## LIFE-CYCLE COST DESIGN BASIS FOR THE NEW PORT MANN CABLE-STAYED BRIDGE



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committee that developed the Guide Specification for Segmental Concrete Bridges, and has been active in AASHTO bridge code developments on behalf of PTI and ASBI. Mr. Goodyear is a graduate of Cornell University in Ithaca, NY. He is a recipient of the **Beavers** Award for Engineering, and is a member of National the Academy of Engineering.

### SUMMARY

The Port Mann Bridge-Highway 1 Project in Vancouver, BC was tendered as a 40-year concession, upgrading approximately 30 km of the Trans-Canadian Highway including a new crossing of the Fraser River between Coquitlam and Surrey, BC. The concession period included the time for construction and allowed a broad range of design options for achieving the lowest net present value (NPV) to design, build, operate and maintain the upgraded highway facility.

The new Port Mann Bridge is the 'tollgate' for the concession, and along with an adjoining interchange, was the critical path for project delivery to initial tolling. The Reference Concept developed by the Province served as the basis for the RFP, and was based on maintaining the older 5 lane bridge, and adding a second 5 lane bridge for the 10 lane thoroughfare required for the Right of way and project. alignment were established in the RFP for this Reference Concept. The new bridge developed in response to the RFP replaced the Reference Concept with a new 10 lane steel-composite cable-stayed bridge, located within the same right of way provided for the Reference Concept.

preferred of the Selection proponent based on NPV set the framework for a rational decision process, monetizing all program costs - right of way, design, construction cost, construction schedule, developer's risk, toll operations, and life-cycle - in maintenance order to determine the lowest net present value price for the development. It is in the context of this process that the twin deck composite steel cable-stayed structure in service today was created.

The presentation will review the basis for key decisions on structure type, layout, form and design details leading to the final design solution. The special advantages with the steel design form chosen relating to the framing plan, connection details, constructability and will be discussed in relation to options considered that were and eliminated based on the NPV metric for reliability and best life cycle cost. The presentation will include review of the erection procedures employed to manage the complexity associated with erecting twin decks supported off of a common tower.

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## Introduction

The Port Mann Bridge Highway 1 project was tendered in 2007 as part of the Gateway Development in Vancouver, BC. The Project was part of the BC government's ambitious program to upgrade the transportation network in the Vancouver Region in order to further the impressive commercial growth and economic vitality of the Region. The Program was centered on a progressive approach to public works development, teaming government with private developers deliver to maior improvements in transportation infrastructure in a fraction of the time of conventional delivery through the use of public-private partnerships.

The scope of the project was impressive. Approximately 30 km of highway would be upgraded, including the venerable bridge crossing of the Fraser River. (Fig 1) The program called for doubling the capacity over the river, expanding the narrow 5-lane facility to 10 lanes. For those who sat in the daily backup of Hwy 1 in Surrey, the expansion would provide welcome relief from the bottleneck in access to Coquitlam, Vancouver and the north side of the Fraser River.

The Project: The new Port Mann Bridge is the centerpiece of, and the tollgate for, the major redevelopment of Highway 1 crossing the Fraser River into Vancouver, BC. The scope and complexity of the project make it one of the most ambitious highway transportation projects in North America. The form of delivery makes the project even more impressive in that the entire development was tendered as a private concession. The instructions to proposers called for a privately financed development with a 40vear concession that included the time of construction. The Request for Proposals (RFP) for this massive project was one of the most comprehensive masterfullv and crafted specifications that this author has seen in over 30 years in the transportation business. Twentyeight schedules covered every aspect of procurement, design, construction and operations, and set forth the terms and processes for a comprehensive development program.

Selection of the preferred proponent was based on a two-step selection process after shortlisting. Invitation to submit a price proposal could only follow the submission of an acceptable, compliant technical proposal for the entire 30+ km development. Selection of the preferred proponent was to be based on submission of the best net present value (NPV) of the annual concession payments proposed for the development among those who submitted a compliant technical proposal.

The Connect BC Team was led by Macquarie as concessionaire, with Kiewit-Flatiron Partnership as the DB contractor, and with TY Lin International leading the Fraser Crossing design and Hatch Mott McDonald-MMM (H5M) leading the on-shore design.

The timing of the tender submission happened to coincide with one of the worst economic recessions in the US since the Great Depression, prompted by the mortgage banking debacle created by the US real estate market. In the time between selection of the preferred proponent and financial close for the project, the financial markets retracted to the point where the financial plan tendered for the project was in jeopardy. The BC Government stepped in to address the financial crisis by forming a Crown Corporation, TICorp, as a replacement for Macquarie as the concessionaire. The project then advanced to closing, with NTP granted to the Design-Builder, Kiewit-Flatiron Partnership in March, 2009.

**Project Development:** The RFP for the project included a Reference Concept (Figs 2 and 3) covering the entire corridor. For the Frasier River Bridge, the Reference Concept called for upgrading the existing bridge and building an adjacent 5 lane cable-stayed bridge to provide the required 10 traffic lanes. The original Port Mann Bridge was designed as a 4-lane bridge, converted to 5 lanes for the traffic volumes on Route 1. The original Port Mann

Bridge was a 366m main span deck tied arch, with the balance of the 2 km crossing comprised of plate girder approaches. The tender documents included documentation of significant numbers of fatigue crack indications in the approaches, and uncertain conditions for the orthotropic decking of the steel arch main span. Members of the Design-Build Partnership had experience working on past upgrades to the bridge, and offered a first hand perspective to the concessionaire on the maintenance effort associated with the existing bridge.

The net present value approach to selection is consistent with the life cycle cost basis for design that is the ambition of most conventional design-bid-build and design-build projects in the US. But being a concession, where the proponent carries the cost and risk of operations, this delivery program improves upon the subjective life cycle cost program of conventional delivery through an objective, hard dollar assessment for design, construction and operations.

Amortizing the initial cost of construction is a major component of the NPV metric. Since all revenue needed to pay down the first cost is from tolls, availability is also a metric that needs to be quantified as part of the financing strategy. Durability, maintainability, access for inspection, forecast of repair and maintenance were all factors that affected the financial model used to develop the project. These financial criteria flow down to the design-builder as goals for design and construction of a best net present value alternative.

**Bridge Type Studies:** Evaluation of alternatives for the new Port Mann Bridge was led by the Kiewit-Flatiron Partnership (KF) team with the singular goal of developing the best net present value alternative for the project. Every conceivable alternative (whether the Engineers thought them practical or not) was considered for the main span, from record-setting portal frame girder bridges, to double-deck trusses and arches; from suspension bridges to cable-stayed bridges; and from long span concrete to steel composite cable-stayed decks. The Reference Concept set out the right-of-way that was associated with pre-tender environmental

documents and expected permitting. The RFP also included a number of restrictions on alignments and pier locations, most notably that one could not have a pier on the south bank of the Fraser River, adjacent to the pier already on the south bank for the old bridge. The last limitation was one that we questioned, since a pier on the south bank of the river would have allowed a considerably shorter main span, and a lower initial cost. Considerations for the risk of rejection, the complications for hydraulics, and the impact of crossing the CN rail yard for access all led to abandoning the short span alternatives. Once settling on the 470-meter main span, the focus was exclusively on cablestayed alternatives.

The initial screening study of alternatives focused on the Reference Concept for keeping the old bridge and constructing a new 5-lane structure. Once the short spans were eliminated, the inquiry broadened to look at both 5 and 10 lane new bridge options. Furthermore, the ongoing assessment of maintenance and financial risk associated with extending the old bridge for another 40 years trended towards the merit of a total replacement. The principals of KF viewed the risk of pricing the scope creep generally associated with a major retrofit as uncompetitive. The lenders engineers apparently agreed – there were visible sighs of relief when the decision to build all new for 10 lanes was announced to the lender's engineer early in the review process for the proposal.

There were two choices for fitting 10 new lanes in a 5-lane corridor. One was to develop a double deck solution with an over-under 5 lane The second was to develop a arrangement. single level, very wide deck system to carry all 10 lanes. TYLI had a recent reference for a double deck truss system. We were involved with investigations to replace the Alaskan Way Viaduct in Seattle after the Nisqually One of the concepts Earthquake in 2001. receiving brief consideration for Seattle was a double deck extradosed bridge along the waterfront. While the double deck configuration itself was not difficult, the transition from a double deck to a single deck approach was quite expensive. In the case of the Port Mann site, the roadway braid required for the approach bridge

to the Surrey side required significant extension of the bridge, expensive substructure and complex geometrics for the roadway and approach. Maintenance of traffic for the approach roadway, and temporary facilities to accomplish the traffic changeover added to the complexity. Based on the geometric limitations and anticipated substructure (straddle bent) costs for the approaches, the double deck solution was dropped as being uncompetitive.

However, the single deck solution had its own geometric challenges. Team member H5M performed all the highway design and civil design work for the project. Once the 10-lane option was preferred, alignment of a 10 lane new bridge within the 5-lane right-of-way became a challenge. Maintenance of traffic required that the old bridge stay in service. The approach geometrics on the Surrey side of the river were constrained by the existing alignment, limited right-of-way, and the CN rail yard passing under the bridge. H5M said they could solve the alignment for a 10-lane roadway, and they did. (Fig 4) However, the solution carried the edge of deck to the right-of-way line, leaving no room for foundations outboard of the roadway deck, and the proximity of old and new decks during construction did not allow for pylons between the two bridges. While the RFP allowed for the proponent to acquire additional right-of-way, the cost and time to do so was a risk to both cost (relatively minor) and schedule (a major factor) for the proponent, So the challenge for bridge designers was how to develop a 10-lane cablestayed structural solution in a 5-lane right-ofway without outboard foundations.

The formulation of the financial package is beyond the scope of this presentation. However, the first cost of construction is a major component of an NPV concession package. While differences in financing plans can make the difference in a winning NPV, those differences will scale against the initial outlay for construction. At the design-builder level of the team, the traditional design-build criteria of cost and schedule were central to the decision process. The time to get to tolling, which was set forth as 8 lanes of traffic across the river, affected design choices and risk pricing. This was never more evident than when evaluating the 10-lane option, and the alignment noted above. The risk of spending an extra six months to a year negotiating right-of-way with the railroad would translate directly to increased NPV pricing, and at the pre-bid plug figure of \$450,000/day, the risk pricing could sway type selection.

Concrete and steel superstructures were considered for both the main and approach spans. The customary preliminary design effort was carried out for each alternative, developing general quantities and sections for comparison. In concert with H5M's alignment studies, the design team developed concept studies for cable-stayed bridges that included either fullwidth 10-lane or twin 5-lane deck systems (notwithstanding right-of-way) supported by a variety of tower types. The difference in tower and foundation quantities when comparing a single pylon and foundation to a twin portal tower with twin 5 lane decks was considerable. Much of the deep foundation structure required for the main towers was to support self-weight of the foundation itself, rather than the deck above. Whether looking at concrete or steel decks, the main tower quantities for the twin portal pylon solution were more than 50% greater than those for the single pylon support system. This level of quantity increase for two towers, coupled with the logistics of larger pylon foundations in the river for the twin portal tower gave a tremendous cost and schedule advantage to the single pylon solution.

The single central pylon concept would support both a two-stay plane full width section and a twin deck four-stay plane section as steel or steel composite deck sections. Sections were developed for both full width steel truss, floorbeam or box section and for a twin composite edge girder section. The steel quantity for a two-cable plane system was approximately 35% greater than for a four-plane system due to the longer floorbeam span. The transverse truss and box girder systems were eliminated from consideration based on unit fabrication costs. Each of the twin composite frame sections was fairly conventional, and similar to many single 4 and 6 lane cable-stayed deck structures built in North America. The routine nature and reliable cost history of these regular sections was an

important selling feature for the twin deck option.

The equipment required for erecting 60+ meter long floorbeams, large box girder sections or transverse truss elements was a different class of equipment than typically used to erect the conventional steel composite cable-stayed deck The Port Mann site had both land and system. water based erection conditions to consider. Moreover, the land based condition for the south side of the bridge had access limitations due to the railroad yard under half of the south cantilever. One of the attractive features of the steel composite deck system is the variety of suitable erection methods that can be employed - from stick built framing with relatively light lifts to full section erection with gantries and heavy lifts. So with the mix of construction logistics associated with the Port Mann site, the steel composite section proved to be the optimum solution for construction. (Fig 5)

# **Details of Design**

**The Framing System:** Each of the two deck frames was a standard floorbeam and edge girder system. However, there were several non-standard aspects of the framing layout associated with the central tower.

- The constraints of the layout described for the type selection included an atypical span layout. While the railroad yard affected the main span layout, the back spans were constrained by the definition of a secondary navigation channel on the north. The resulting backspan ratio was .4 of the main span, which is less than optimum for girder and anchor pier design on a highway bridge.
- The offset of deck relative to the tower resulted in splayed cables emanating from the single towerhead. The frame included struts between each deck to balance the resulting horizontal cable force across the width of the bridge.
- The approaches to the main unit were segmental concrete box girders. The 10-meter spread of parallel main span deck frames required to accommodate the pylon would either require a 4<sup>th</sup> box girder, or

exceptionally wide units for 3 boxes. The approaches also had to accommodate the transition of the new bridge alignment to the existing structure, which involved building an initial 8 lane unit, and finishing out the 10 lanes plus multiuse path after demolition of the old bridge. This traffic logistics and construction pricing for box fabrication and foundation construction all favored a 3-box solution. In order to allow lanes from the main spans to meet an economical 3-box frame in the approaches, the backspan frames were tapered towards each other. This was only practical with the central pylon scheme, extending the cost advantages of this concept beyond those of just the main span system.

- The width of the single central tower was • limited by the available right-of-way at the south pylon, and would affect the cost of framing across the inter-roadway gap. The narrow section had limited lateral strength as a freestanding pylon. So the lateral system was also designed as a stayed system, with transverse stabilizer stays connecting the base of the towerhead to stabilizer beams emanating from the tower. The resulting stay system created a cable-stayed pylon that was similar in concept to a sailboat mast, allowing a slender pylon section to work as a pure column instead of the more typical bending mode of a portal frame.
- Tower height is typically gaged to the span length for optimum stay cable performance. With the single central pylon and twin decks, the truck clearance required a taller tower for minimum roadway clearance to the stay plane. The tower height was increased approximately 12 meters for this condition.

## **Special Details:**

**Towerhead cable anchors:** The typical towerhead for a composite frame cable-stayed bridge anchors two cable planes. Anchorage for four cable planes, along with access to anchorages and the requisite elevator access resulted in an "H" shaped concrete section for the towerhead. An "H" shape provided two core

walls to anchor typical stay anchor boxes. Although the geometry for anchor box fabrication was unique for each box, these elements were otherwise standard components when compared to conventional cable-stayed towerheads. The outside face of the "H" section was left open during construction for access, later closed off though the use of precast fascia panels. (Fig 6)

**Deck cable anchors:** Deck anchorages for composite steel cable-stayed bridges generally follow one of two forms – fin anchors above deck (extensions of the edge girder web) or bucket anchors below deck (attachments to the side of the edge girder). For the more typical framing systems, these deck anchors are both regular in geometric configuration, and either vertical or only slightly splayed against the vertical frame. The wider offset associated with the 4-plane, 10-lane structure resulted in both irregular geometry and considerable lateral cable angles for deck anchorages.

We investigated three basic configurations for these deck anchors. Each had advantages and disadvantages. These were

- Fin anchors with bent web plates above the deck
- Fin anchors with canted edge girder geometry
- Bucket anchors with bolted anchorage assemblies

One aspect of splayed stay geometry is that the lateral cable angle of the stay plane is not in the vertical plane. (Fig 7) Cable sag, and change in cable sag with changing stay force and vibration, follows the vertical plane. For the typical roadway geometry, the difference in these angles from vertical is slight. But as the offset gets larger, so does the lateral component associated with the difference in vertical cable sag vs. lateral stay plane angle.

Looking at each option in turn, the advantages and disadvantages considered for each include the following: • Fin anchors with bent plates (Fig 8):

#### Advantages:

- 1. Above deck access for installation of lower stay anchorage elements
- 2. Continuity of web plate in fabrication (though either cjp weld or bent plate)

#### Disadvantages:

- 1. Uninspectable (buried by deck pour) seal and strength weld between slotted flange and web plate (or cjp weld to top flange) for shear continuity at or near bent plate plastic strain region
- 2. Tolerance of bent plate geometry to meet stay plane angle, or CJP weld for web connection
- 3. Lateral load component due to vertical sag plane on flange-web weld detail or bent plate
- 4. Additional floorbeam span needed to align edge girder with stay plane
- Fin anchors with canted edge girder (Fig 9):

#### Advantages:

- 1. Above deck access for installation of lower stay anchorage elements
- 2. Avoids bent plate or cjp web weld by direct alignment with stay plane
- 3. Continuity of web plate connection to stay cable

#### Disadvantages:

- 1. Slotted flange to web weld for shear transfer (can be avoided by asymmetric top flange to inside of web)
- 2. Lateral load component due to vertical sag plane on web plate and flange to web weld
- 3. Higher fabrication cost for inclined web configuration, and variable configurations for inside and outside edge girder lines
- 4. Additional floorbeam span needed to align edge girder with stay plane

• Bucket anchors (Fig 10):

Advantages:

- 1. Shorter floorbeam span and narrower precast deck width
- 2. Fully inspectable and replaceable anchorage structure without impact on traffic
- 3. Continuous, typical flange to web welded connection with standard (square) plate girder fabrication
- 4. Orthogonal strength and stiffness for sag plane of stay
- 5. Superior out of plane stiffness for anchoring stay damper

Disadvantages:

- 1. Increased fabrication for stay pipe frame connections
- 2. Transfer of lateral load (due to eccentricity from edge girder) through edge girder to floorbeam connection
- 3. Below deck installation of stay hardware at dead end anchorage

Decision points included both first costs and considerations related to maintenance cost and traffic risk. In terms of first cost, when comparing the steel weight of longer floorbeams and deck panel to the fabrication weight for bucket anchors, the figures did not show a decided advantage either way. In terms of long term inspection and maintenance of critical connection areas, the bucket anchors had a significant advantage. Both inspection and repairs could be conducted from travellers below, without any impact to traffic. Critical welds can be observed and tested throughout bridge life, since the concrete deck does not conceal them. The entire anchorage assembly can be replaced. The superior stiffness for out of plane movement and stiffness for stay damper performance also favored the bucket anchors. Therefore, the bucket anchorage system was selected for final design on the basis of both performance and serviceability.

### **Bridge Articulation**

The project prospectus included very significant seismic design criteria. The ground motions specified for design were comparable to those applicable to designs in regions near Los Angeles. A 3-stage ground motion was stipulated; with a 475-year return period for the operating event, a 975-year return period for the repairable damage event, and a 2475-year return period for the no-collapse event. Foundations were a significant portion of construction cost, and bridge articulation was evaluated to minimize overall foundation design requirements for seismic demands.

Initial studies focused on providing rigid connections to both towers and back span piers. Initial evaluations showed that when compared to isolation of selected piers through bearings or dampers, the collective demand for all piers (the sum of piles) went down with the addition of bearings for the anchor piers. Studies also showed that creating a fixed point for the river tower did not significantly alter overall response, but did increase pile demands for the river pier.

The south landside tower was selected as the fixed point for the longitudinal system. Foundation construction on land is typically less expensive than that in the water. So the south tower was selected as a primary restraint point for deck articulation. The anchor piers were allowed to slide for seismic conditions. Arrangements with rigid connections at those piers added a third more piles to the anchor pier foundation in the water, which was a considerable additional cost based on the plug figures for the 1.8 meter steel shell piles used at bid time. The use of sliding bearings at the anchor piers provided the necessary degree of freedom for dampers at these piers, which for some motions cut pier demands by 40%.

Vertical support was provided at each tower with bearings over the stabilizer beams. This type of support has become typical for composite frame bridges, and allows a longer span to the first stay, which is always a complicating factor for stay anchorage geometry in the towerhead. Lateral bearings are provided at each pier, and a temporary longitudinal restraint is included at the north river tower to enable jacking to replace longitudinal bearings at the south landside tower.

### **Aerodynamic Studies**

Of the suite of special studies for hydraulics, vessel impact, geotechnical engineering and aerodynamics, the latter study was most relevant for the steel deck design. The twin deck structure created an unusual design condition for section design, with a series of relatively flexible bluff sections in close proximity, one being in the wake of the other. In addition, for the first 2 years of service, the existing bridge would affect the wind stream for downstream wind directions, adding wake effects from the old bridge to considerations for the new.

The aerodynamic studies included the classical section model studies as well as 1:225 aero elastic model studies in RWDI's wind tunnel facility in Guelph, Ontario. (Fig 11) The need for a main span wind fairing was assumed in the pre-bid design based on the character of the twin deck proposal, and the need for the fairing was confirmed through wind tunnel testing. Stability was enhanced by the cable configuration in a similar fashion to the benefits seen with a more typical A-frame stay arrangement for twin cable plane bridges, where the cable convergence in the towerhead forces a single node response that helps separate torsional and vertical frequencies. Motion forecasts were less with a pinned strut between the two deck frames, so the design went forward with a simple pinned strut instead of a rigid frame.

The critical operating condition for traffic comfort was the case with downstream winds resulting in wake buffeting of the new bridge due to the old arch. Further study of the site wind and terrain analysis for critical angles of attack narrowed the exposure for the short-term condition with the old bridge in place to an acceptable return period for interim service without the need for additional mitigation measures.

# **Steel Erection**

For those who like variety, the erection planning program was an ideal assignment. And with two major bridge contractors on the same team, there was no shortage of experience and ideas for erection.

The south cantilever had to deal with limited access over the railroad and over-water erection for the main span, but had an open field for erection of the south backspan. (Fig 12) The north cantilever was all over water. The logistics of the south backspan required that erection be fed from outside the railroad yard. So direct lifting by derrick in the standard fashion was not practical. In addition, the heavy weight of the first field section at each backspan pier was more than a typical deck mounted derrick would handle. The over-water access for the north cantilever permitted lifting a fully assembled steel section. Deal gantries from the adjacent Golden Ears project were available, and were upgraded for the erection requirements at (Fig 13) For all of the above Port Mann. reasons, three separate erection methods were adapted for steel erection. In addition to the gantries used for the north cantilever, derricks were used for stick erection of the south main span, with crane erection for the south backspan. (Fig 14)

Erection efficiency is one of the advantages of the steel composite deck system. Profile of the flexible steel frame can be controlled during erection with stay adjustments before making the frame composite with the precast deck. The more challenging control is generally the lateral drift, since typically there is nothing in the permanent frame to adjust alignment. That challenge was amplified for the twin barrel deck system on Port Mann. In order to avoid sidesway the two deck frames had to be erected in parallel. Should they get out of line, there would be a time consuming and challenging process to pull two decks back in line at the same time if drifts differed between the two. So as we started erection, the number 1 objective was to hold alignment throughout assembly. The erection crew's diligence paid off, for the alignment during erection was better than any we have seen on even simpler bridges.

## Closing

The Port Mann Highway 1 development project was tendered on the basis of a best value defined as the lowest net present value cost over the operating period for technically compliant alternatives. The project development by the successful proponent led to a twin roadway steel composite cable-stayed bridge solution based on the economic advantages in first cost, schedule and maintenance, that when blended with operating factors, produced the lowest net present value offering to the Owner.

### Credits:

Owner: Transportation Improvement Corporation, a BC Crown Corporation

Original Concessionaire for Tender: Macquarie Infrastructure

Design-Builder: Kiewit-Flatiron Partnership

Highway and Civil Design: H5M, a joint venture of Hatch Mott McDonald and Marshall Macklin Monaghan

Bridge Design: T.Y. Lin International in collaboration with International Bridge Technologies

Aerodynamics: RWDI

Steel Fabrication and Supply: Canron Western Constructors, Vancouver BC; Oregon Iron Works, Clackamas, OR





Figure 2 - Reference Concept Layout



Figure 3 - Reference Concept - Bridge Section



Figure 4 - New Port Mann Bridge Layout



Main Span Typical Section









Figure 7 - Inclined Cable Plane



Figure 8 - Bent Plate Fin Anchor



Figure 9 - Inclined Web Fin Anchor



Figure 10 - Bucket Anchor



Figure 11 - Full Aeroelastic Model at RWDI



Figure 12 - South Mainspan Erection Method



Figure 13 - North Mainspan Erection Method



Figure 14 - General Erection Layout



Figure 15 - New Port Mann Cable-Stayed Bridge