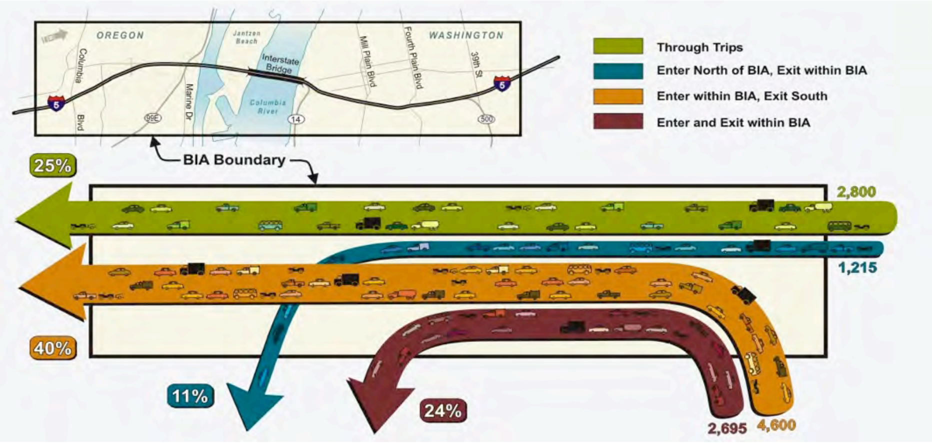

Figure 46 – 75 Percent of Southbound Traffic to/from Seven Interchanges

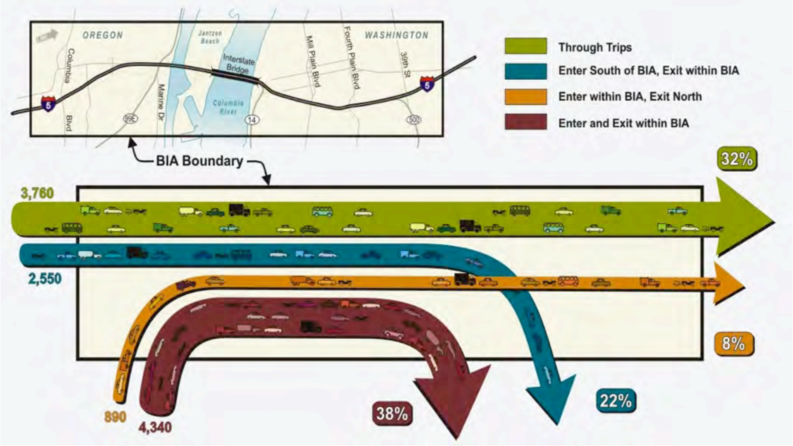

Figure 47 – 68 Percent of Northbound Traffic To/From Seven Interchanges

Specific reasons why such a traffic approach is so untenable in this corridor include:

- If full arterial connectivity is assumed to all interchanges, any connectivity to the upper level main-line results in *additional ramps*. Given the density of interchanges in this corridor, additional ramps, from the perspective of first cost, maintenance, congestion, and footprint makes the problem notionally worse.
- Interconnectivity between main-line and arterial is eliminated. The only possibility to get on the mainline would have to be via an interchanges which mix mainline and arterial access. Given how much interchange movements drive the overall cost and footprint of the project, this is not ideal.
- The proximity of the Hayden Island interchange and the SR-14 interchange to the Columbia River requires ramp movements over the river. Any "signature" two level structure over the river must accommodate ramp movements through the structural system. This significantly compromises the design of a "signature" structure, and will require many more river piers to support ramps and the upper and lower levels independently as a truss, cable stay or spandrel arch cannot readily accommodate lower level ramp movements.
- Ramp movements will also require outrigger bents and deep transverse beams that will necessitate far greater clearances between upper and lower levels than currently contemplated.

- The position of the light rail and pedestrians conflicts directly with ramp movements from the lower level. This conflict is problematic and as stated above occurs over the Columbia River where it is difficult to solve and will result in more piers in the water.
- There are significant security issues with under/over configurations with vehicular traffic, particularly from the perspective of vehicular fire (which can be accidental or intentional). Of particular concern is the bridge portion over the Columbia River, where access for fire-fighting would be only by fireboat, the two level structure represents a significant problem, as the transverse members are highly vulnerable to damage, and the fire is difficult to fight (there are also indications that asphalt contributes to the fire load). The scenario that a fire on the lower level damages the entire structure (i.e. both levels, as was the case in the MacArthur Maze fire, Oakland, CA) cannot be ruled out. This represents a major challenge for two level bridges throughout the United States and the solutions are often expensive and messy.

An alternative to this configuration that has many benefits without some of the severe negative impacts is a main-line two level structure with light rail underneath and an arterial (local) two level structure with pedestrian/bicycles underneath. While this has the same disadvantage that it requires additional ramps for freeway access (items 1 and 2 above) but has the following advantages:

- The arterial traffic design speed could (and should be) 45 miles per hour. This is more consistent with interchanges spaced at less than one mile and would reduce ramp lengths and minimize weave design deficiencies.
- Shoulders (both inside and outside) could be reduced on the arterial bridge, resulting in a reduced footprint. Note that given a median and the need for full shoulders on the mainline, the overall footprint of the bridges for the crossing will be (at best) approximately the same as the current configuration, but will more than likely require additional width. It is noted that this may be thought of as a disadvantage as compared to the current configuration.
- This configuration allows for a truly redundant pair of bridges (though with somewhat reduced interchange connectivity if the arterial bridge is out of service). In the current

configuration, if one bridge is out, given the directionality associated with interchange movements, there is no way to use the alternate bridge, without severe complications.

- The conflict between pedestrians/bicycles and traffic is avoided, as is the similar conflict for light rail. The panel believes it makes sense to tie the pedestrian/bicycles with the arterial given the smaller footprint of the cross-section. The light rail with tied with the main-line does not appear to be problematic.
- The avoidance of two-level traffic is preferable from a security perspective. Pedestrians/bicyclists do not represent a fire hazard, and the fire hazard associated with light rail is manageable (much more so than commercial vehicles with flammable liquids).

After a careful review of this alternative, the negative cost and footprint impacts associated with the need for additional interchange movements are too problematic for additional consideration. In fact, a strong case can be made to reduce some of the interchange connectivity based upon traffic volume to further reduce interchange costs and footprints of the current configuration. In the view of the BRP, any additional interchange connectivity associated with a reconfiguration of traffic on the bridge is unwarranted.

Appendix F – North Portland Harbor Bridge Replacement?

The assessment of a straight or tangent alignment for I-5 as it crosses the Columbia River resulted in a number of other project related issues being exposed to analysis. One of those was the North Portland Harbor Bridge as it spans the slough from the mainland to Hayden Island. During the project planning process the CRC team considered and eventually adopted a strategy to replace the bridge. More recently, in an effort to reduce the overall cost of the project, the staff eliminated the North Portland Harbor Bridge from the scope. As it stands now, the existing bridge would receive some rehabilitation work but remain largely as it is when the corridor is reconstructed.

This appendix provides a summary of the analysis that the BRP did in regards to their review of the question of whether or not to replace the North Portland Harbor Bridge[7].

Alignment

In order to match up to the existing NPHB, a 2-degree curve is needed in the bridge alignment near the north bank of Hayden Island and another 2-degree curve on Hayden Island. These two curves result in an "S" alignment that is not necessary if the existing NPHB is replaced. The Columbia River Crossing bridges are expected to be in service for 150 years or more, and so the benefits of an improved alignment will be enjoyed for several generations.

Aesthetics of the NPHB

The existing NPHB is an award-winning design. It received a 1989 PCI Design Award. The proposed seismic retrofit scheme will significantly change the appearance of this bridge. Because of the multitude of homes located within the harbor, the appearance of this bridge should be factored into any replacement decision. The BRP strongly believes the decision should favor replacement over seismic retrofit. Replacement provides the opportunity for a

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[7] Detailed references describing the sources of the data used in this Appendix are contained in an ODOT Report, "North Portland Harbor Bridge Options - References", available at the following web site: http://www.oregon.gov/ODOT/HWY/BRIDGE/index.shtml.

crossing with substantially improved aesthetics over a retrofitted structure that will be in harmony with the main river crossing.

Local Access

If a new mainline NPHB is built, the existing bridge may have some value for local access. Although this would require significant redesign of ramps and access points, it would result in reduced overall cost. Use of this structure for the lower volume local access use would still result in seismic risk issues (assuming no Phase II seismic retrofit). Due to lower volumes and lower speeds, the overall seismic risk to the public would be substantially reduced compared to mainline service.

Seismic Resistance

Replacement of NPHB would allow the new bridge to be designed and constructed to current seismic standards in the same manner as the main river crossing. This would ensure a similar level of seismic resistance and serviceability from the Washington shore to mainland Oregon. The BRP believes there is significant value in ensuring a high level of seismic resistance given the threat of a subduction zone earthquake. Following a subduction zone earthquake, this Columbia River Crossing will be a key link allowing timely recovery and rebuilding efforts of both Vancouver and Portland. Without a secure NPHB mainline crossing, recovery efforts will be significantly hampered. The NPHB ramp structures will not provide capacity or connectivity to satisfy demand. Also, collapse of the existing NPHB could cause damage to adjacent ramp structures.

If the existing NPHB must be retained, the BRP recommends a full Phase I and Phase II seismic retrofit. Allowing a mainline water crossing to remain un-retrofitted on a mega-project of this scale is unheard of. Although it is true that current ODOT policy only requires a Phase I seismic retrofit for typical bridge projects, this policy is based on lack of funding for seismic retrofit work. With a daily traffic of 126,800 vehicles, the panel recommends seismic retrofit to mitigate this significant risk.

Due to future funding level projections, ODOT will be changing the focus of their Bridge Program from primarily replacement to almost exclusively maintenance and rehabilitation.

Before this change, the seismic risk for vulnerable bridges was limited to a 20-40 year period at the end of which the bridge would be expected to be up for replacement. Under ODOT's new focus, ODOT will be increasing emphasis on maintenance in order to obtain a much longer service life. Therefore, the period of time a vulnerable bridge, such as the existing NPHB, will remain in service will be substantially longer. In turn, the risk of a damaging seismic event during the life of the bridge is greatly increased. There will never be a more economical time to mitigate this risk than now, through replacement or retrofit as part of the Columbia River Project.

Environmental Risks

One possible risk resulting from the replacement option is the need for possible changes to the draft biological assessment. Some additional coordination may be needed if there is an apparent increase in impacts from additional pier construction. This risk may be countered by a reduction in impacts from fewer piers in the main channel if the main crossing bridge type is changed as recommended by the Panel. (See the Steel vs. Concrete section below.)

Cost Implications

There is a cost premium to replacing the NPHB. The raw cost estimate numbers (using 60% CEVP) taken from official CRC documents are:

Table 15 – Estimated Cost to Replace the North Portland Harbor Bridge

Item	Cost
Proposed Steel Bridge with 380' main span	$ 95,000,000
Demolition of the existing bridge	26,000,000
Reduced Deck area of new NPHB Ramps	-19,000,000
Reduced Deck area of river crossing	-17,000,000
Total effective cost of new 380' span NPHB	85,000,000

If the NPHB is retained with a full seismic retrofit, the comparable cost estimate would be as follows:

Table 16 – Estimated Cost to Retrofit the NPHB

Item	Cost
Jump span addition to NPH	$ 10,000,000
Seismic Retrofit of NPH	60,000,000
Total effective cost of retrofitted NPHB	70,000,000

The estimated additional cost of replacing the NPHB is $ 15,000,000. This additional cost is based on the simple summation of the cost estimates above. The BRP believes the actual additional cost may be significantly less since BRP recommendations will result in structures that are simpler and more constructible.

It should be understood that this is a preliminary cost analysis. The purpose of this exercise is to illustrate that there is little difference in cost between the replacement option and an option with a full seismic retrofit of the NPHB.

Ground improvement for approach roadways has not been included in the estimates above. The estimated cost (with CEVP markup) is estimated to be $25,000,000 under either scenario.

Steel vs. Concrete for a Replacement NPHB

The proposed new NPHB is assumed to be a steel structure with a main span length of 380 feet. Some cost savings could be realized by using a concrete structure with shorter spans. A concrete structure with 280-foot spans was proposed for the NPHB in the October 2007 draft Type, Size and Location Report. The estimated savings for a concrete NPHB with shorter spans is conservatively estimated at $17,000,000.

The new ramp structures crossing the Oregon Slough are also proposed as 380-foot steel spans. If shorter concrete spans were also permitted for these structures, the additional estimated savings would be $18,000,000. And so together, $35,000,000 could potentially be saved if all of the Oregon Slough crossings were allowed to use shorter concrete spans. If so, the replacement alternative may actually generate a savings over the Phase II seismic retrofit option.

These savings will have to be weighed against the project risk and delays of revising the Biological Assessment of the NPHB due to additional piers in Oregon Slough as a result of shorter bridge span lengths. Potential delay to obtain a revised BA could be six months to two years. If the Project Sponsor's Counsel decides to pursue the proposed BRP main river crossing structure type, additional environmental work may also be necessary to document impacts of the main river changes. If so, any changes to the Oregon Slough can be documented at the same time. Documenting such changes to Oregon Slough is not likely to be on the critical path.

The BRP believes a strong case can be made that the proposed improvements with a longer span main river crossing far outweigh any additional impacts to Oregon Slough. The reduced impacts in the main river crossing will be protecting high value river habitat compared to the anticipated increased impacts to the lower value habitat in Oregon Slough.

Replace vs. Retrofit Life Cycle Analysis

To achieve an additional 150-year service life (to match the new Columbia River Crossing), the existing NPHB is estimated to accrue the following maintenance and rehabilitation costs:

Table 17 – Life Cycle Cost for a Retrofitted North Portland Harbor Bridge

Task	Total Cost (2010 dollars)
Annual Maintenance ($3,000/yr x 150 yrs)	$ 450,000
Deck Overlays @ 35 yrs (3 x $9,800,000)	29,400,000
Major Rehab, one @ approx. 63 yrs, $425/SF	83,000,000
Total Maintenance and Rehab, existing bridge	113,000,000

In the summary above, a fourth deck overlay is assumed to be needed with the major rehabilitation project. Annual maintenance costs may include minor concrete repair, minor joint repair, adjusting and/or repaving approaches, and other work typically performed by ODOT maintenance staff. Major rehabilitation could include scour mitigation, parapet repair and/or replacement, structural deck overlay or deck replacement, bearing repair or replacement, mitigation of corrosion of post-tensioning strand, and/or strengthening for load capacity.

A new NPHB will also require maintenance and rehabilitation, but at a lower cost. The new bridge maintenance and rehabilitation cost estimates are shown in Table 18 below:

Table 18 – New NPHB Maintenance and Rehabilitation Estimate

Task	Total Cost (2010 dollars)
Annual Maintenance ($3,000/yr x 150 yrs)	$ 450,000
Deck Overlays @ 40 yrs (2 x $9,800,000)	19,600,000
Major Rehabilitation @ 80 yrs, $220/SF	43,000,000
Total Maintenance and Rehab, new bridge	63,000,000

Due to industry improvements in concrete, steel, and post-tensioning technology, a new NPHB would be expected to incur lower maintenance and rehabilitation costs. Deck overlays, however, would still be required at a similar interval and similar cost to the existing bridge.

In summary, a new NPHB will result in approximately $50,000,000 life cycle savings (2010 dollars) in future maintenance and rehabilitation costs compared to the existing.