Independent Technical Review of the George Massey Crossing

FINAL REPORT

September 2018

WESTMAR ADVISORS

WESTMAR
ADVISORS

September 7, 2018

British Columbia Ministry of Transportation and Infrastructure
Room 306 Parliament Buildings
Victoria, BC V8V 1X4

Attention: Hon. Claire Trevena
Minister of Transportation and Infrastructure

Reference: George Massey Crossing Independent Technical Review

In response to your request in October of 2017, I am pleased to provide you with the enclosed final report describing the Independent Technical Review of the George Massey Crossing.

The Review has benefitted from the assistance of several subject matter experts in various fields, based both locally here in British Columbia and from across the globe. Without exception, everyone involved was eager to contribute their knowledge to support the Province of British Columbia in the process of making an informed decision on the best path forward for the Crossing.

It is important for me to acknowledge the GMTR Team who were extremely helpful and forthright throughout the Review process.

I greatly appreciate having the opportunity to complete this Review and would like to thank you for entrusting me to lead it.

I am available at your convenience to address any comments you may have.

Sincerely,

Stanley R. Cowdell, P.Eng.
Executive Director
Westmar Advisors Inc.

Encl.

George Massey Crossing
Independent Technical Review

Final Report
September 2018

Prepared by:

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2018-09-07

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Executive Summary

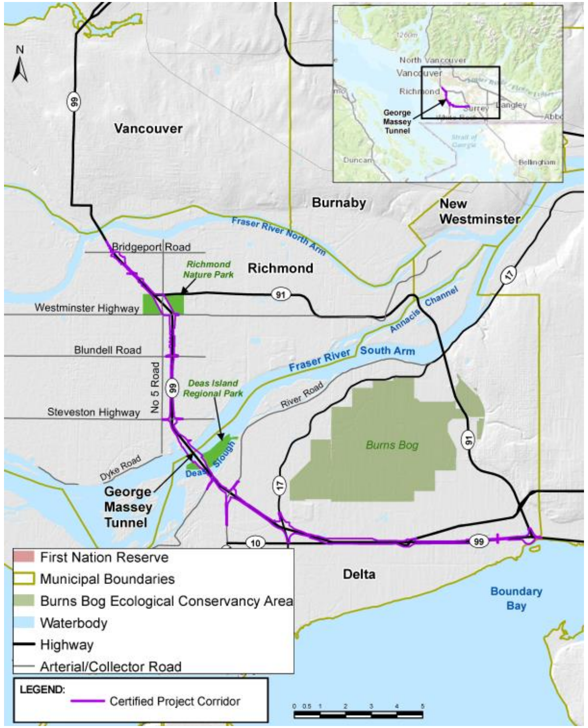
The George Massey Tunnel Replacement Project (the Project) was established to improve transportation along the Highway 99 corridor from Highway 91 in Delta to the north end of Richmond. The Project was first announced in September of 2012 and in October of 2016 the Reference Concept for the Corridor improvements, which included a 10 lane cable-stayed bridge to replace the George Massey Tunnel (the Tunnel) and interchange and highway improvements, was finalized for procurement.

Some Project stakeholders remained opposed to the scope and scale of the Project and, in September of 2017, the Province of British Columbia (the Province) announced the procurement process had been cancelled and that the Project would be subject to an Independent Technical Review (the Review). The Province stated:

> *The review will focus on what level of improvement is needed in the context of regional and provincial planning, growth and vision, as well as which option would be best for the corridor, be it the proposed 10-lane bridge, a smaller bridge or tunnel.*

On November 1, 2017, the Province announced it had retained Stan Cowdell, P.Eng., of Westmar Advisors Inc. (Westmar Advisors) to complete the Review. The Terms of Reference for the Review are provided in Appendix A.

Project documentation, including related engineering studies, was developed over many years and is extensive and voluminous representing many thousands of hours of work. The Review found no reason to complete independent verification of all investigative field work and engineering completed for the Project. Further, this work has been completed by engineering, and other related, professionals registered in British Columbia. It is reasonable to accept that the work is technically sound and that detailed checking or full design audits are not necessary for this Review.



Project overview map.

The Review Team is confident that sufficient and relevant information has been reviewed such that there is unlikely to be any documentation that would materially alter the findings and recommendations of the Review. It is also important to note that the Review did not speak to any of the Proponent Teams about their proposed designs and was not provided with the commercial offers made to the Province prior to the procurement process being terminated. Any findings or recommendations in this report that may mirror optimizations of the reference Concept by one, or more, of the Proponent Teams are coincidental.

The Project was planned on the basis of funding from toll revenue. With the removal of tolls from the Port Mann and Golden Ears bridges on September 1, 2017, the Review has based its analysis on the assumption of no tolling or mobility pricing for the George Massey Crossing and the other major crossings in the Lower Mainland.

Westmar Advisors used an established process that has been applied to assessments of other projects to complete this Review. The process includes three general steps:

1. **Understanding the Project needs, goals and objectives**
   i.e., why is the Project being contemplated?

2. **Assessing the solutions planned to meet the needs, goals and objectives**
   i.e., what functions (i.e., number of lanes, transit service) is the Project planned to provide?

3. **Providing findings and recommendations for improvements to the Project**
   i.e., would the planned functions have met the Project's needs, goals and objectives and are there opportunities for improvement?

Existing Tunnel History and Design

The South Arm of the Fraser River (the River) has, for generations, been important to First Nations whose traditional territory the George Massey Crossing is located within. As non-indigenous settlement of the Lower Mainland expanded in the late 1800s and early 1900s, the River continued to be an important marine transportation route but was also a barrier to the increasing use of vehicles for transportation.

A 1956 study by Foundation of Canada Engineering Corporation, with the assistance of Christiani & Neilsen of Denmark, recommended a crossing at Deas Island in the form of a four lane tunnel. At the time, the reasons for recommending a tunnel included:

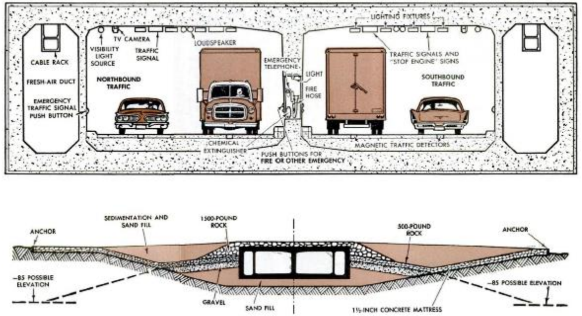
- A tunnel was seen as being a preferred solution based on the site geotechnical conditions and perceived operational benefits. Vehicles using the roadway would be diverted only about 25 metres (m) below horizontal in a tunnel rather than about 50 m above horizontal over a bridge.
- The cost was estimated to be approximately $17 million for a tunnel in comparison to about $24 million for the bridge in 1956 dollars.
- 85 percent (%) of the cost of labour and materials would be spent in British Columbia for a tunnel compared to only 60% for a bridge.

In 1956, the Province announced that a tunnel would be constructed at Deas Island. The overall construction period for the Tunnel was three and a half years. The installation of the tunnel elements in the River took less than five months to complete.

The Tunnel design was "state of the art" at the time and the original design team considered significant seismic induced forces but did not consider the effects of soil liquefaction as this was not well understood. A 1991 study by the British Columbia Ministry of Transportation and Infrastructure (MoTI) determined that the soil around the Tunnel was susceptible to liquefaction in a seismic event, which could adversely affect the serviceability of the Tunnel through induced cracks and resulting flooding.

Deas Island with the ferry landing visible. *(above)*

Cross-sections through the originally constructed George Massey Tunnel. *(below)*

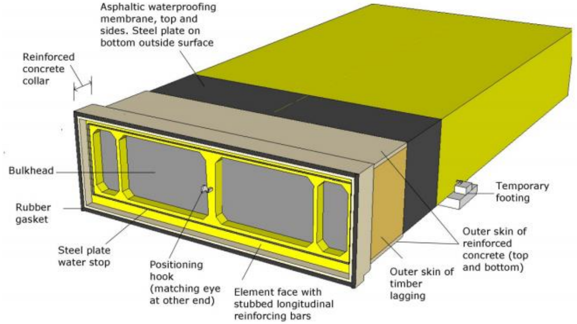


In 2004, Buckland & Taylor Ltd., now COWI North America, Ltd. (COWI), completed the detailed design of a Tunnel retrofit program with the objective of improving the tunnel to meet MoTI's Seismic Retrofit Design Criteria for lifeline bridges. The planned seismic retrofit program had two parts: *Part 1 - Structural Retrofit;* and *Part 2 - Ground Improvement (GI) Retrofit.*

The *Part 1 – the Structural Retrofit* was completed in 2006 and consisted of installing steel plates at the ends of the Tunnel elements (see schematic at right) and reinforced concrete through the full Tunnel length (see details at below right) to reduce the risk of large cracks forming and related flooding. The proposed *Part 2 – GI Retrofit* consisted of densifying soils and installing seismic drains along the sides of the Tunnel, including the approaches, to locally prevent liquefaction and reduce seismically induced Tunnel movements to acceptable levels. The *Part 2 - GI Retrofit* was not completed by the Province. Without the GI, the Project estimated that the Tunnel would perform satisfactorily in a seismic event with a maximum return period of 275 years.

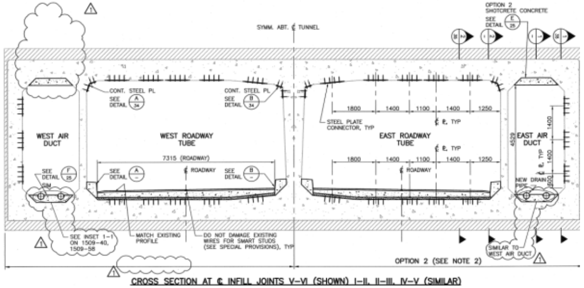
Other than the seismic design limitations, the submerged portion of the Tunnel is in good condition with a remaining service life in the order of 50 years. The existing Tunnel electrical and mechanical systems require upgrades; and the level of lighting provided is below that which would be installed in a new tunnel.

The Tunnel suffers from congestion and reliability issues with significant queuing during peak times due to only a single lane being available in the non-counterflow direction. Average northbound travel time along Highway 99 (from the Highway 91 interchange in Delta to the Highway 91 interchange in Richmond) is approximately 20 minutes, which can vary up to 50 minutes. The northbound direction during the afternoon peak sees some of the highest delay times and variability in the region. Multiple studies between 1991 and 2006 were completed by the Province and other governmental and non-governmental organizations, all with MoTI participation. The studies recommended increasing the capacity of the existing Tunnel crossing, with most recommending a second tunnel.



Schematic of the existing George Massey Tunnel typical section end details. *(above)*

Details of the George Massey Tunnel structural retrofit completed in 2006. *(below)*

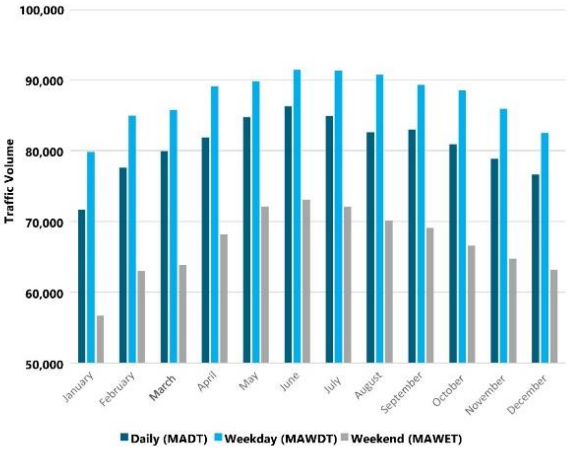


The Independent Technical Review

General

While the Project is often characterized as the replacement of the existing Tunnel with a new bridge, the proposed new bridge was only one component of a much more extensive scope of highway improvements. The *Request for Proposals* describes the Project as follows:

> *The George Massey Tunnel Replacement Project (the Project) includes the design, construction, partial financing, operation, maintenance and rehabilitation of the Highway 99 corridor between Bridgeport Road in Richmond and Highway 91 in Delta. The Project will include a new bridge to replace the Existing Tunnel, widening of the highway, improvements to transit and HOV infrastructure, replacement of a number of interchanges and overpasses and decommissioning of the Existing Tunnel.*



Daily traffic volumes by month for the George Massey Tunnel in 2015.

Project Scope & Planning

In planning the Reference Concept, the Project identified the following principal reasons for why the Project is needed:

- Traffic congestion at the Tunnel (see daily traffic volumes at right);
- Traffic continues to be diverted to the Alex Fraser Bridge, using up its capacity;
- It is not practical to seismically retrofit the Tunnel;
- The Tunnel has substandard highway geometries;
- The Tunnel does not provide direct pedestrian or cycle use, only with a shuttle;
- There are limited opportunities to improve transit; and
- Traffic congestion makes it difficult for first responders to access the Tunnel.

Project Goals and Functional Criteria

From the needs, the Project then established the following **Project Goals**:

1. **Reduce congestion.**
   Improve travel times and reliability for all users.
2. **Improve safety.**
   This includes improving traffic and seismic safety, as well as emergency response capabilities.
3. **Support trade and commerce.**
   Improve access to local businesses and gateway facilities and improve travel time reliability for goods movers and service providers.
4. **Support increased transit on the Highway 99 Corridor.**
   Provide dedicated HOV/transit lanes on the new bridge to improve travel time reliability and add capacity for long-term transit improvements.
5. **Support options for pedestrians and cyclists.**
   Provide a multi-use pathway on the new bridge to connect cycling and pedestrian corridors in Richmond and Delta.
6. **Enhance the environment.**
   Enhance the environment under the new bridge and in the Project right-of-way on Deas Island.

Consistent with previous studies, the Review finds the need to reduce congestion in the one lane off-peak direction to be one of the most important reasons for improvements to be made.

During the planning and stakeholder engagement process for the Project, three draft **key design considerations** identified in 2012 were not carried forward as primary goals into later stages:

1. **Alignment with Community, Regional and National Objectives**
   Including concentrating growth in designated areas and providing access to regional town centres.
2. **Community Livability**
   Including property, visual and noise impacts, as well as community access.
3. **Cost**
   Including capital cost, technical viability, time to implement and impacts to road users during construction.

The Project did not formally record how these key design considerations were handled in the Project planning; the lack of formal inclusion in the Project Goals, and the accompanying solutions necessary to address them, is seen as a significant factor in the resulting stakeholder concerns and a potential deficiency in the planning process.

The Review finds that the goals the Mayors Council on Transportation, TransLink (shown at right), Metro Vancouver, and local governments have for the Crossing are closely aligned. It is widely accepted that additional capacity is required to improve reliability and that there are economic, social and environmental disbenefits if no improvement is made. The Review believes it is important to highlight that while some groups opposed the Reference Concept, they do not generally oppose improvements to the Crossing.

With the Goals established, the Project developed specific functional criteria to define what the solutions for each goal would need to achieve. The Review finds that most stakeholder concerns regarding the Reference Concept can be traced to those functional criteria.

Vision

As a region, we maintain our global position as one of the best places in the world to live because we meet our transportation needs in a way that simultaneously enhances the health of our people and communities, economy and environment.

Goals

Make transportation decisions that:

CHOICE
Provide sustainable transportation choices
Support a compact urban area

PEOPLE
Foster safe, healthy and complete communities

ECONOMY
Enable a sustainable economy

ENVIRONMENT
Protect the environment

Headline Targets

As a region, we can best achieve these goals by designing our communities and transportation in a way that:

- Makes it possible to reduce the distances people drive by one-third.
- Makes it possible to make half of all trips by walking, cycling and transit.

Strategy Areas

There are three key transportation levers the region can use to achieve our overarching goal of getting people and goods where they need to go as reliably, safely, efficiently and cleanly as possible. We can:

INVEST strategically to maintain and expand the transportation system.

MANAGE the transportation system to be more efficient and user focused.

PARTNER to make it happen.

Regional Transportation Strategy Framework.

The Functional Criteria are sufficiently objective to define the Project scope but subjective enough to allow for some interpretation and analysis to arrive at suitable provisions.

However, the following criteria are specific, do not allow for interpretation, and determined the Project scope:

> Goal 1 - Reduce Congestion
> ***Functional Criteria*** *(i) Eliminate queuing at any time to 2045.*
>
> Goal 4 - Support Increased Transit on the Highway 99 Corridor
> ***Functional Criteria*** *(i) Provide convenience of transit by improving infrastructure (ex: integrated bus stops similar to Sky train stations).*
>
> Goal 6 - Enhance the Environment
> ***Functional Criteria*** *(i) Provide a clear span structure with no piers in the Fraser River.*
> *(ii) Construct project within existing corridor and reduce footprint of project infrastructure.*

While achieving the Project Goals, the above criteria do so without the limitations that might have occurred had the three “key design considerations” previously described also been Project Goals.

Further, it is expected, given the impact of these criteria on the Project scope and cost, formal trade-off studies and present value analysis would have been completed to confirm that the Reference Concept components that resulted from meeting the functional criteria were appropriately optimized with respect to all criteria.

The Review did not locate any such trade-off studies in the Project documentation that had been provided for review and approval by the Province; and if this was not done, the Review considers that to be a deficiency in the Project planning.

The Review understands that the Province was certainly aware of needs, goals and criteria throughout the Project, however, the formal trade-off studies would have assisted the Province in being fully aware of alternative solutions and which solutions provided the greatest benefit against all Project criteria. This is supported by MoTI’s practice to plan projects to the “minimum requirements to meet project needs and assess incremental improvements on a value for money basis.”

By way of example, Goal 1 to reduce congestion is subjective and can be achieved with a range of potential solutions, from: relieving the non-peak direction congestion but allowing the level of congestion in the peak direction to remain as it is; to eliminating queuing any time to 2045. The first solution would be more in line with what the studies prior to the Project had outlined: two additional lanes of capacity; while the latter (combined with other criteria) resulted in six additional lanes of capacity.

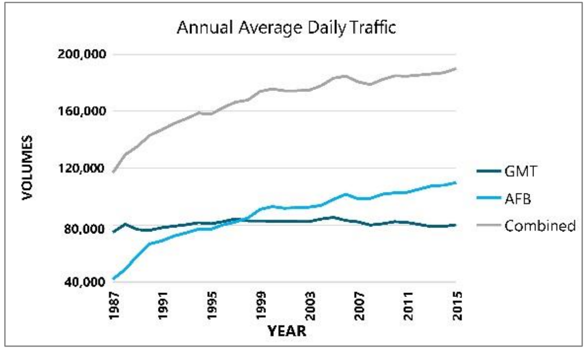
The above is provided as an example to highlight the subjectivity of the goals and to raise the prospect that different interpretations could have been made that could have resulted in a different Reference Concept based on different functional criteria.

While commuters may perceive long delays at the Tunnel, delays in the peak direction with three lanes are not substantially different than the 20 to 30-minute delays at other crossings, including: the Lions Gate Bridge, Iron Workers Memorial Bridge and Alex Fraser Bridge. However, the variability and magnitude of delays in the off-peak direction, especially in the northbound direction during the afternoon peak are unprecedented. The Review finds that addressing reliability in the off-peak direction is the primary need for adding capacity to the Crossing.

Traffic Modelling and Forecasting

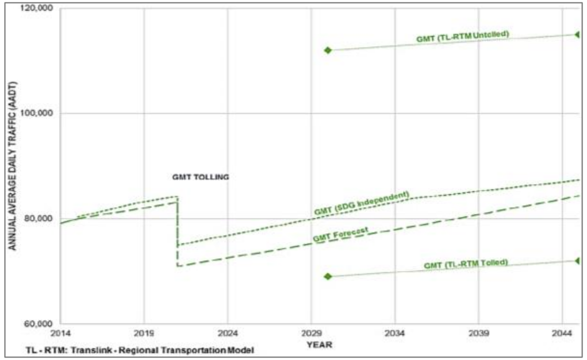
While traffic has grown little at the Tunnel over the past three decades (see Average Annual Daily Traffic at above right), all models (including the one completed for the Review; see the range of forecasts at below right) forecast traffic to grow as the Alex Fraser Bridge becomes more congested. In the case the planned bridge Crossing was tolled, the first-year daily traffic was forecast to reduce to 71,000 vehicles, representing a 14% drop from forecast volumes under continued Tunnel operation. The Project predicted demand at the planned bridge Crossing of 84,000 vehicles per day by 2045; essentially what the Tunnel is handling today.

It is this paradox that has caused stakeholder confusion about the Project; building a significant new asset, which if tolled, would handle less traffic than the Tunnel does today and, if not tolled, would still handle less traffic than the six lane Alex Fraser Bridge is handling today.



AADT at the Tunnel and Alex Fraser Bridge. *(above)*

Range of previous Project traffic forecasts. *(below)*



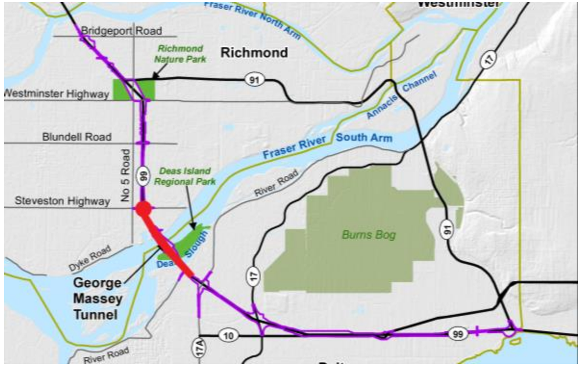
The Project with tolls forecasted a small decrease in traffic for the Knight Street Bridge, Arthur Laing Bridge, and Oak Street Bridge. Traffic on the Alex Fraser Bridge would have increased by 17% compared to without the Project, primarily because of off-peak diversion from the tolled facility to the untolled facility; emphasizing the importance of including all crossings in any future Project planning to avoid unintended consequences.

For the updated forecast of traffic the Review, in addition to the existing Crossing, examined the: Reference Concept; a minimum investment scenario consisting of a six and eight general purpose (GP) lane crossing with only the Steveston Highway overpass upgraded (minimum highway improvements, the 'Do Minimum' scenario shown in red in the figure at right); and an eight lane GP crossing with the Reference Concept highway improvements.

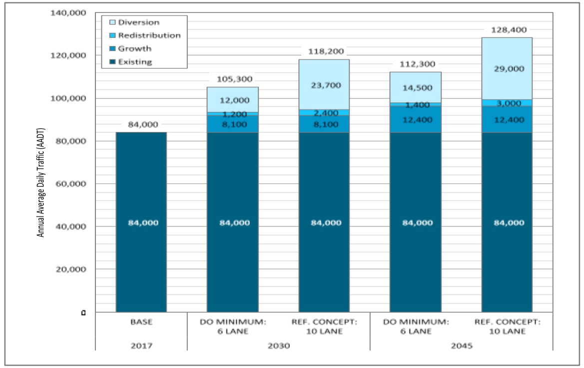
The bar chart shown at right provides a breakdown of the components of the traffic forecasts for the six-lane 'Do Minimum' and 10-lane Reference Concept. Existing traffic is based on actual traffic count information today and forms the foundation for the traffic forecast. Growth is based on land use and economic development and generally depicts overall growth in travel demand across the River. Redistribution includes more travel with decreased access costs (travel times) across the River and can be interpreted as induced traffic.

The largest component of the increased traffic demand for the Crossing is derived from trip diversions from the Alex Fraser Bridge as the Highway 99 Corridor becomes a much more attractive corridor following any capacity improvements.

The Reference Concept achieves the maximum available user benefits as it accommodates all future forecast traffic to 2045 without delays. In terms of lane utilization, the northbound GP lanes are about 74% utilized and the HOV/transit lane is about 55% utilized during the morning peak hour. Similarly, the southbound GP lanes are about 84% utilized and the HOV/transit lane is about 71% utilized showing that there is spare capacity even in 2045 with these improvements.



'Do Minimum' scope in red. *(above)*
2014 AM peak hour traffic forecasts. *(below)*



As a percentage of the Reference Concept (shown graphically at right):

- The six GP lane "Do Minimum" concept accommodates 87% of the 2045 traffic, and achieves 42% of the travel time and operating cost benefits and 36% of the Reliability benefits;
- The eight GP lane "Do Minimum" concept accommodates 91% of the 2045 traffic and achieves 50% of the travel time and operating cost benefits and 46% of the reliability benefits; and
- The eight GP lane with the Reference Concept highway improvements concept accommodates 99% of the 2045 traffic and achieves 95% of the travel time and operating cost benefits and 98% of the reliability benefits.

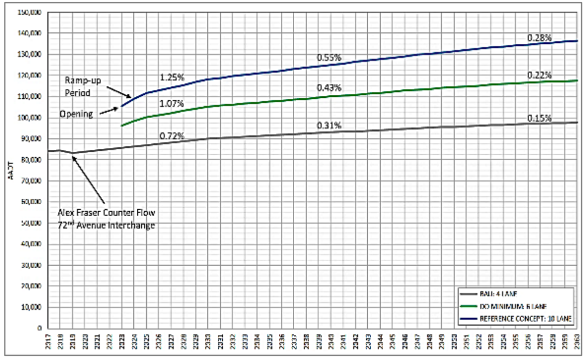
For the six GP lane and eight GP lane "Do Minimum" concepts, travel times in the peak directions would be 15 minutes to 17 minutes greater than the Reference Concept in 2045; very similar to what is experienced today. In both cases, the non-peak direction would experience almost no delay.

With respect to the above forecasts, the Review cautions that both the traffic models used by the Project and the new Regional Transportation Model, Phase 3 (RTM3) are based on historical traffic behavior. As such, future forecasts are a best guess based on known travel conditions observed today. There is inherent uncertainty given technological change (i.e. autonomous vehicles and ride sharing services) that could significantly impact travel demand and efficiency of highway operations (i.e. highway capacity and vehicle occupancy).

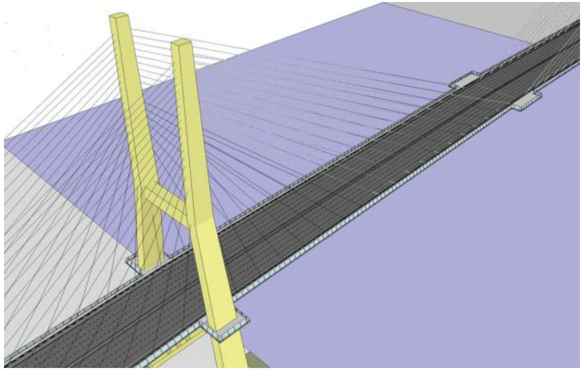
Highway and Bridge Review

The Reference Concept highway and bridge provisions (bridge schematic shown at right) generally achieve the stated requirements and comply with current design standards and practices.

The Reference Concept was not intended to be a final design, which was fully optimized in every aspect. It was provided for information to the Proponents as a potential viable solution. The proposal process allowed and encouraged Proponents to value engineer and optimize the Project to provide maximum value while respecting key Project requirements.



Project traffic forecast. *(above)*
Schematic of the Reference Concept bridge. *(below)*

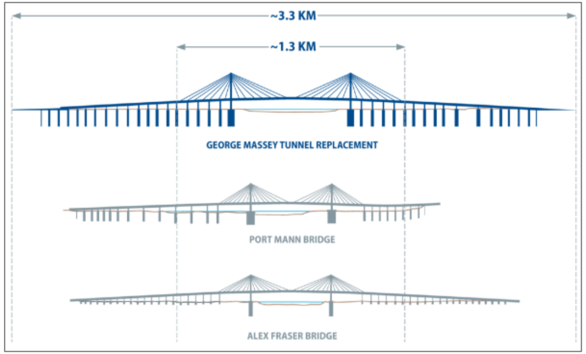


Bridge

The specified functional requirements for the bridge (constructing on the same alignment as the existing highway, and providing a clear span with no piers in the River) resulted in a very large structure with significant fabrication and construction complexity:

- Constructing the new Crossing on the existing highway alignment, while minimizing the impact on adjacent properties, creates added complexity that are anticipated to result in significantly greater costs than if an alignment offset from the existing highway and tunnel was utilized.
- The Requirement for the clear span over the River resulted in a main span length of 660 m requiring a more sophisticated structural arrangement at greater cost than on the other cable-stayed bridges in the Lower Mainland such as the Alex Fraser Bridge and Port Mann Bridge, which have span lengths of 465 m and 470 m, respectively, and both of which have structures in the River (see comparison at right).

The Review concludes that the elimination of the two noted functional criteria to allow construction on an alignment offset from the main highway and to allow construction adjacent to, or in, the River will significantly simplify the bridge design. This, in combination with a reduction in the number of lanes, has the potential to reduce the Project cost in the order of $500 million, or more.



Comparison of bridge sizes. *(above)*

Reference Concept Steveston Highway Interchange. *(below)*

Highway and Interchange

The highway improvements were an essential component of the Reference Concept generating 45% of the user benefits and are, therefore, a necessary and integral component of the Project.

The planned Steveston Highway (shown at right) and Highway 17A interchanges are imposing and complex structures facilitating HOV/transit provisions and free flow ramps. The interchanges were constrained by the Project objective to minimize the footprint of the interchanges to avoid using additional agricultural land and impacts to adjacent commercial development.

The opportunities to reduce the number of lanes to six or eight will allow the scale of the two interchanges to be significantly reduced; particularly if that includes the elimination of the median transit provisions discussed next. The lane reduction will also create the opportunity to stage the highway improvements, other than upgrading the Steveston Highway overpass, to when traffic demonstrates the need or when the necessary funding is available.

HOV/Transit Review

The Project developed a comprehensive solution consisting of HOV/transit lanes adjacent to the median, which could at some point in the future accommodate LRT. In conjunction with the lanes, centre median transit stops were to be provided at the Steveston Highway and Highway 17A (shown at right) interchanges. Access to, and from, the transit stops required the inclusion of multi-use pathways in the interchange design to allow for pedestrians and cyclist to have safe access to, and from, those stations (shown at below right). Further, longer span overpasses over Highway 99 at all highway crossings and a two-lane free-flow fly-over across the highway for buses at Bridgeport Road to reach a Canada Line station were planned.

Reference Concept Highway 17A Interchange. *(above)*

Reference Concept centre median transit stop. *(below)*

The Project estimated that the cost for the HOV/transit provisions was in the order of $500 million and, based on the Review's traffic forecasting, achieves only 5% of the Project Benefits. The Review completed a present value analysis on the HOV/transit provisions, using the above figures, and determined that the present value using the Province's 6% discount rate is negative $422 million and the benefit cost ratio is 0.31.

The MoTI 2009 *Highway 99 (King George Highway to Oak Street Bridge) Corridor Assessment* report noted the limited benefits of median stops, including the relatively high cost of ramps to eliminate buses having to cross multiple lanes of traffic to exit the highway and recommended against median transit lanes.

TransLink noted that there are no future plans to extend LRT south of the River at the Crossing and that the existing shoulder bus lane with off-highway pullouts and queue-jumping access at the Crossing is functioning well and has substantial capability for expansion. Proposed on-facility transit lanes and stations would achieve only incremental total transit time savings.

The Review, while recognizing that the HOV/transit provisions are a desired Provincial objective, recommends that the Province consider eliminating the median HOV/transit provisions in favour of lower cost alternatives.

Business Case

The Project's business case estimated capital costs for the Reference Concept to be $3.5 billion in as-spent dollars, which represented approximately $2.0 billion in 2014 dollars, before allowing for interest during construction. This resulted in a User Benefit Cost Ratio of 1.2:1.

The Review found the user benefits estimated by the Project to be comparable to the Review's RTM3 estimate, if not conservative. The Review finds the safety and seismic benefits to be reasonable and agrees that with 10 lanes the Project has a benefit/cost ratio greater than 1.0.

The Project also calculated additional economic development benefits to further justify the Project, resulting in a combined benefit/cost ratio of 2.1:1. The economic development benefits were correctly shown as a separate line item and with a separate combined benefit cost ratio.

Provincial policy indicates that economic development benefits most likely should not have been considered in the Project justification for a project of this magnitude. It was also observed that the method of calculating economic development benefits is based on the capital investment: the more spent, the greater the benefits. The inclusion of these benefits, if improperly considered, can mask project economics.

The Project completed the business case analysis for the Project on a holistic basis and demonstrated that the total estimated Project cost could be supported by user tolls. Individual components of the Project, derived from meeting the Project's Goals and functional criteria, were not tested separately on a value for money basis. The approach taken by the Project does not mean the Reference Concept is incorrect or inappropriately developed, only that other, less comprehensive solutions may have been selected that could also have been interpreted to meet the Project's Goals. Testing individual components is consistent with the MoTI practice noted previously to plan projects to the minimum requirements to meet project needs and assess incremental improvements on a value for money basis.

Component	$ millions at 2014 level
Net Project Costs	**$2,016**
Quantified User Benefits	
Travel Time Savings & Increased Travel Time Reliability	$2,154
Construction-related Traffic Delays	(-$26)
Cost of traffic loss due to tolling	(-$93)
Future-year bridge congestion	(-$24)
Sub-total	**$2,012**
Fuel Cost Savings Benefit	$183
Traffic Safety Benefits	$135
Seismic Risk Reduction Benefits	$192
Total Quantified User Benefits	**$2,522**
Net Present Value of User Benefits	**$505**
User Benefit-Cost Ratio	**1.2 / 1**
Economic Development Benefits	**$1,652**
Total User & Economic Development Benefits	**$4,173**
User & Economic Development Benefit-Cost Ratio	**2.1 / 1**

Present value of benefits and costs.

Further, there is an inherent issue in planning projects that maximize travel time savings, reliability savings, and vehicle operating cost savings in that benefits continue to accrue until all congestion is relieved. While the functional criteria selected for the Project deliver the greatest benefits, they may not have led to the development of a Reference Concept that yielded the greatest value for money and alignment with regional and community plans.

Retrofit of the Existing Tunnel

In the early planning stages, the Project assessed the Tunnel to determine if it was suitable to be re-used as a component of the new Crossing. The Tunnel was assessed by the Project as not being suitable primarily based on a preliminary determination that it was not technically feasible to construct the *Part 2 - Ground Improvement Retrofit* to the Tunnel to achieve acceptable performance during a 1 in 475 year return period seismic event and, therefore, the bridge code requirement of meeting the 1 in 2,475 year criteria for a critical structure could also not be achieved.

The Review, following the completion of a new technical assessment and discussions with the COWI team that completed the original work, has concluded that seismically retrofitting the Tunnel is technically feasible; creating the opportunity to incorporate it as one component of a new Crossing.

The estimated order of magnitude costs to retrofit the Tunnel to an improved seismic standard (1 in 475 year event or 1 in 2475 year event) could be in the range of $250 million to $300 million, without the consideration of the potential synergies that would be achieved with a new tunnel crossing.

An important caveat to the above is that, despite the upgrade being technically feasible to design and construct, the total Project cost to upgrade the Tunnel may exceed the cost to provide an equivalent level of capacity in a completely new structure. The inherent value of the asset if it was to be constructed today combined with the demolition costs need to be considered in any cost benefit evaluation.

The Review recommends that the retrofit of the Tunnel, including components other than seismic improvements such as lighting, safety, and mechanical improvements shown at right, be considered in more detail.

Lighting, safety, and mechanical improvements made to the Second Midtown Tunnel in Virginia.

New Tunnel Crossing

The recommendation that a new tunnel Crossing be constructed to supplement the capacity of the existing Tunnel was made repeatedly over several years prior to 2012 when full replacement of the existing Tunnel was announced by the Province.

The Project assessed a new immersed tube tunnel (ITT) for the Crossing and, based on a multi-factor evaluation, determined it was not a preferred option due to: the construction in the river; the inability to provide all 10 traffic lanes in a single tunnel; the risk of constructing adjacent to the existing tunnel; the estimated project schedule being significantly longer than a new bridge; and a greater capital cost.

To assess the feasibility of a new tunnel Crossing in the context of the constraints of the Crossing location, the Review completed benchmarking of similar ITT projects globally and convened a Tunnel Expert Panel to discuss the relevancy and applicability of those projects, and other projects that the experts had been involved in. The Panel's opinion was that: the conditions at the Crossing location and the needs of the Project are similar to those that have been addressed within successful past design and construction experience with ITTs; eight traffic lanes can be easily accommodated in a single tunnel; the installation of a tunnel can likely be completed in a single construction season; the risk to the adjacent Tunnel can be mitigated; and the Project cost will be competitive with the cost of a bridge.

It is the Review's opinion that an ITT crossing option is feasible and may result in increased benefits and cost savings in comparison to a new bridge when such options as staged development and utilizing existing infrastructure are considered. There are several international precedents where ITTs have been selected over other options and successfully constructed in similar conditions including environment (shown at above right), seismic conditions, and proximity of adjacent structures (shown at below right).

The Review recommends that a new ITT be considered in more detail for the Crossing; on its own or in combination with a retrofitted Tunnel.

New ITT constructed in a sensitive estuary near Limerick, Ireland. *(above)*

Second new ITT constructed next to existing older ITT in Rotterdam, Netherlands. *(below)*

Principal Findings and Recommendations

The following provides a summary of the Review's principal findings and recommendations.

Project Needs, Objectives and Functional Criteria	▪ There is an obvious need to increase the capacity to improve travel time reliability in the non-peak direction during peak hours. ▪ The absence of community alignment, community livability, and cost from inclusion in the Project Goals, and the solutions to address them, contributed to stakeholder concerns. ▪ The goals of the Mayor's Council on Transportation, TransLink, Metro Vancouver, and local Governments are closely aligned on the need to improve the Crossing. ▪ The Functional Criteria developed for Goals 1, 4, and 6 were principal factors in defining the Project scope.
Traffic Modelling and Forecasting	▪ The Reference Concept highway improvements achieve 45% of the total Project user benefits and are equally important to the Crossing solution. ▪ The Translink RTM3 model is reliable and suitable for future traffic forecasting on the Corridor. ▪ Reducing the number of lanes from 10 to either six or eight will accommodate the majority of the 2045 predicted traffic but with delays in the peak direction in 2045 similar to today.

Highway and Bridge	▪ The scale, complexity, and cost of the Reference Concept bridge can be substantially reduced by changing the functional criteria to allow an alternative alignment to the main highway and construction in the River. ▪ The Review Recommends that the Province consider changing the specified functional criteria for the bridge to allow for an offset alignment and for construction to occur in, or adjacent to, the River.
HOV and Transit	▪ Eliminating the median transit provisions and corresponding lane reductions will significantly reduce the complexity of the Steveston Highway and Highway 17A interchanges. ▪ The Reference Concept HOV/transit provisions do not provide value for money.
Business Case	▪ The major components of the Project, which defined the scope, were not tested individually through trade-off studies and independent value for money analysis, which is not consistent with MoTI normal practice. ▪ The Review finds that estimated user benefits are reasonable and agrees that for the 10 lane Reference Concept the Project has a benefit/cost ratio greater than 1.0. ▪ The Project's inclusion of economic development benefits to further increase the benefit/cost ratio in the business case is not consistent with MoTI practice for projects of this magnitude.
Existing and New Tunnel	▪ Retrofitting the Tunnel to modern seismic standards is technically feasible. ▪ Utilizing a new ITT for the new crossing either on its own or in conjunction with the retrofit of the existing Tunnel is feasible and likely cost competitive with a bridge.

Concluding Recommendations

The planning for the Project was completed based on the identification of Project needs and the functional criteria to provide a comprehensive solution. The resulting Reference Concept achieves the functional requirements, resulting in a Project that maximized quantifiable user benefits and had a positive benefit cost ratio.

The Reference Concept was prepared with functional criteria that were expansive and avoided adverse effects that might otherwise have been mitigated, or compensated, for. As such, the resulting Reference Concept is an all encompassing solution. Most groups agree with improvements to reliability at the Crossing, however, the scope and scale of the Reference Concept remains a concern to many. The Review has highlighted specific functional criteria, which if modified, could result in a reduced Project scope and cost savings, while still providing increased capacity and reliability. These changes would better align the Project with regional transportation and community planning goals and would likely result in broader acceptance of the Project.

It is the Review's opinion and recommendation that the Province should re-examine the Project needs and functional criteria to facilitate a Project that:

- Provides capacity to improve current reliability and reduce future congestion to levels consistent with other crossings in the Lower Mainland;
- Provides transit infrastructure that is appropriate based on regional transportation planning;
- Respects the environment by including necessary mitigation and compensation measures to allow for alternative Crossing designs that may include a shorter bridge span, retrofit of the Tunnel, or a new ITT; and
- Respects the need to maintain agricultural and park lands by including necessary mitigation and compensation measures to allow for lower risk, alternative interchange and Crossing designs that are less imposing and better reflect the surrounding lands and communities.

The Review recommends that the Province complete a new comprehensive feasibility study that would initially re-visit the Project Goals and functional criteria addressing the findings and recommendations in this Review. The feasibility study should consider:

- Allowing for congestion to be reduced, but not eliminated;
- Allowing the new tunnel or bridge Crossing to be located off of the existing highway alignment;
- A more detailed consideration of adding new capacity in the form of a tunnel;
- The reuse of the existing Tunnel;
- Maintaining and improving the existing shoulder bus transit system;
- Allowing construction in the River with suitable mitigation and compensation measures; and
- Allowing for some encroachment on agricultural and park lands with suitable mitigation and compensation measures.

1 Introduction

On October 4, 2016, the Province of British Columbia (the Province) initiated procurement for the design and construction together with the operation, maintenance and rehabilitation of the George Massey Tunnel Replacement (GMTR) Project (the Project). The Project is described in Section 3.

The term of the Concession Agreement (CA) was 30 years, including approximately four to five years of design and construction followed by an approximately 25 year operating period.

1.1 The Independent Technical Review

On September 6, 2017, the Province announced the procurement process for the Project had been cancelled and that the Project would be subject to an Independent Technical Review (ITR or the Review)[1]. The Province stated:

> *The review will focus on what level of improvement is needed in the context of regional and provincial planning, growth and vision, as well as which option would be best for the corridor, be it the proposed 10-lane bridge, a smaller bridge or tunnel.*

On November 1, 2017, the Province announced it had retained Stan Cowdell, P.Eng. of Westmar Advisors Inc. (Westmar Advisors) to complete the Review[2]. The Province stated:

> *The first task of the review will be to independently undertake a technical review of the lifespan, safety and seismic vulnerability and current congestion of the existing tunnel. As well, Cowdell will review the technical assumptions and analysis for the tunnel and bridge options. As part of this, he will review the technical information already produced for the project and challenge or verify the assumptions made out of that work. This assessment may identify the need for further technical work.*

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[1] Province of British Columbia. (2017, September 6). *Government to conduct independent review to find best solution for George Massey corridor* [Press release]. Retrieved from https://news.gov.bc.ca/releases/2017TRAN0230-001540

[2] Province of British Columbia. (2017, November 1). *George Massey crossing technical review underway* [Press release]. Retrieved from https://archive.news.gov.bc.ca/releases/news_releases_2017-2021/2017TRAN0271-001845.htm

As part of the announcement, the Province released Terms of Reference[3] for the Review (provided in Appendix A). The Terms of Reference required that this report be submitted to the Minister of Transportation and Infrastructure by Spring 2018.

1.2 The Review Team

In completing the Review, Mr. Cowdell has been supported by the staff at Westmar Advisors and subject matter experts (SMEs) that together form the Review Team. The SME's include:

- John Fussell P.Eng., bridge engineering;
- Brian Stone, highway engineering;
- Fred Culbert M.Sc., P.Eng., engineering economics;
- Gary Williams, M.Sc., R.P.Bio, PWS, environmental considerations;
- Blair Gohl, Ph.D., P.Eng., Wood Environment and Infrastructure Solutions, geotechnical engineering;
- Basse Clement, M.A.Sc., P.Eng., McElhanney Consulting Services Ltd., traffic forecasting;
- Bruce McAllister, project planning; and
- Scott A. Anderson, Ph.D., P.E., BGC Engineering Inc., tunnel engineering.

The Review worked with the Ministry of Transportation and Infrastructure (MoTI) to engage companies that had not been involved in the procurement process for the Project that commenced in 2016. McElhanney Consulting Services Ltd. (McElhanney) was a subcontractor on a team that submitted a bid as part of the procurement process. An exception was granted by MoTI for McElhanney to assist with the Review on the basis that McElhanney was intimately familiar with TransLink's traffic models and had a working relationship with MoTI. Further, the individuals within McElhanney that assisted with the Review were not involved in the previous bid process and did not have access to bid documents.

McElhanney assisted the Review with traffic forecasting (Section 3.3) and highway engineering (Section 3.4).

[3] Province of British Columbia. (2017, November 1). *Independent Technical Review George Massey Tunnel Terms of Reference* [Letter]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/11/TOR-Independent-review.pdf

BGC Engineering Inc. (BGC) assisted with the assessment of the feasibility of new tunnel construction at the George Massey Crossing (Crossing). As part of this assessment, BGC facilitated a workshop with a panel of international tunnel experts (Tunnel Expert Panel) (Section 3.8.1).

Wood Environment and Infrastructure Solutions assisted the Review with:

- Reviewing geotechnical information developed for prior studies and the Project;
- Assessing the requirement for, feasibility of, and effectiveness of the necessary ground improvements to reduce the risk of liquefaction; and
- Assisting with developing and assessing concepts for Tunnel retrofit and stabilization (Section 3.7).

1.3 The Review Process

Westmar Advisors, in completing previous reviews of major projects, has developed an effective process. This process was used for the completion of the Review of the Project and is summarized below.

Step 1 – How Did We Get Here?

The Review commenced with a series of meetings with the Project Team to understand the activities and analysis which resulted in the Reference Concept used as the basis for the October 4, 2016 *Request for Proposals*[4] (RFP) for the CA. This included:

- Project Goals, objectives, criteria;
- Investigative studies;
- Comparative options analysis;
- Trade-off studies completed;
- Technical analysis and design; and
- Business case analysis.

It is important to note that the Review was greatly assisted by the transfer of knowledge from the Project Team who were candid and forthcoming in sharing Project information.

[4] British Columbia Transportation Investment Corporation. (2016, October 4). George Massey Tunnel Replacement Project – Requests for Proposals [Request for Proposal]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/10/Request-for-Proposals-Oct-2016.pdf

Step 2 – Where Were We Headed?

Identifying the Project Goals and objectives, and the functional criteria that resulted from the Project Team's interpretation of those objectives.

Step 3 – What Was the Problem to Solve?

Identifying and completing an overview of the Project documents, including:

- Historical reference documents;
- Project specific studies, analysis, and final finished products;
- The Application to the BC Ministry of Environment – Environmental Assessment Office (EAO) for an Environmental Assessment Certificate (EAC), including requests for information and responses; and
- Stakeholder and Indigenous Groups communications and commentaries.

Step 4 – What Do Stakeholders Have to Say?

Meeting individually with the City of Delta, the City of Richmond, and Metro Vancouver to understand their concerns with, and expectations for, the Project. This was in addition to reviewing the EAC and requests for information and responses.

Step 5 – How Does This Project Fit In?

Meeting with TransLink on several occasions to understand:

- TransLink's view of the Project and the traffic analysis that had been completed by the Project Team;
- The TransLink Regional Transportation Model (RTM) used by the Project Team, including its specification and limitations;
- TransLink engagement with the Project;
- The updated current RTM Phase 3 (RTM3);
- Present and future transit planning for the Highway 99 Corridor;
- TransLink's input into the development of the Project high occupancy vehicles (HOV) and transit provisions; and
- TransLink's approach to congestion analysis and reliability.

In addition to the above discussions, the Review facilitated an information meeting with TransLink at which the Project Team described the detailed corridor queuing modelling used in the development of the Reference Concept.

Step 6 – Detailed Review and Formation of Findings

Once the foundational elements of the Project were understood, a detailed review of the Project information database was completed. Any gaps that were identified within the information necessary to form findings were explored in greater detail by the SMEs on the Review Team.

The following list summarizes the components of the Project that were reviewed or explored further.

1. A review of the multi-factor assessments of Crossing alternatives completed by the Project during Project development, including additional meetings and communication with the Project Team to inform the basis for the assessment of risk, benefit, cost and feasibility of each alternative considered.
2. A review of the site geotechnical conditions, including:
    a. Historical and recent project specific geotechnical investigations;
    b. Site seismicity and foundation response to design events;
    c. Existing tunnel foundation seismic stability and previous analyses used to make those assessments;
    d. Requirements to improve existing George Massey Tunnel (Tunnel) foundation seismic stability to meet current codes, including potential mitigation measures necessary to avoid excessive settlement and damage to the Tunnel if carried out;
    e. Reference Concept bridge foundation design; and
    f. Foundation and ground improvement requirements for a new tunnel crossing.
3. A review of the existing Tunnel structural design including:
    a. The original design;
    b. The analysis and the design of structural improvements made to the Tunnel in 2006 designed by Buckland & Taylor Ltd., now COWI North America, Ltd. (COWI);
    c. Meeting with the COWI technical team that designed those improvements to understand their analysis and objectives;
    d. Independently developing pre-feasibility concepts to improve the existing Tunnel to meet present seismic standards, which were updated in 2010; and
    e. Developing comparative order-of-magnitude capital costs for seismically upgrading and retrofitting the Tunnel to assess if there is merit in including the Tunnel as a component of a new Crossing project.

4. Completion of a revised traffic forecast for the Reference Concept including assessing:
    i. The TransLink RTM available to the Project at the time;
    ii. Adjustments made to that RTM by the Project;
    iii. Validation of the RTM;
    iv. Traffic forecasts and benefits analysis derived from the RTM results; and
    v. Queuing simulations.
5. Validating the most recent, and improved, TransLink RTM3 as the appropriate tool to be used to forecast traffic;
6. Incorporating regional transportation improvements into the RTM3 that have been agreed to, and approved by, the Province, TransLink, and Metro Vancouver;
7. Completing traffic forecasts and benefits analysis for the following alternative Crossing scenarios:
    a. The Project Reference Concept (10-lane) un-tolled;
    b. An eight-lane crossing with, and without, the highway improvements; and
    c. A six-lane crossing without the highway improvements.
8. A review of the Reference Concept bridge arrangement and design.
9. A review of the Reference Concept highway design.
10. A workshop attended by internationally recognized experts in immersed tube tunnel (ITT) and bored tunnel design and construction to assess the feasibility, practicality, and order-of-magnitude cost of a tunnel as an alternative to a new bridge based on the present global state of practice.
11. A review of the Project Reference Concept business case, including assessing compliance with mandated Provincial and Federal requirements for major projects.
12. Identifying options to potentially further optimize the Project, including necessary additional concept studies and feasibility studies to further evaluate alternatives prior to initiating a new procurement process.

The results of the Review are described in detail in Section 3 and summarized in Section 4.

1.4 Information Sources

Project documentation made available to the Review Team included:

- Publicly available materials on the Project website (https://engage.gov.bc.ca/masseytunnel/);
- Documentation provided by the Project Team; and
- Publicly available materials sourced by the Review.

The documentation for the Tunnel and the Project includes hundreds of documents and drawings, totalling thousands of pages. Other documents describing regional transportation planning are available from MoTI, TransLink, Metro Vancouver, municipalities, and stakeholders.

The Goals and objectives for the Project described in Project documents, including the *George Massey Tunnel Replacement Project – Project Definition Report*[5], are summarized in Section 3.2.1. The functional criteria for the Project were provided by the Project Team to the Review Team and are summarized in Section 3.2.1.1.

Trade-off studies for the Project are found on the Project document library[6]. A primary reference is the *George Massey Tunnel Replacement Project – Review of Replacement Options* report[7].

Option 2, or Scenario 2, a 10-lane bridge and highway improvements, was selected as the preferred option and a Reference Concept was developed. The design criteria for the Reference Concept are found in *Schedule 4 - Design and Construction*, that form part of the *Draft Concession Agreement* found in *Volume 2* of the *Request for Proposals*[4].

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[5] British Columbia Ministry of Transportation and Infrastructure. (2015, December). *George Massey Tunnel Replacement Project – Project Definition Report* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2015/12/GMT-Project-Definition-Report-Dec-2015.pdf

[6] Province of British Columbia Ministry of Transportation and Infrastructure. (2018). *George Massey Tunnel Replacement Project Engagement Website – Document Library* [Website]. Retrieved from https://engage.gov.bc.ca/masseytunnel/documentlibrary/

[7] WSP | MMM Group. (2016, July). *George Massey Tunnel Replacement Project – Review of Replacement Options* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/02/GMT-Review-of-Replacement-Options-July-2016.pdf

A concise summary of the Reference Concept is provided in the certified Project Description[8,9] that forms part of the Application to the EAO for an EAC.

The business case for the Project is summarized in the *George Massey Tunnel Replacement Project - Project Business Case*[10].

The interests of stakeholders and Indigenous Groups are summarized in the Working Group comments submitted as part of the *George Massey Tunnel Replacement Project – Application for an Environmental Assessment Certificate* that were considered in the EAO's referral to the Province[11].

The Review Team completed a brief site tour of the existing Tunnel with MoTI staff and representatives from the Project Team. The site tour included a ventilation building, an emergency access and mechanical tube within the Tunnel, roadway approaches to the Tunnel, and an area that had been prepared for a new BC Hydro transmission tower adjacent to the Project.

1.5 The Scope of the Review

Over the course of the Review, different groups expressed varying expectations for the outcomes of the Review. Before the results of the Review are discussed later in this report, it is important to clarify the scope of the Review, including information that was not considered and the tasks that could not be completed within the time and funding available.

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[8] Province of British Columbia. (2017, February 8). *George Massey Tunnel Replacement Project – Environmental Assessment Certificate #T17-0 – Schedule A Part 1 of 2* [Certificate]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/02/Environmental-Assessment-Certificate-Schedule-A-Certified-Project-Description-1-of-2.pdf

[9] Province of British Columbia. (2017, February 8). *George Massey Tunnel Replacement Project – Environmental Assessment Certificate #T17-0 – Schedule A Part 2 of 2* [Certificate]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/02/Environmental-Assessment-Certificate-Schedule-A-Certified-Project-Description-2-of-2.pdf

[10] Province of British Columbia. (2015, October). *George Massey Tunnel Replacement Project – Business Case* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2015/12/Business-Case-Oct-2015.pdf

[11] British Columbia Ministry of Environment – Environmental Assessment Office. (2016, October). *George Massey Tunnel Replacement Project – Application for an Environmental Assessment Certificate - Technical Working Group comments and responses* [Application]. Retrieved from https://projects.eao.gov.bc.ca/api/document/58923179b637cc02bea1640b/fetch

As per the Terms of Reference, the Review is not a reconsideration of decisions made by the Environmental Assessment (EA) process, the Agricultural Land Commission (ALC) review, or by other statutory decision makers.

Engineering Verification & Review of Information

The Project documentation, including related engineering studies, was developed over many years and is extensive and voluminous representing thousands of hours of work. The Review found no reason to complete independent verification of all investigative field work and engineering completed for the Project. Further, this work has been completed by engineering, and other related, professionals registered in BC. It is reasonable to accept that the work is technically sound and detailed checking or full design audits, which would have greatly expanded both the time and budget required to complete the Review are not necessary to provide an informed opinion. The Review Team is confident that sufficient and relevant information has been reviewed such that there is unlikely to be any documentation that would materially alter the findings and recommendations of the Review.

2016 to 2017 Concession Procurement Process

The Reference Concept was issued as part of the CA RFP by the Province in October of 2016[4]. The Province announced the cancellation of the procurement process in September of 2017 at the same time as the Review was announced.

While the tender documents were made available to the Review Team, the bids were deemed to be "Commercial in Confidence" and were not made available to the Review Team.

The Review Team did not speak to any of the Proponent Teams about their proposed designs. Any findings or recommendations in this report that may mirror optimizations of the Reference Concept by one, or more, of the Proponent Teams are coincidental.

Tolling and Mobility Pricing

As part of the Review, an updated forecast of traffic for the Crossing was undertaken. In absence of tolls on all major crossings in the area, the Review's traffic forecasts are based on no tolling or mobility pricing for the Crossing and the other crossings in the Lower Mainland.

2 The George Massey Tunnel

The Tunnel, in service since 1959, was designed by Christiani & Nielsen of Canada Ltd. (Christiani & Nielsen), together with Foundation of Canada Engineering Corporation (FENCO). It was the second pre-fabricated concrete rectangular cross-section tunnel in the world to be installed using immersed tube technology. The first such tunnel, the Maastunnel in Rotterdam, Netherlands, which opened in 1942, is still in use today. The Maastunnel is a National Monument and is currently undergoing a maintenance retrofit to extend its life.

2.1 Pre-George Massey Tunnel

The South Arm of the Fraser River (River) has, for generations, been important to First Nations[12] whose traditional territory the Crossing is located within. As non-indigenous settlement of the Lower Mainland expanded in the late 1800s and early 1900s, the River continued to be an important marine transportation route but was also a barrier to the increasing use of vehicles for transportation.

> The primary reasons in 1956 for recommending a tunnel rather than a bridge were that the cost was estimated to be 30% lower and a larger proportion of labour and materials would come from BC.

Crossing the River was initially overcome by a system of ferries. The Ladner-Woodward's Landing ferry transported people and goods between Ladner and Richmond (see Figure A).

Starting in 1955, alternative crossings of the River and the feasibility of both bridge and tunnel crossings were studied. A 1956 study by FENCO, with the assistance of Christiani & Nielsen, recommended a crossing at Deas Island in the form of a four-lane tunnel.

[12] British Columbia Ministry of Environment – Environmental Assessment Office. (2016, October). *George Massey Tunnel Replacement Project – Application for an Environmental Assessment Certificate - Part C – Aboriginal Consultation* [Application]. Retrieved from https://projects.eao.gov.bc.ca/api/document/5886aa64e036fb0105769443/fetch

Figure A Deas Island with the ferry landing visible at the south end of Deas Island[13].

The reasons for recommending a tunnel included[14]:

- A tunnel was seen as being a preferred solution based on the site geotechnical conditions and perceived operational benefits. Vehicles using the roadway would be diverted only about 25 metres (m) below horizontal in a tunnel rather than 50 m above horizontal over a bridge.
- The cost was estimated to be approximately $17 million for a tunnel in comparison to about $24 million for a bridge in 1956 dollars.
- 85 percent (%) of the cost of labour and materials would be spent in BC for a tunnel compared to only 60% for a bridge.

In 1956, the Province announced that a tunnel would be constructed at Deas Island. FENCO and Christiani & Nielsen were chosen as the designers of the Tunnel.

[13] City of Richmond Archives. (1962). *Deas Island Tunnel area February 20, 1962* [Photograph]. Retrieved from http://archives.richmond.ca/archives/InmagicImages/ImagesNew/2010_87/2010-87-44.jpg?width=1200&404=no-img.jpg

[14] Lafleur, C.J. (1979, July). George Massey Tunnel Information Manual. *British Columbia Ministry of Transportation and Infrastructure.*

2.2 George Massey Tunnel Construction

The construction period for the Tunnel was three and a half years; however, the placement of the six tunnel elements in the River took less than five months during the low river flow months (see Figure B). The first unit was placed on January 6, 1958 and the last unit was placed on April 17, 1958 just as river flows were starting to increase significantly. The time required to place tunnel sections decreased with each placement; the sinking of the first tunnel section took over 17 hours while the last section took one and a half hours. The construction equipment and systems available in 1958 were generally less sophisticated and of lower capacity than those available today.

Refer to Appendix E for a more detailed description of the original design and construction of the Tunnel and Figure C for a schematic of cross sections through a tunnel element and the buried protection systems.

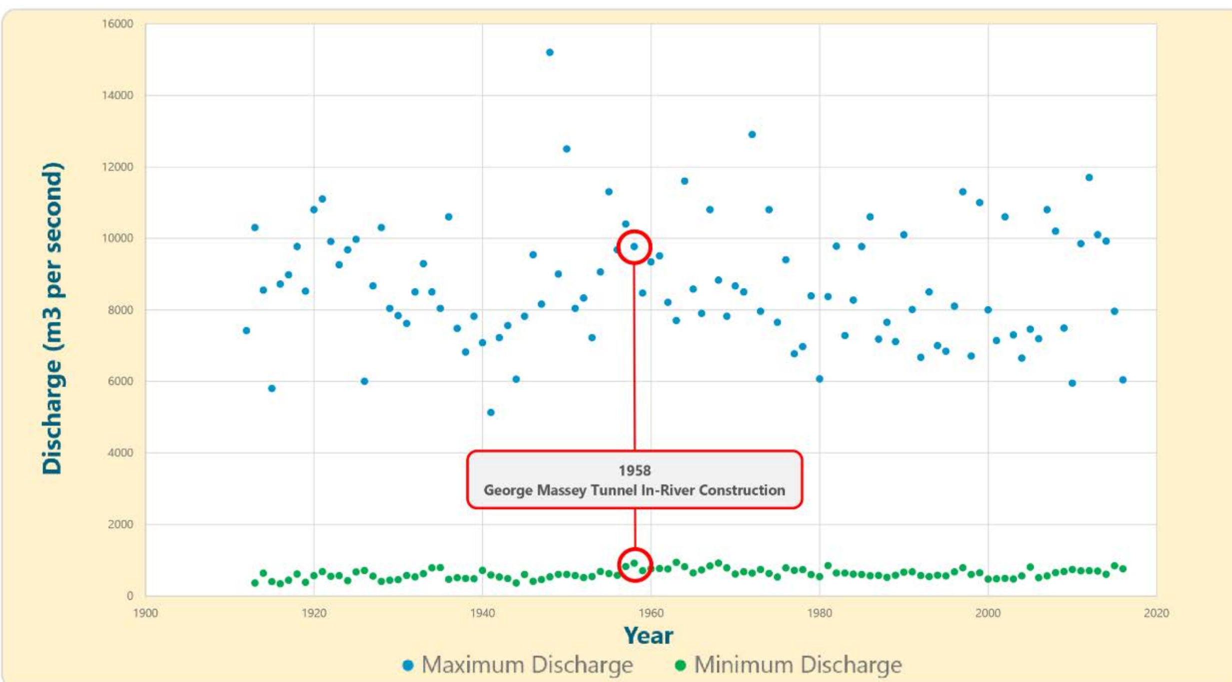
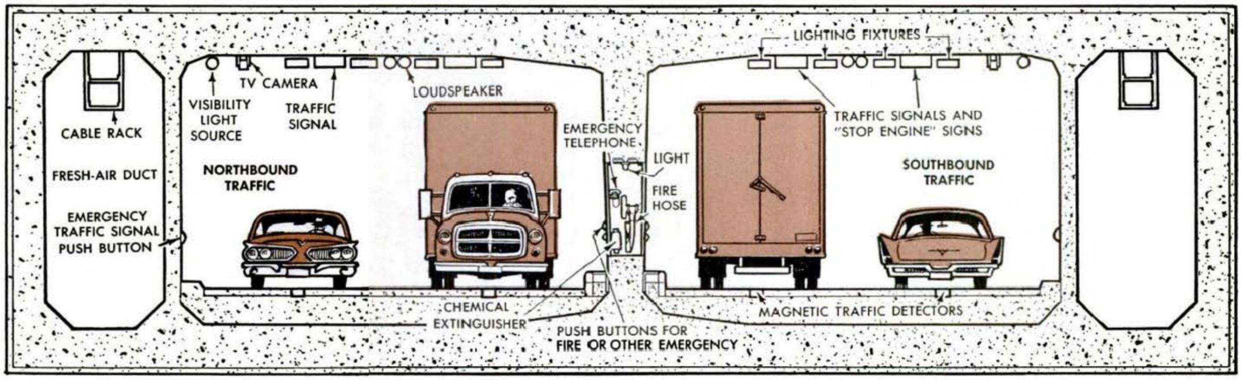


Figure B Annual max and min flows for the Fraser River at Hope[15].

[15] Environment and Climate Change Canada. (2018). *Annual Maximum and Minimum Daily Discharge Graph for FRASER RIVER AT HOPE (08MF005) [BC]*. Meteorological Service of Canada [Website]. Retrieved from https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html



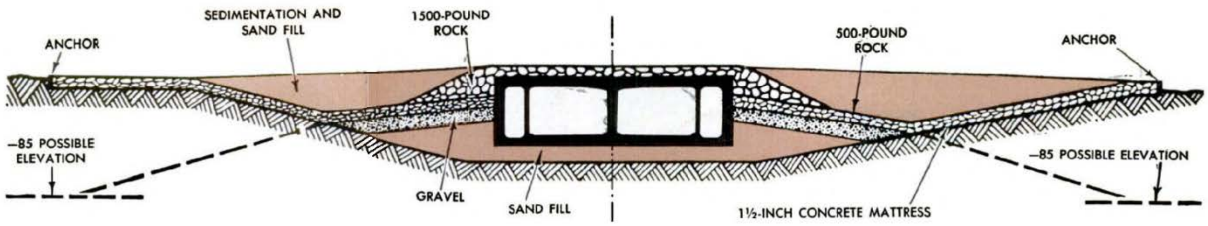


Figure C Cross section through the originally constructed George Massey Tunnel: prefabricated concrete tunnel element (above); and buried tunnel element with protection systems (below)[16].

The Tunnel, then known as the Deas Island Tunnel, opened in May 1959. Tolls for the Tunnel were removed in March of 1964 and it was renamed in 1967 in recognition of the role that George Massey played in its development.

2.3 Seismic Assessment and Improvements

2.3.1 History of Seismic Design Considerations

The original design of the Tunnel included consideration of significant environmental loads including differential pressures associated with 5 m high moving riverbed sand dunes, scour to 14 m below the riverbed, and an earthquake shaking (seismic) load resulting from peak ground accelerations as high as 21% of gravity in the horizontal direction (0.21 g)[17].

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[16] Kerr, C. (1959, March). A Prefab Tunnel Conquers a Tough River. *Popular Mechanics Magazine*, 122-126; 226-228.

[17] Hall, P., Brøndum-Nielsen, T., Kivisild, H.R. (1957, November). *Deas Island Tunnel. ASCE Journal of the Structural Division, Paper 1436*.

Although state of the art at the time, the original design of the Tunnel did not consider the effects of soil liquefaction (loss of strength and stiffness, usually during an earthquake) as this was not well understood.

In 1991, MoTI investigated the liquefaction potential of the soils around the Tunnel and determined that the soils around the Tunnel were liquefiable to an estimated depth of 10 m or 12 m below the base of the Tunnel, which if it occurred could affect the serviceability of the Tunnel. A description of the progression of understanding of the risk of soil liquefaction around the Tunnel and seismic risk since 1991 is provided in Appendix F.

2.3.2 Program for the Seismic Upgrade of the Tunnel

In the early 2000s, COWI completed studies of the Tunnel, including the surrounding soils, with the objectives of determining what level of seismic event the Tunnel could resist and the options available to improve the seismic performance.

COWI identified the following concerns about Tunnel displacements that might occur in a seismic event:

- Liquefaction induced heave upwards (liquefied soils could flow towards the underside of the Tunnel because the pressure is lower under the air-filled Tunnel than the pressure in the adjacent soils that are more heavily loaded);
- Lateral translation downriver (due to horizontal loading from lateral soil flows); and
- Post-seismic settlement downwards (when the shaking stops, the pore pressures that build up during the shaking dissipate and the soils consolidate).

Because the Tunnel was lightly reinforced, the tunnel elements would behave in a brittle manner, particularly at the joints (see Figure D for a schematic of the typical joint detail), resulting in large cracks in the tunnel wall and flooding in the Tunnel that could create a life safety risk.

In 2004, COWI completed the detailed design for a Tunnel retrofit to meet MoTI's *Seismic Retrofit Design Criteria*[18] for lifeline bridges subject to a 1 in 475-year return period design seismic event (the relevant design event in the early 2000s). The retrofit design included: *Part 1 - Structural Retrofit* to strengthen the tunnel walls; and *Part 2 - Ground Improvement Retrofit* to improve the surrounding soil to reduce the risk of liquefaction.

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[18] British Columbia Ministry of Transportation and Infrastructure. (2005, June 30). *Seismic Retrofit Design Criteria* [Guideline].

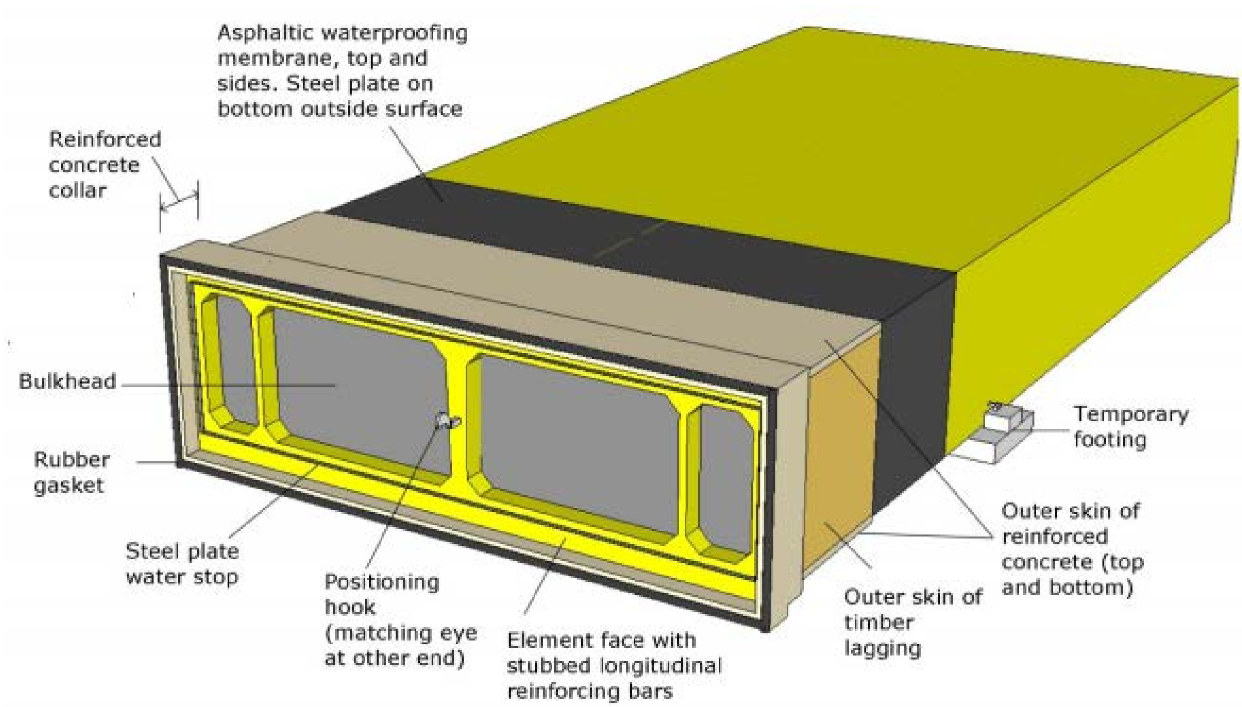

Figure D Schematic of the existing George Massey Tunnel typical section end details[19].

The *Part 1 - Structural Retrofit* was completed in 2006 and consisted of installing steel plates and reinforced concrete through the full length of the Tunnel. Additional steel was added at each joint.

Figure E shows a cross section of the structural retrofit at a typical joint between tunnel elements.

The structural retrofit significantly improved the estimated ductility of the Tunnel in a potential seismic event resulting in better calculated crack distribution in the tunnel walls; i.e. more, smaller cracks instead of fewer, larger cracks. The provision of greater ductility and related better distribution of cracks and reduced crack widths was predicted to reduce the rate of water inflow into the Tunnel.

Larger pumps and drain pipes were also installed to increase the rate at which water could be removed from the Tunnel. These pumps were a life safety improvement measure that increases the available time for the evacuation of the Tunnel after a seismic event.

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19 WSP | MMM Group. (2017, February). *George Massey Tunnel Replacement Project –Tunnel Decommissioning Options* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/02/GMT-Tunnel-Decommisioning-Options-Feb-2017.pdf

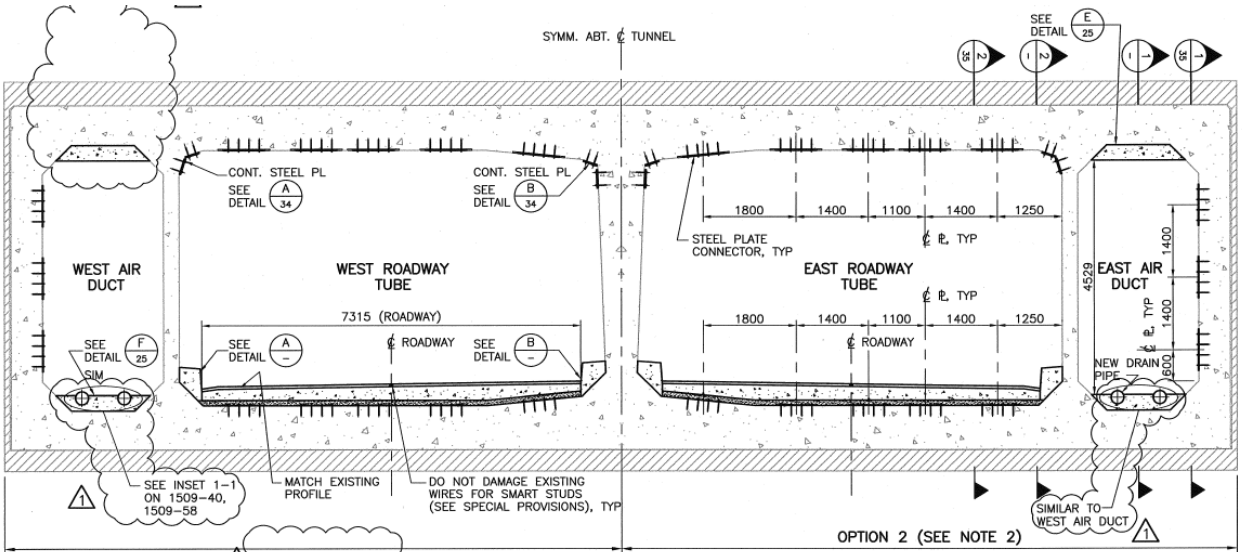

Figure E Details of the George Massey Tunnel structural retrofit completed in 2006[20].

Tunnel lighting was also replaced in 2005 and 2006 as part of the retrofit; however, due to power limitations at the time, the lighting upgrade was to a standard that is below what would be provided in a new tunnel of this type[21].

The proposed *Part 2 - Ground Improvement Retrofit* consisted of densifying soils and installing seismic drains along the sides of the Tunnel, including the approaches. This ground improvement (GI) retrofit, a necessary requirement to achieve the specified seismic criteria, was never constructed. The cancelled *Part 2 - Ground Improvement Retrofit* is described in more detail and assessed in Section 3.7.

In 2007, the estimated cost of the proposed *Part 2 - Ground Improvement Retrofit* program was approximately $25 million. Although this amount is not large in the context of infrastructure expenditures today, it was considered significant enough at the time that the Province decided to undertake a Value Engineering (VE) Study to determine if costs could be reduced. This VE Study resulted in eight VE proposals being put forward for further consideration and these are described and assessed in Section 3.7.2. There is no documentation to confirm that the VE recommendations were formally assessed.

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[20] Buckland & Taylor Ltd. (2001, March 26). *George Massey Tunnel No. 1509 – Seismic Safety Retrofit and Rehabilitation - Project No. 11469-0001, Drawing No. 1509-26 Rev 1* [Drawing].

[21] DMD & Associates Ltd. (2013, February). *Massey Tunnel Lighting Improvement Options* [Report] Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/07/GMT-Lighting-Improvement-Options-Feb-2013.pdf

Following the VE Study, the Province did not proceed with the *Part 2 - Ground Improvement Retrofit* program. The reason(s) for the decision not to proceed are believed to have been:

- Funding constraints;
- The perceived risk of settlement and related damage to the operating Tunnel from the external GI work; and
- Concern as to the effectiveness of the GI should silty soils be encountered.

It is the opinion of the design team for the planned ground improvement around the existing tunnel that, with careful sequencing and monitoring, the risk of settlement and related damage to the operating tunnel could be managed.

COWI's design team advised it is their opinion that, with careful sequencing and monitoring, the settlement risk to the Tunnel during the GI process risk can be managed.

In 2008, COWI was retained by MoTI to estimate the seismic event that the structurally retrofitted Tunnel could tolerate without life safety risk in the absence of the recommended GI work. The previous COWI studies determined that the Tunnel structurally could tolerate 0.30 m of lateral displacement and 0.09 m maximum upward displacement (heave) without a threat to life safety. Using these displacements, COWI estimated that the Tunnel, without the GI, could withstand a seismic event with a return period of between 150 years and 240 years.

The Project reported that it is expected that the Tunnel in its current condition can tolerate an earthquake with a return period of 275 years[22].

[22] George Massey Tunnel Replacement Project. (2016, April 19). *Seismic Retrofit Chronology* [Memorandum]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/04/Seismic_Retrofit_Chronology_April_20161.pdf

2.4 Existing Physical Status of the Tunnel

Although concerns have been expressed about the condition of the concrete in the Tunnel, testing indicates that the concrete in the submerged portion of the Tunnel is in good condition with a remaining service life in the order of 50 years[23,24].

The cast-in-place concrete retaining walls along the Tunnel approaches show irregular surface cracking, especially near the top of the walls, and concrete has spalled from the cross beams located over the Tunnel entrances outside of the Tunnel portals. This deterioration is considered to be repairable.

The existing Tunnel electrical and mechanical systems require upgrades; the level of lighting provided is below that which would be installed in a new tunnel[25,26,27,21,22]. The pumping system was upgraded in 2006 but, if the Tunnel becomes a component of a new crossing, further increases to the pumping system capacity may be necessary.

2.5 Evolution of Crossing Improvements

Multiple studies between 1991 and 2006 were completed by the Province and other governmental and non-governmental organizations, all with MoTI participation. The studies, which will be briefly summarized in this section, recommended increasing the capacity of the existing Tunnel crossing with most recommending a second tunnel.

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[23] Buckland & Taylor Ltd. (2001, March 26). *George Massey Tunnel No. 1509 – Seismic Safety Retrofit and Rehabilitation – Assessment Phase – Seismic Retrofit Strategy Report – Volume 2 of 2 – Final* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/04/2001_GMT-Seismic_Safety_Retrofit_and_Rehabilitation_-_Assessment_Phase_Seismic_Retrofit_Strategy_Report_Vol.2of21.pdf

[24] EVM Project Services Limited. (2007, April 20). *Value Engineering Study - Project 11469-0002: George Massey Tunnel Seismic Densification* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/04/2007-04-20_George_Massey_Tunnel_Seismic_Densification_VE_Report1.pdf

[25] PBA Consulting Engineers. (2010, December 15). *George Massey Tunnel High Voltage Upgrade* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/07/GMT-High-Voltage-Upgrade-Report-Dec-2010.pdf

[26] PBA Consulting Engineers. (2011, November 2). *George Massey Tunnel Fire Alarm and CO Detection System Upgrade* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/07/GMT-Fire-Alarm-and-CO-Detection-Systems-Upgrade-Nov-2011.pdf

[27] PBA Consulting Engineers. (2012, January). *George Massey Tunnel High Voltage Design* [Report].

2.5.1 Ward Consulting Group

The first study for MoTI that looked at adding new lanes to the Crossing was completed by Ward Consulting Group in 1991[28]. The study found significant benefits from the construction of a new two-lane tunnel adjacent to the existing Tunnel.

The study found that this option would:

- Maximize the use of the existing infrastructure;
- Provide one more lane in each direction during peak periods (i.e. four lanes in the peak direction with two in the off-peak direction) and three in each direction during off-peak periods;
- Have a minor impact on existing infrastructure;
- Require no new freeways or River crossings;
- Create one earthquake resistant tube below the River; and
- Enable one tube to be closed for maintenance purposes while keeping two tubes, or four lanes, open.

2.5.2 Reid Crowther & Partners Ltd. and Ward Consulting Group

A study for MoTI was completed in 1995 by Reid Crowther & Partners Ltd. and Ward Consulting Group[29]. The study also recommended that a new two-lane tunnel be constructed adjacent to the Tunnel and, instead of a new crossing between Delta and Richmond, it was recommended that:

- The Oak Street Bridge be widened,
- The South Fraser Perimeter Road be constructed, and
- A new crossing be constructed across the North Arm of the River just west of the Queensborough Bridge.

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[28] Ward Consulting Group. (1991, March 21). *George Massey Tunnel Expansion Planning Study* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2012/11/D11501907A-George-Massey-Tunnel-Expansion-Plan-Study-1.pdf

[29] Reid Crowther & Partners Ltd. and Ward Consulting Group. (1995, July). *Fraser River North and South Arm Crossing Study* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2012/11/1995-07-01-Fraser-River-North-and-South-Arm-Crossing-Study-FINAL-Ward-Group-1-1.pdf

2.5.3 Lower Mainland Highway Improvement Outlook

In 1997, the BC Transportation Finance Authority (BCTFA) issued a *Lower Mainland highway Improvement Outlook*[30] that recommended no increase in capacity across the Fraser River over the following 10 years:

> *This not only reflects the desire to be supportive of the development of a more compact metropolitan area, and of LRT lines on the Burrard Peninsula, but also the reality that the addition of general purpose river crossing capacity has to be preceded by improvements to relieve current congestion on the peninsula. Without such improvements, additional river crossing capacity would make congestion on the peninsula worse. After 10 years, additional river crossing capacity is contemplated to the George Massey Tunnel, Port Mann Bridge and/or Annacis Bridge.*

2.5.4 Greater Vancouver Gateway Council

In 2003, the Greater Vancouver Gateway Council, which is an industry-led organization of executives from the seaports, airport, carriers and other companies engaged directly in the transportation business in the Lower Mainland[31], prepared a report that looked at the *Economic Impact Analysis Of Investment In A Major Commercial Transportation System For The Greater Vancouver Region*.[32] The report was prepared with guidance from an advisory panel comprised of representatives from the Province, Western Economic Diversification Canada, UBC, TransLink, Port of Vancouver, and Transport Canada.

A series of road improvements were identified by members of the Greater Vancouver Gateway Council to maintain the efficient movement of goods through the Lower Mainland over the following 20 years. One of the projects was improvements to the Highway 99 Corridor at the Crossing.

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[30] BC Transportation Finance Authority. (1997, October). *Lower Mainland highway Improvement Outlook* [Memorandum]. Retrieved from http://www.llbc.leg.bc.ca/public/pubdocs/bcdocs2011/317536/lower%20mainland%20highway%20improvement%20outlook.pdf

[31] Greater Vancouver Gateway Council. [Website]. Retrieved from http://www.gvgc.ca/

[32] Greater Vancouver Gateway Council. (2003, July). *Economic Impact Analysis of Investment In A Major Commercial Transportation System For The Greater Vancouver Region* [Report]. Retrieved from http://www.gvgc.ca/pdf/SW1040_FinalReport_Revised2.pdf

The recommended improvements at the Crossing consisted of the following:

> *Significant upgrade of the existing Massey Tunnel river crossing along Highway 99. Upgrade to include new immersed tube tunnel section, separated approximately 50 metres upstream from existing tunnel. New tunnel section to possess only two lane cross section consisting of two northbound general-purpose lanes. Existing tunnel to consist of two southbound general-purpose lanes and two HOV lanes (one in each direction).*
>
> *Reconfiguration of interchange at Steveston Highway to accommodate six through lanes. Current structure pier configuration may accommodate these lanes. Counterflow system to be radically changed to accommodate the four lanes northbound during AM peak periods and four lanes southbound during the PM peak periods.*
>
> *Reconstruction of interchange at Highway 17 to accommodate six through lanes. This interchange will tie in with upgraded River Road (South Fraser Perimeter Road to the east).*
>
> *The HOV lanes would be reconfigured such that these are located in the median. The HOV lanes will be extended southward to King George Highway. The HOV lanes will be extended northward to the Westminster Highway interchange.*
>
> *The Westminster Highway interchange will need to be reconstructed to accommodate six through lanes. Widening of Highway 99 north of the Westminster Highway to the Oak Street bridge will be required to accommodate the six lanes (4 + 2 HOV).*

Multiple studies between 1991 and 2006 recommended increasing the capacity of the George Massey Tunnel crossing with most recommending a second tunnel.

The cost of these improvements was estimated to be between $500 million and $700 million in 2003 dollars.

2.5.5 Gateway Program

Between 2003 and 2006, the Province undertook a regional transportation review called the Gateway Program[33] that focused on addressing congestion in three priority corridors, including:

- Along the south shore of the Fraser River;
- Along the north shore of the Fraser River; and
- Highway 1 corridor from Vancouver to Langley.

With reference to expansion of the Crossing, the *Program Definition Report* noted:

> *Consideration was given to widening the George Massey Tunnel in conjunction with development of the South Fraser Perimeter Road.*
>
> *To capture sufficient benefits, twinning the tunnel would also require improvements to other crossings over the North Arm of the Fraser River, such as the Oak Street or Knight Street bridges, or a new crossing to serve projected commuting patterns associated with employment growth in central Burnaby.*

In 2006, following the release of the *Program Definition Report*, the Province clarified its position on the future of the Tunnel[34].

> *The George Massey tunnel will be twinned and both Highway 99 approaches widened from four lanes to six once the Province's more pressing transportation projects are complete.*

Following the completion of the *Part 1 - Structural Retrofit* to the Tunnel in 2006 and the cancellation of the *Part 2 - Ground Improvement Retrofit* to the Tunnel in 2007, the Province further clarified the path forward for the tunnel[35] noting that:

> *Building a new span over the South Arm would only be a temporary solution.*
>
> *Vancouver, of course, has made it very clear that they're not interested in improving the Oak Street Bridge corridor. So you basically make a very large investment to move the choke point down a little bit further to the Oak Street Bridge.*

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[33] Province of British Columbia Gateway Program. (2006, January 31). Program Definition Report [Report]. Retrieved from http://www.ticorp.ca/wp-content/uploads/2016/02/Gateway-Program-Definiton-Report-PDR.pdf
[34] Hoekstra, M. (2006, February 18). Tunnel will be twinned. *Richmond Review*.
[35] Hoekstra, M. (2009, May 8). Tunnel good 'for another 50 years,' says minister. *Richmond Review*.

2.5.6 Replacement Considered

In September of 2012, the Province, in an update to the Union of BC Municipalities[36], announced that the planning and consultation would begin immediately for the replacement of the Tunnel, noting:

> *It will be a major project. It'll take up to 10 years to plan and deliver, but with the population of communities served by the Massey Tunnel growing by 300,000 people over the next 20 years, we do not have a moment to lose. Starting today we'll begin engaging Delta, Richmond and other communities to determine what a replacement will look like.*

The Province noted that the Tunnel was a bottleneck in the Pacific Gateway, a reference to the Asia-Pacific Gateway and Corridor Initiative that was started in 2006[37]. This initiative aimed to develop "strategic infrastructure projects that support Asia-Pacific trade and boost the competitive advantages of the Gateway by reducing bottlenecks, addressing capacity issues and enhancing the efficiency of the transportation system."[38]

The 2012 announcement coincided with the formation of the Project, which evaluated different Crossing alternatives, including options to maintain the Tunnel.

[36] Province of British Columbia. (2012, September 28). *Text of Premier Christy Clark's Keynote Address to UBCM* [Press release]. https://news.gov.bc.ca/stories/text-of-premier-christy-clarks-keynote-address-to-ubcm

[37] Transport Canada. (2017, October). *Evaluation of the Asia-Pacific Gateway and Corridor Initiative and the Gateways and Borders Crossing Fund* [Website]. Retrieved from https://www.tc.gc.ca/eng/corporate-services/evaluation-asia-pacific-gateway-corridor-initiative-borders-crossing-fund.html

[38] Transport Canada. (2018, March 31). *Asia-Pacific Gateway and Corridor Initiative* [Website]. Retrieved from https://www.tc.gc.ca/eng/corporate-services/planning-dpr-2012-13-1061.html

3 The Independent Technical Review

3.1 General

The Project scope is described in detail in the *George Massey Tunnel Replacement Project - Request for Proposals - Volume 1- Instructions to Proponents*, dated October 4, 2016, and its related schedules and appendices and *Volume 2 – Draft Concession Agreement*[4]. These documents were provided to a short list of qualified Proponent Teams who prepared offers for the design, construction, and operation of the Project.

While the Project is often characterized as the replacement of the existing Tunnel with a new bridge, the proposed new bridge was only one component of a much more extensive scope of work. As will be discussed later in this section, the user benefits derived from the planned new Crossing and Highway 99 improvements are close to being equal in value emphasizing the importance of improving the Corridor in conjunction with a new Crossing.

3.2 Project Scope Overview and Planning

The following is the Project scope overview and summary of principal requirements from the above documents that resulted in the Project design for the Crossing and related Highway 99 improvements. A plan of the scope of the Project is provided in Figure F.

> *The George Massey Tunnel Replacement Project (the Project) includes the design, construction, partial financing, operation, maintenance and rehabilitation of the Highway 99 corridor between Bridgeport Road in Richmond and Highway 91 in Delta. The Project will include a new bridge to replace the Existing Tunnel, widening of the highway, improvements to transit and HOV infrastructure, replacement of a number of interchanges and overpasses and decommissioning of the Existing Tunnel.*
>
> *Summary of Anticipated Design and Construction SUMMARY DESIGN AND CONSTRUCTION SCOPE:*
>
> - *Construction of a new 10-lane bridge (eight lanes plus two transit/HOV lanes) following the existing alignment, including a multi-use pathway for cyclists and pedestrians on each side of the bridge. The bridge shall have a 125-year Design Life;*
> - *Replacement of the Westminster Highway, Steveston Highway and Highway 17A interchanges, and 5 overpasses/underpasses;*

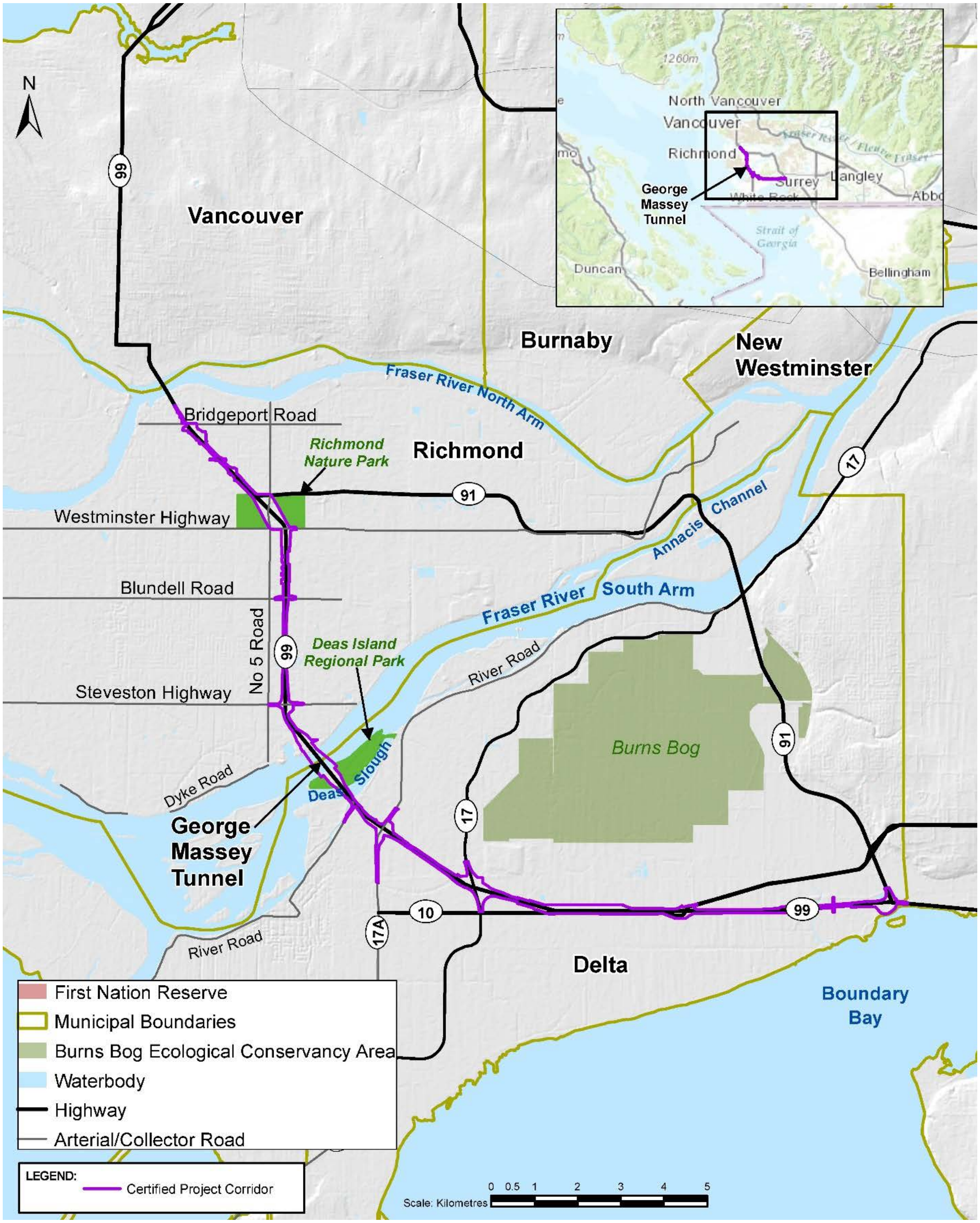

Figure F Project overview map[8].

- *Transit infrastructure, including integrated transit stops at the Steveston Highway and Highway 17A interchanges and median transit connection at Bridgeport Road;*
- *Roadway widening and related roadway infrastructure including construction of approximately 50 km of new dedicated transit/HOV lanes, between Bridgeport Road in Richmond and Highway 91 in Delta;*
- *Decommissioning of the Existing Tunnel, including removal of the four middle sections (approximately 400 metres);*
- *Improvement of connections to adjacent municipalities;*
- *Traffic management, including operation and maintenance of a counterflow system;*
- *Marine traffic management;*
- *Utility relocations;*
- *Tolling infrastructure (gantry and Roadside Tolling Facility); and*
- *Meeting quality, health and safety, communications and engagement, and environmental requirements.*

The scope of the Review focused on the planning for, and design of, the proposed Reference Concept. The Review did not include the proposed CA and the specified broader operational, maintenance, quality, health, and safety requirements other than to confirm specific relevant criteria or scope definitions.

The Reference Concept was developed by the Project as information and general direction to the selected Proponent Teams and is specified in *Schedule 4 - Design and Construction*[4] of the proposed CA and related documents. The Reference Concept was not fully optimized for functionality and cost, nor was it intended to be so. Consistent with CA philosophy, the Project intended that the Proponent Teams would optimize all aspects of the Project to deliver maximum value within the specified requirements of the CA RFP.

In planning the Reference Concept, the Project identified the following principal reasons why the Project is required[5]:

1. *An average of 80,000 vehicles use the Tunnel every day. This is more than the capacity of the Tunnel and a counterflow system is used to manage the resultant congestion in the peak direction. Even with a counterflow, the congestion at the Tunnel results in significant delays that can range up to 30 minutes on a typical weekday, and can be several hours if there is an incident at the Tunnel or adjoining Highway 99 corridor.*

2. *The Tunnel is at its capacity and as such significant traffic is diverted to the Alex Fraser Bridge. This additional traffic pressure on the Alex Fraser Bridge results in its capacity being "used up" faster.*
3. *The Tunnel was designed to the very limited seismic design considerations of the 1950s. Even with extensive seismic retrofit work, it is not practical to bring the Tunnel to current seismic standards.*
4. *The Tunnel has substandard highway geometrics including narrow lanes, virtually no shoulders and a substandard vertical clearance. These deficiencies contribute to the Tunnel having a high accident rate and also restricts the movement of goods through the Tunnel.*
5. *Cyclists and pedestrians must take a shuttle through the Tunnel. Walking or cycling through the Tunnel would be very dangerous and is not permitted.*
6. *Although the Tunnel has some of the highest transit usage in the Province and significant efforts have been made to increase transit reliability and use along Highway 99 over the past 15 years, remaining opportunities to improve transit on Highway 99 are limited without providing additional traffic capacity at the Tunnel.*
7. *If there is an incident in the Tunnel, traffic congestion often makes access for first responders slow and difficult, causing unnecessary additional risk to the lives of injured people.*

The Project also found that given the high proportion of goods movement, services, and extra-regional trips through the Tunnel each day for which transit and HOV travel is not a viable option, improvements in HOV and transit alone would not substantially address the current Highway 99 traffic challenges.

The Project reports that an average of 80,000 vehicles use the Tunnel every day. However, this number increases to over 90,000 on weekdays during some months[39] (see Figure G).

Once the Project articulated the reasons (or the needs) for the Project, it then established the following objectives[5]:

1. **Reduce congestion.** Improve travel times and reliability for all users.
2. **Improve safety.** This includes improving traffic and seismic safety, as well as emergency response capabilities.

[39] George Massey Tunnel Replacement Project. (2015, December). *Daily Traffic Volumes by Month - George Massey Tunnel 2015* [Handout].

3. **Support trade and commerce.** Improve access to local businesses and gateway facilities and improve travel time reliability for goods movers and service providers.

4. **Support increased transit on the Highway 99 corridor.** Provide dedicated HOV/transit lanes on the new bridge to improve travel time reliability and add capacity for long-term transit improvements.

5. **Support options for pedestrians and cyclists.** Provide a multi-use pathway on the new bridge to connect cycling and pedestrian corridors in Richmond and Delta.

6. **Enhance the environment.** Enhance the environment under the new bridge and in the Project right-of-way on Deas Island.

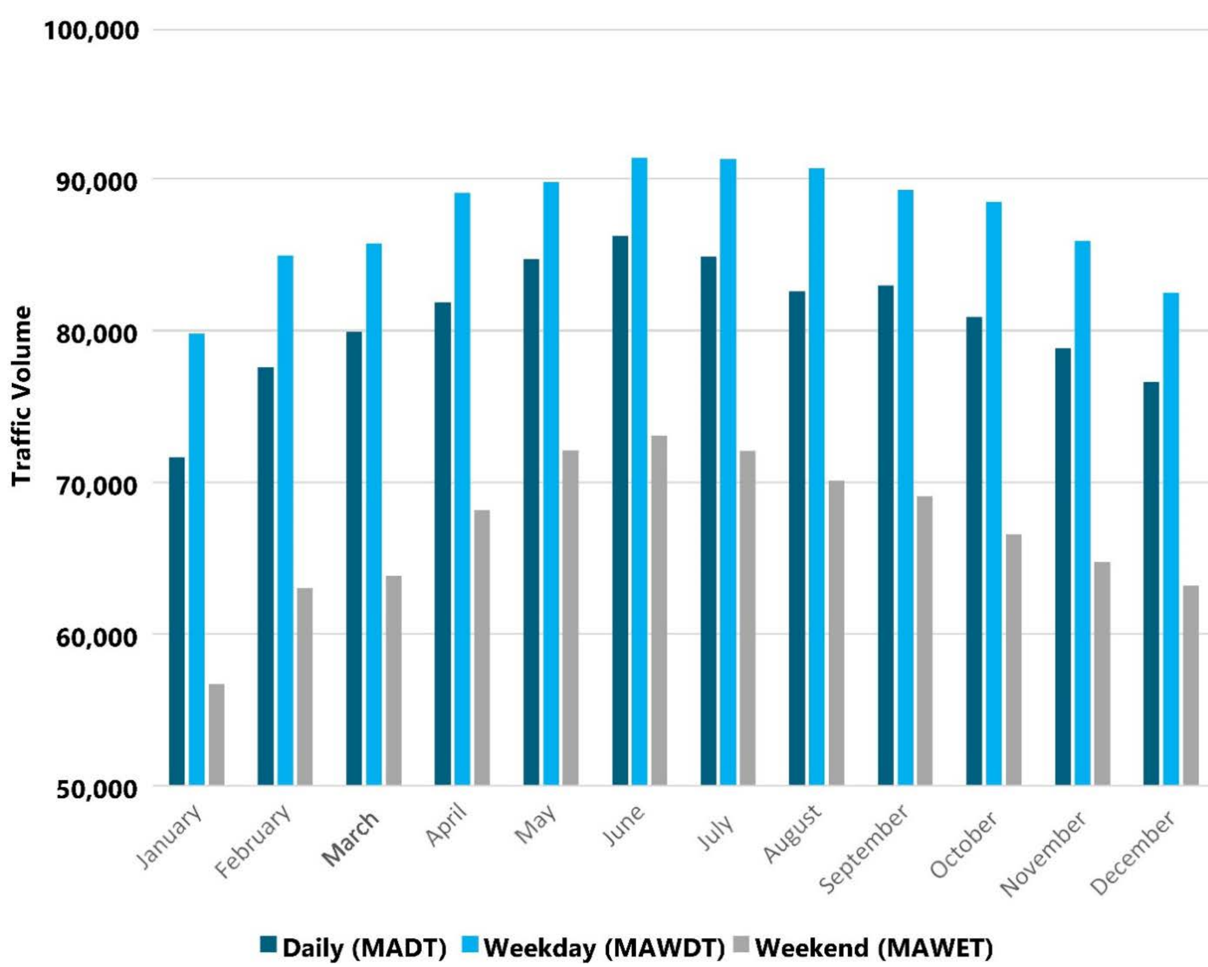

Figure G Daily traffic volumes by month for the George Massey Tunnel in 2015[39].

The Project then determined how best, in the opinion of the Project, these broad objectives could be satisfied and subsequently developed specific functional criteria to define what the solutions for each objective would need to achieve[40], as summarized below.

1. **Goal: Reduce congestion.**
    a. Functional Criteria:
        i. Eliminate queuing at any time to 2045,
        ii. Accommodate forecasted population and employment growth,
        iii. Enable traffic to recover after a traffic incident,
        iv. Provide transit infrastructure,
        v. Provide benefits to HOV traffic,
        vi. Provide free flow interchanges at Steveston Highway and Highway 17A, and
        vii. Provide a new direct Rice Mill Road connection.
2. **Goal: Improve safety.**
    a. Functional Criteria:
        i. Provide life safety following a seismic event,
        ii. Provide access for first responders, and
        iii. Design for safety and crisis prevention.
3. **Goal: Support trade and commerce.**
    a. Functional Criteria:
        i. Improve the functioning of interchanges, and
        ii. Provide for the transport of dangerous goods.
4. **Goal: Support increased transit on the Highway 99 Corridor.**
    a. Functional Criteria:
        i. Provide convenience of transit by improving infrastructure (e.g., integrated bus stops similar to SkyTrain stations).
5. **Goal: Provide options for pedestrians and cyclists.**
    a. Functional Criteria:
        i. Provide multi-use pathway and connections to local networks,
        ii. Grade separate pathways from vehicle traffic,
        iii. Limit pathway grades, and
        iv. Restoration of existing surplus Highway 99 roadway to natural environment, with re-aligned Millennium Trail.

[40] George Massey Tunnel Replacement Project. (2017, November 15). [Email].

6. **Goal: Enhance the environment.**
   a. Functional Criteria:
      i. Provide a clear span structure, with no piers in the Fraser River;
      ii. Provide detention storage and include biofiltration features;
      iii. Construct Project within existing corridor and reduce footprint of Project infrastructure; and
      iv. Provide connections for agriculture vehicles across Highway 99 and facilitate connections at Rice Mill Road.

3.2.1 Project Goals

It is expected that the Project Goals reflect the goals of the proponent, the Province, and specifically, MoTI. MoTI's goals, objectives, and strategies are summarized in the *2018/2019-2020/21 Service Plan*[41]:

> 1. *Improved infrastructure supports communities;*
> 2. *B.C.'s transportations sector is globally competitive;*
> 3. *Greenhouse gas emissions from the transportation sector are reduced;*
> 4. *B.C.'s highway system is safe and reliable; and*
> 5. *Excellent service.*

In February 2014, the Province asked the Metro Vancouver Mayors' Council on Regional Transportation to confirm its transportation vision and to clarify the costs, priorities and phasing for investments and actions[42]. A Subcommittee on Transportation Investment worked with TransLink and staff from municipalities around the region to define this Vision, to establish spending priorities, and recommend new funding mechanisms capable of supporting those priorities (see Figure H).

Regional stakeholders highlighted the importance of The Metro Vancouver Mayors' Council and expressed some concern that the Project's functional criteria were not entirely consistent with Metro Vancouver's Vision and Official Community Plans[11].

[41] British Columbia Ministry of Transportation and Infrastructure. (2018, February). *2018/2019-2020/21 Service Plan* [Report]. Retrieved from http://bcbudget.gov.bc.ca/2018/sp/pdf/ministry/tran.pdf

[42] Metro Vancouver. (2015, March). *Mayors' Council on Regional Transportation – Regional Transportation Investments, a Vision for Metro Vancouver* [Report]. Retrieved from https://www.translink.ca/-/media/Documents/about_translink/governance_and_board/mayors_vision/mayors_council_vision_mar_2015.pdf

Vision

As a region, we maintain our global position as one of the best places in the world to live because we meet our transportation needs in a way that simultaneously enhances the health of our people and communities, economy and environment.

Goals

Make transportation decisions that:

CHOICE

Provide sustainable transportation choices

Support a compact urban area

PEOPLE

Foster safe, healthy and complete communities

ECONOMY

Enable a sustainable economy

ENVIRONMENT

Protect the environment

Headline Targets

As a region, we can best achieve these goals by designing our communities and transportation in a way that:

- Makes it possible to reduce the distances people drive by one-third.
- Makes it possible to make half of all trips by walking, cycling and transit.

Strategy Areas

There are three key transportation levers the region can use to achieve our overarching goal of getting people and goods where they need to go as reliably, safely, efficiently and cleanly as possible. We can:

INVEST strategically to maintain and expand the transportation system.

MANAGE the transportation system to be more efficient and user focused.

PARTNER to make it happen.

Figure H Major features of the Regional Transportation Strategy Framework[42].

3.2.1.1 Functional Criteria

In part, Stakeholder concerns (Section 3.9.2) related to the large scale and extent of the Reference Concept that resulted from how the Project's Goals were translated into functional criteria:

- The Goal to "Reduce congestion. Improve travel times and reliability for all users" was translated into the functional criteria as "Eliminate all congestion to 2045." This then resulted in the 10-lane Crossing and related corridor improvements based on the following:
  - *The counterflow operation, which exists today, was deemed to be unacceptable for a new Crossing from an operational and safety perspective. The existing counterflow operation provides three lanes in the high-volume direction. Even with three lanes in the high-volume direction, there is congestion. Therefore, the new Crossing required capacity beyond six lanes to eliminate all congestion for today's traffic volumes in the peak direction; requiring at least an additional two lanes.*
  - *Dedicating two additional lanes as HOV/transit lanes, per MoTI practice on prior major crossings, will only relieve a portion of the congestion as the total traffic volume using those lanes is approximately 50% of the main travel lanes. The primary benefit of the HOV/transit lanes is to encourage a modal shift away from single occupancy vehicles (SOV). To achieve no congestion, further additional capacity is still required.*

- *The Crossing facilitates significant commercial truck activity in Richmond and Delta for both general commerce as well as for the Port of Vancouver terminals. Trucks will lose speed on the uphill grades of the planned new bridge resulting in traffic weaving and a decrease in overall traffic capacity.*

As a result, an eight-lane crossing was estimated to not have sufficient capacity in the peak direction, and an additional two lanes would be required resulting in a total of 10 lanes.

- The Goal to "Support increased transit on the Highway 99 corridor" was translated into the functional criterion to "Provide convenience of transit by improving infrastructure (such as integrated bus stops similar to SkyTrain stations)". This resulted in the median HOV/transit lanes and transit stations.

The above are provided as examples and are not intended to suggest that the Project was incorrect in its interpretation as to how best to achieve the Project Goals; particularly given that the Project was designed for future conditions and could be supported by the business case. This is only to highlight the subjectivity of the Goals and to raise the prospect that different interpretations could have been made that could have resulted in a different Reference Concept based on different functional criteria.

Some of the Project's functional criteria are objective and based on well established codes, standards or Provincial and/or MoTI policy. MoTI has a cycling policy[43] that states: "Provisions for cyclists are made on all new and upgraded provincial highways. All exceptions to this Policy will be subject to an evaluation procedure, as described in the reference material."

Other functional criteria are not based on written codes, standards, or policy but are based on the precedence of previously completed MoTI transportation projects. For example, the criterion to include a provision for LRT similar to the Port Mann Bridge[44]. The Review could not find a provincial policy requiring new bridges to have an LRT provision.

The Review assumes, but has not verified, that subjective interpretation led to the objective criteria that were reviewed with, and accepted by, the MoTI Project Board and/or MoTI Executive.

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[43] British Columbia Ministry of Transportation and Infrastructure. (2000, May 3). *Cycling Policy* [Policy]. Retrieved from https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/technical-circulars/2000/t11-00.pdf

[44] Partnerships British Columbia (2011, March). *Project Report: Achieving Value for Money Port Mann/Highway 1 Improvement Project* [Report]. Retrieved from http://www.ticorp.ca/wp-content/uploads/2016/04/PartnershipsBC-Project-Report-14-March-2011.pdf

3.2.1.2 Technical Design Criteria

The technical design criteria are provided in *Schedule 4 - Design and Construction*, that form part of the *Draft Concession Agreement* found in Volume 2 of the *Request for Proposals*[4].

The design of the Reference Concept is underpinned by extensive field work (e.g., geotechnical, traffic counts, etc.) and detailed study. The Review found the technical design criteria to be appropriate.

3.2.2 Review Findings

The Review found that the Reference Concept properly addressed the requirements of the Project functional criteria and technical criteria within the total Project context discussed in the foregoing; and with the understanding that it was a concept only, and not a fully optimized final design.

3.3 Traffic Modelling and Forecast

An essential component of the Review was to re-assess the traffic forecasts made for the Project. This included:

- Reviewing the modelling tools and processes used by the Project;
- Assessing those results using the RTM3 developed by TranLink; and
- Using the revised model to assess how, if at all, the Reference Concept could be optimized.

The following presents a summary of the above work, which is included in detail in Appendix C.

3.3.1 Project Forecasts

The AADT through the Tunnel is currently 82,500 vehicles. Without an improved Crossing, the Project predicted traffic through the Tunnel will grow to approximately 100,000 vehicles per day by 2045.

With respect to current congestion at the Crossing, the Project noted[45]:

- *Despite the three lanes available (counter flow) during the morning peak for northbound traffic, there is congestion from just after 6:00 a.m. until 10:30 a.m. Delays associated with this congestion are typically 5 to 10 minutes but can often be as high as 23 minutes.*
- *Congested conditions return from 3:00 p.m. until after 6:00 p.m. when the counter-flow system reduces the northbound traffic to one lane. This results in typical delays of 20 to 50 minutes.*
- *Southbound traffic is reduced to one lane during the morning peak period, which results in congestion with delays up to 20 minutes from just after 6:00 a.m. to just after 9:00 a.m.*
- *Conditions are again congested, with delays up to 15 minutes, from 3:00 p.m. until 6:00 p.m., despite the three lanes available via the counter-flow system.*

While traffic has grown little at the Tunnel over the past three decades, all models forecast traffic to grow as the region continues to grow. In the case the Crossing was tolled, the first-year daily traffic was forecast to be reduced to 71,000 vehicles, representing a 14% drop from forecast volumes under continued Tunnel operation, and similar to current Pattullo Bridge traffic. Traffic on the Alex Fraser Bridge (AFB) would have increased by 17% compared to without the Project, primarily because of off-peak diversion from the tolled Crossing to the untolled AFB.

The Project forecasted a small decrease in traffic with the Project for the Knight Street Bridge, Arthur Laing Bridge, and Oak Street Bridge owing to the increased cost (tolls and congestion) across the River.

The Project predicted future auto growth to average approximately 0.65% annually, and future truck growth to average 1.5% annually resulting in a predicted demand at the new tolled Crossing of 84,000 vehicles per day by 2045.

In the case the Reference Concept is not tolled, the Project predicted that by 2045 traffic would be approximately 115,000 vehicles per day, less than what the AFB currently handles (see Appendix C).

The Project Team estimated the Net Present Value (NPV) of travel time savings and reliability benefits for the 10 lane Reference Concept to be $1,977 million, based on a 6% real discount rate. Additional vehicle operating cost savings resulting from more efficient travel speeds and avoided idling times were estimated to be $182 million. The Project also calculated additional safety related benefits and economic development benefits, which will be discussed in Section 3.6.

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[45] Ministry of Transportation and Infrastructure. (2016, July). *Figure 5.1-2, 5.1 Traffic, George Massey Tunnel Replacement Project – Part B, Traffic Assessment, Environmental Assessment Application* [Application].

3.3.2 Traffic Overview

The Tunnel provides a significant 'gateway' facility for the Lower Mainland along the Highway 99 Corridor connecting the US border, BC Ferries, deep sea terminals at Roberts Bank and communities on both sides of the River. Both the Tunnel and AFB crossings provide a couplet system linking both Highway 91 and 99 through Delta and Richmond. For longer distance trips, the choice between the Tunnel or AFB is very close in terms of travel times.

With both facilities experiencing significant congestion levels during peak times today, there is likely a level of traffic suppression occurring where people choose to not cross the River. This is similar to the effect that happened when the AFB opened in 1986 or when the Golden Ears Bridge opened in 2009 and there was a significant ramp up in traffic volumes in the first few years of operation.

To accommodate the peak-oriented nature of traffic patterns, the Tunnel is operated with a counter-flow system during peak commuting times. The Tunnel/AFB couplet suffers from congestion and reliability issues with significant queuing during peak times, especially when incidents (accidents, vehicle stalls, etc.) occur.

Traffic volumes across the Tunnel have remained relatively stable over the past few decades (around 80,000 vehicles per day) owing to capacity constraints.

Average northbound travel time along Highway 99 (from the Highway 91 interchange in Delta to the Highway 91 interchange in Richmond) is approximately 20 minutes, which can vary up to 50 minutes. The northbound direction during the afternoon peak sees some of the highest delay times and variability in the region, with perhaps the exception of the Lions Gate Bridge, which also operates with a counter-flow system.

3.3.3 Project Traffic Forecasts

As part of developing the Project business case, several methods to forecast traffic volumes were employed with the "Project Forecast" being the officially adopted version that was used in the business case. Figure I provides a summary of the range of previous traffic forecasts that were developed. The following describes how the Project estimated traffic impacts and future demand levels. In each case, the models were generally developed using sound judgement and traffic engineering/travel demand modelling principles accepted in industry at that time. As such, the traffic forecasts result in reasonable estimates within the accuracy of the models available at the time. Lack of base year validation within the study area corridor, however, was a deficiency in some of these previous attempts. In other words, there was limited information that provided a comparison of the modelled versus observed travel conditions (i.e. traffic volumes, travel times, etc.) in the current year. This appears to be a deficiency in the project traffic forecasting that was undertaken.

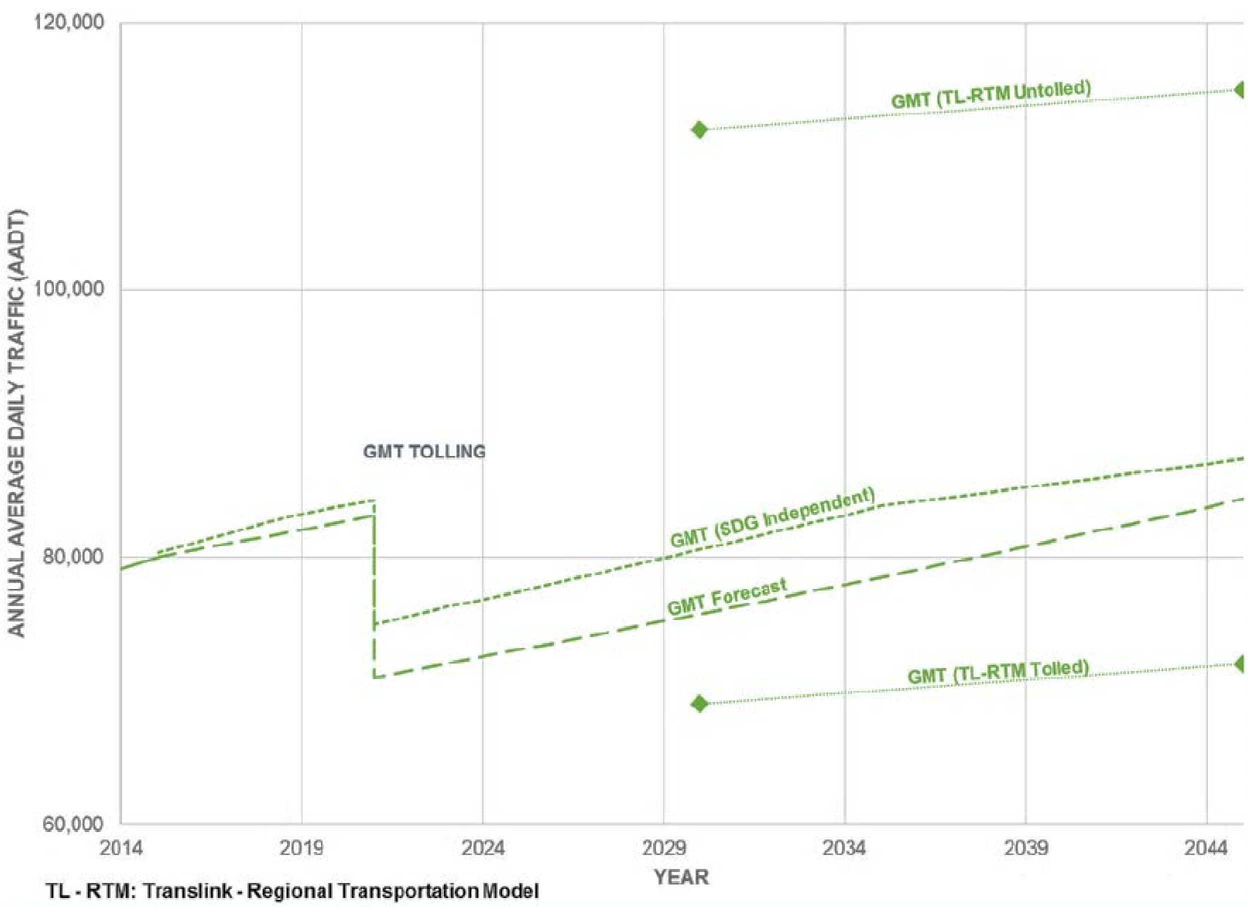

Figure I Range of previous Project traffic forecasts[44].

3.3.3.1 GSAM

Regional traffic demand models have been applied to evaluate infrastructure investments in Metro Vancouver for many years. Developed as part of the MoTI Gateway Program in the early 2000s, the Gateway Sub-Area Model (GSAM) modelled the AM and PM peak period travel volumes through the 2031 horizon year. Each peak period was modelled independently and used to develop the benefits cases for projects such as the Port Mann/Highway 1 Expansion, Pitt River Bridge, South Fraser Perimeter Road, and Golden Ears Bridge. Variants of this approach were also used to evaluate the Canada Line and Evergreen Line regional rapid transit projects.

The GSAM model was updated with additional detail for the Project in 2013 where additional detail was added in the Corridor and contemporary information on land use, transit services, and truck generators was provided to produce an updated base model. The model formulation was largely the same as the 2003 baseline, with some updates made to improve the response to tolling based on early experience with Golden Ears Bridge and Port Mann Bridge operations.

3.3.3.2 RTM

Separately from the GSAM development, TransLink had developed the RTM, which modelled regional travel behaviour on a 24-hour basis and provided individual time slices for the AM and Midday periods. This model was formulated using information from the 2011 Trip Diary and 2011 Census surveys. The trip diary survey includes a random sample of households that are asked questions about their previous days travel including trip origin/destination, time of day, trip purpose, trip mode, etc. The level of network detail was significantly less than the GSAM model, which had seen numerous updates over the previous decade in the Gateway project corridors. The behavioural complexity and level of disaggregation of the RTM was significantly more detailed than the previous peak-period focused models. An early development snapshot (Phase 0) was provided to the Project for use in evaluating the Project.

A PM time period was added to the Phase 0 snapshot for the Project as a separate slice of the 24-hour demand, but was not integrated into the overall model formulation, leaving it fundamentally driven off of the AM and Midday time periods. A validation report that provides a comparison of modelled versus observed travel conditions for the modified model was not provided making it difficult to evaluate the appropriateness of the model for use on tolled facilities or the Corridor in general. There were significant issues identified in this model being overly sensitive to tolling in addition to the large levels of demand adjustment present in the base model calibration. Demand adjust is applied to the model matrices as an adjustment factor to force the model to fit observed traffic counts.

3.3.3.3 Congestion Throughput Model

The RTM's lack of a validation report to observed conditions prompted the creation of a congestion estimation model based on calibrating measured delay to Tunnel throughput measured by the MoTI's Advanced Traveller Information System (ATIS) through Bluetooth sensor capture along the Corridor. This model was calibrated to the directly measured volume and delay information for an entire year and provided a link from the modelled delay to total annual delay based on direct measurement.

The throughput model appears to be well calibrated to observed conditions and provides some insight into how weekday volume and delays relate to total annual values in the Corridor, which is very useful when expanding the peak period models to annual values, particularly for user benefits. The congestion values produced by this model are highly dependent on the traffic arrival patterns and per-lane throughput assumptions made when evaluating the Project options in the future and are difficult to quantify as the model is directly estimated from observed conditions and not a separate theoretical model based on traffic engineering fundamentals. In other words, this model fits well to observed conditions today but there is no theoretical basis from traffic engineering principles to support the levels of congestion forecast in the future. Some benchmarking of future congestion levels would be helpful to validate the congestion throughput model.

3.3.3.4 Econometric Demand Model

An independent econometric model was commissioned as a comparator to the forecasts developed previously by the Project and estimates the change in travel demand based on indicative regional measurements such as GDP, population, employment and other regional indicators. Retention of demand after applying tolling was estimated from the limited experience on the Port Mann Bridge to that point in time. The elasticity in travel demand to these indicators can vary widely and is highly context dependent as it implicitly represents the availability of alternatives in the urban setting and are most appropriate to benchmark the long-term growth potential of travel demand into the future. A review of this model shows that the assumptions and approach were sound and the outcomes reliable given the availability of data at the time.

3.3.4 Review Traffic Forecast

The purpose of this section is to demonstrate the validation of the RTM3 model within the Highway 99 Corridor context and application for travel demand forecasting. Updated traffic forecasts for the Project were produced for various options for the 2030 and 2045 horizons. Consumer surplus calculations were then carried out to estimate user benefits in terms of travel time savings, vehicle operating cost savings and reliability benefits. The objective of this analysis is to demonstrate the effectiveness of each option to address congestion issues at the current Crossing. Key model outputs include traffic volume forecasts, components of traffic volume forecasts, travel time savings and vehicle operating cost savings and reliability benefits.

Since the previous Project traffic forecasts and related business case were developed, an updated version of the RTM has been developed by TransLink, which is the entity that maintains the RTM3. This includes updates to land use inputs (population, households and employment), road and transit networks, and the formulation of the model. These refinements provide this tool with a higher level of detail and predictive capability for travel demand forecasting of major infrastructure projects. Recent application of the model to predict the traffic impact of toll removal on the Port Mann Bridge and the Golden Ears Bridge, as well as ridership on the Evergreen Line, has shown that it is a reliable tool for travel demand forecasting of major infrastructure improvements. It is the latest available regional travel demand model and includes more recent land use and network inputs.

3.3.4.1 Base Year Validation

Before forecasting future conditions, the base year model required extensive validation to ensure that it is replicating observed conditions. Off the shelf, RTM3 is calibrated and validated to regional traffic volumes, mode shares and travel patterns, and does not necessarily provide a sufficient level of detail and validation within a specific corridor such as Highway 99 or Highway 91. Greater confidence in traffic forecasts is provided by ensuring that traffic volumes, trip distribution patterns and travel times are well represented for a specific facility. Various data sources were compiled to provide a set of validation metrics including automated traffic counts, ramp volumes (for trip distribution) and Google Maps API travel times. Some updates to network coding and model specification were required to fine tune the RTM3 within the Highway 99/91 study area. With these improvements, a sufficient level of model validation was achieved and provided a solid basis for developing the updated traffic forecasts.

3.3.4.2 Scenarios Analyzed and Key Assumptions

The following provides a summary of the various time periods, horizon years, and network configurations that were modelled using RTM3:

- **Land Use Horizons.** The model was used to develop a 2017 base year and 2030 and 2045 future horizons. Land use forecasts for population, households, and employment were based on Metro Vancouver's officially adopted Regional Growth Strategy numbers.

- **Time Periods.** The RTM3 model develops travel demand estimates on a 24-hour basis. Time slices from the model are then developed to provide estimates of travel demand for the morning peak hour (07:30-08:30), the midday period (12:00-13:00) and the afternoon peak hour (16:30-17:30). Note that these peak hours may not be the true peak, in which case time of day adjustment factors can be applied to represent this condition.

- **Network Configuration.** The model roadway network was updated for the following configurations:

  a. **Four-lane Existing.** To represent a future business as usual (no change) configuration, which provides a basis for estimating travel time savings of any future improvement options.

  b. **Six-Lane "Do Minimum" Concept.** Provides a new six-lane Crossing of the River with no counter-flow operation and with improvements to the Steveston Highway Interchange, including the replacement of the two-lane Highway 99 overpass.

  c. **Ten-Lane Reference Concept.** This includes a new ten-lane Crossing with extensive highway interchange and laning improvements as defined in the Project Reference Concept.

These scenarios are illustrated in Figure J, which differentiates the 'Do Minimum' scenario in green and the Reference Concept in blue.

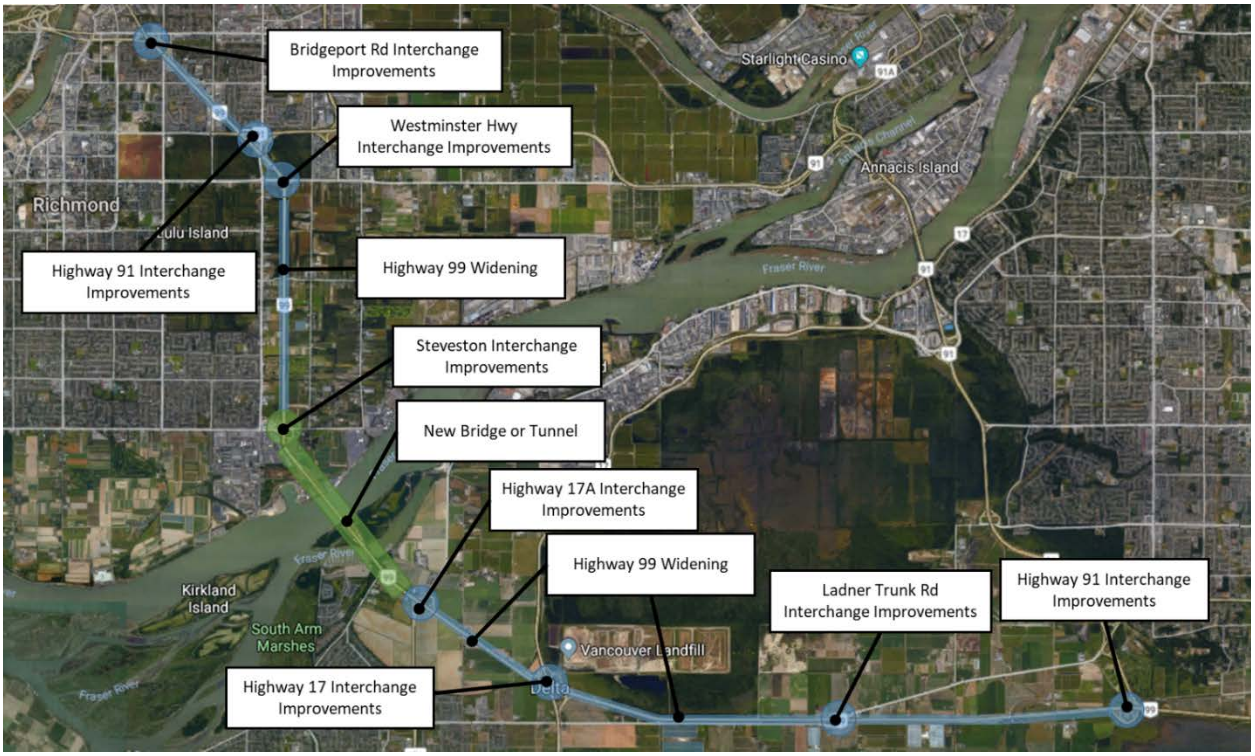

Figure J Do Minimum and Reference Concept improvements.

Other key model assumptions include the following:

- **Other Relevant Infrastructure Improvements.** Includes network improvements that have a high likelihood of occurrence (i.e., funding committed or already underway) and a material impact to traffic using either Highway 91 or Highway 99 within the study area. These include the following:
  - AFB Counterflow,
  - Pattullo Bridge Replacement,
  - 72nd Avenue. Interchange,
  - 216th Street Interchange, and
  - Surrey Light Rail Transit.
- **Special Traffic Generators.** Includes expansion of Roberts Bank Terminal 2, which would double the container handling capacity at the Port of Vancouver's outer port.
- **Pricing Variables.** All economic variables are assumed to inflate at the same rate, such as incomes, value of time, fuel prices, parking, etc. No tolls or mobility pricing options were included in this analysis.

3.3.4.3 Traffic Forecast Results

The RTM3 was used to develop updated traffic forecasts based on the growth and network assumptions. Figure K below shows the traffic forecasts for the business as usual, six-lane 'Do Minimum' and 10-lane Reference Concept improvement options expressed as AADT (weekday and weekend). Note that there is a small decrease in Tunnel traffic volumes in 2019 with the opening of the AFB counterflow system.

From opening day, the annual growth rates for the short, medium, and long-term show that traffic initially grows fairly quickly, and then levels out over the long term. Capacity constraints in the business as usual case suppresses growth in traffic volumes, while any improvements provide travel time savings making the Corridor more reliable and attractive. The 10-lane option grows to approximately 130,000 AADT in 2045.

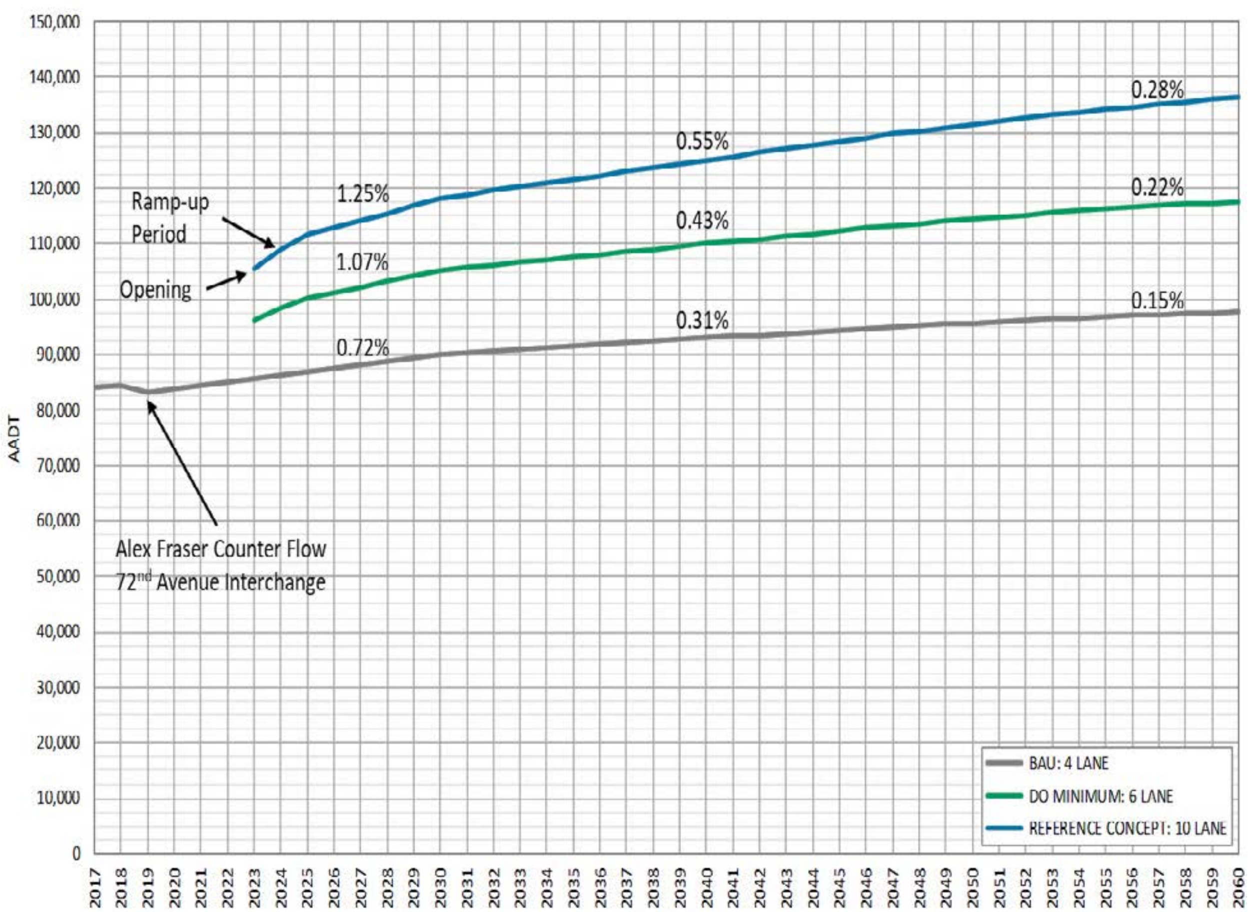

Figure K Project traffic forecasts.

Figure L provides a breakdown of the components of the traffic forecasts for the six-lane 'Do Minimum' and 10-lane Reference Concept. Existing traffic is based on actual traffic count information today and forms the foundation for the traffic forecast. Growth is based on land use and economic development and generally depicts overall growth in travel demand across the River. Redistribution includes more travel with decreased access costs (travel times) across the River and can be interpreted as induced traffic. The largest component is derived from trip diversion from the AFB as the Highway 99 Corridor becomes a much more attractive corridor with capacity improvements.

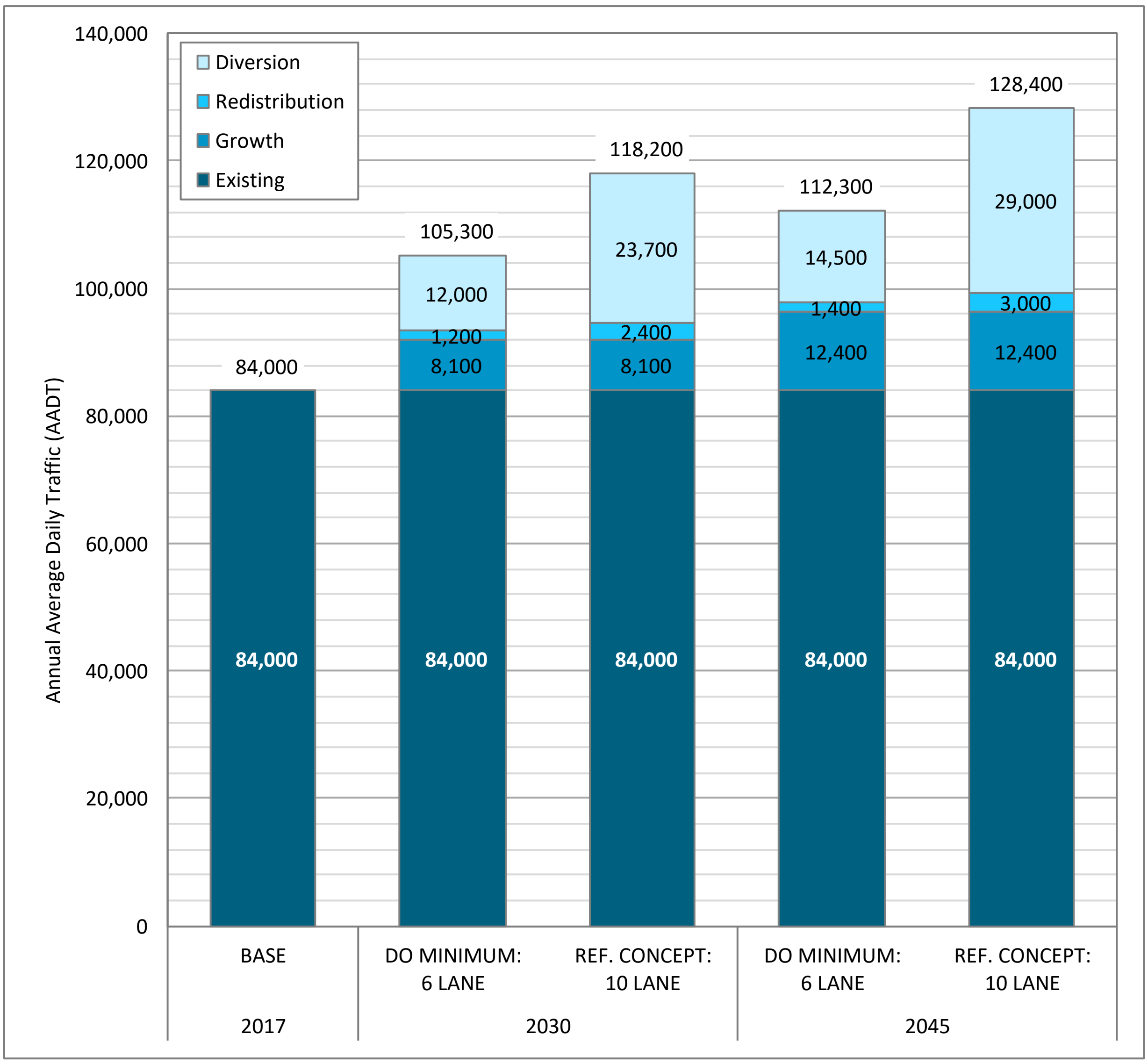

Figure L 2045 AM peak hour traffic forecasts for the 10-lane Project Reference Concept.

The 10-lane Reference Concept clearly provides more capacity to cross the River. In terms of lane utilization, the northbound general purpose (GP) lanes are about 74% utilized and the HOV/transit lane is about 55% utilized during the morning peak hour. Similarly, the southbound GP lanes are about 84% utilized and the HOV/transit lane is about 71% utilized showing that there is spare capacity even in 2045 with these enhancements.

3.3.4.4 Comparison to Previous Traffic Forecasts

The Project Team produced traffic forecasts for a tolled and un-tolled 10-lane Reference Concept scenario using the RTM Phase 0. Figure M provides a comparison of the Review's RTM3-based traffic forecasts compared to the previous Project forecasts. As shown, the updated model with extensive validation in the Highway 99 and Highway 91 corridors is producing long-term traffic forecasts that are about 10% higher. There are several reasons why the comparison to the previous un-tolled forecast produces a higher forecast. Generally, the RTM3 model is less sensitive to higher network costs in the distribution component of the model pushing more traffic generally across the River. With more delay and slower network speeds, the RTM3 model is more sensitive to changes in capacity in the assignment component of the model.

3.3.5 User Benefits

User benefits in the form of travel time and vehicle operating cost savings were calculated based on a 2023 opening date and 25 years of operation using the latest RTM3. All results were streamed back to 2018 using a 6% discount rate and are presented in 2018 dollars. The 10-lane reference concept produces the highest benefits of $1,730 million while the six-lane 'Do Minimum' concept captures 42% of these benefits at $720 million. The high proportion of the benefits captured by the six-lane concept is due to the large capacity increase in the off-peak directions during the peak periods, which sees significant congestion effects on the single lane provided during counterflow operation. The peak direction also sees additional benefits as a new six-lane crossing would be built to modern design standards and the inside lane would be physically separated from oncoming traffic. Today, the counterflow lane operates without a physical barrier, which some drivers may shy from resulting in a fairly low lane utilization rate. The six-lane concept provides significant travel time benefits in the off-peak direction in the peak periods, providing operational speeds similar to the midday, off-peak period.

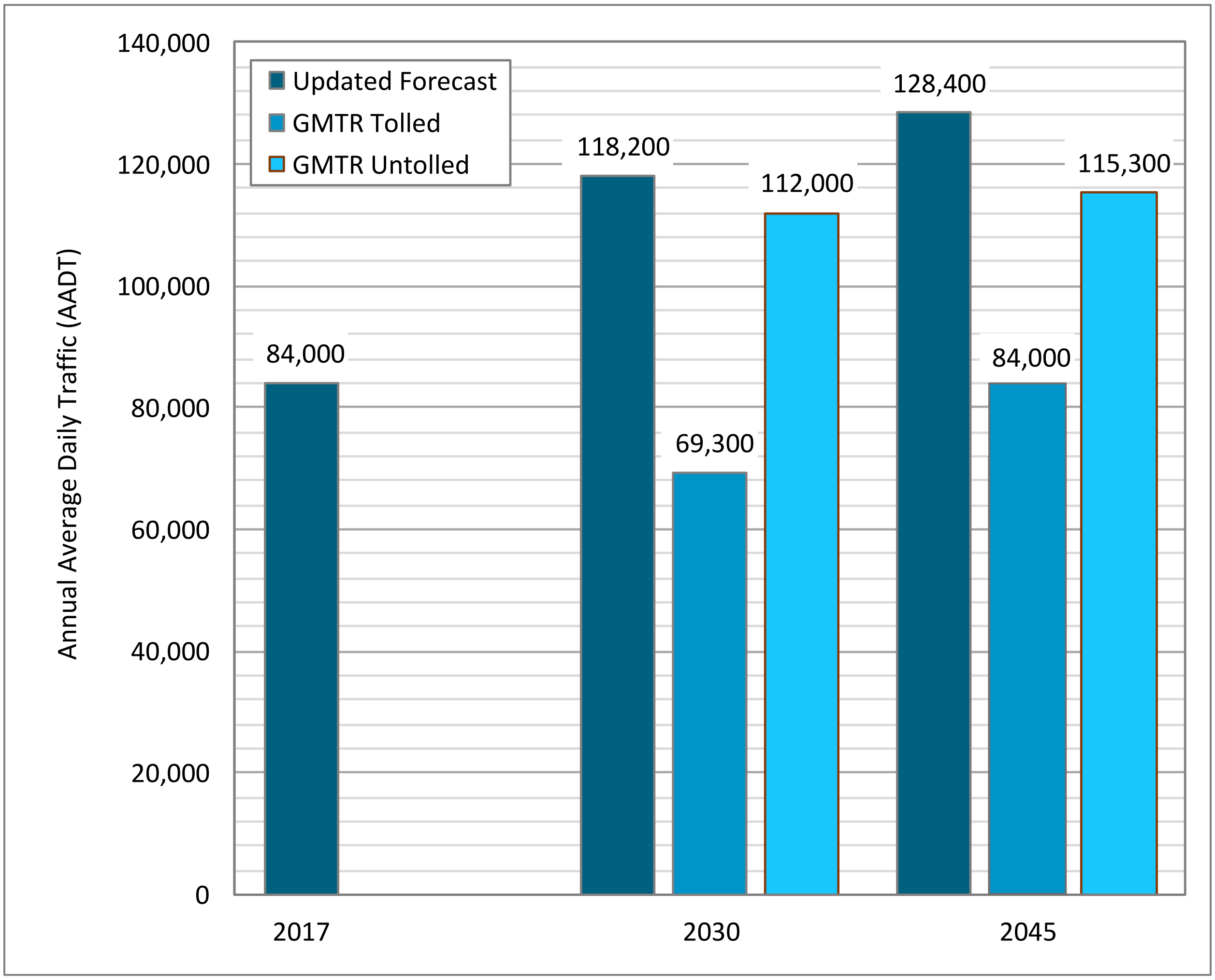

Figure M 10-lane Project Reference Concept traffic forecast comparison.

There are additional travel time, reliability and capacity benefits of providing additional capacity in the peak direction on the Crossing, but approximately half of the benefits provided by the Reference Concept are attributable to the highway mainline and access improvements at interchanges along the Corridor on either side of the Crossing. These benefits are not captured in a 'Do Minimum' scenario.

There are limited additional benefits provided by the 10-lane concept in the short-term as the majority of the congestion has been relieved by the six-lane concept. The 10-lane concept does provide benefits in the longer term with improvements to peak direction travel times and provides additional relief to the AFB as well due to traffic diversion from Highway 91.

An eight-lane 'Do Minimum' scenario and an eight-lane Reference Concept scenario were modelled as well to determine how benefits are derived in the study area.

These two scenarios are defined as follows:

- Eight-Lane 'Do Minimum' – Same as the six-Lane 'Do Minimum' but with auxiliary lanes between the Steveston and Highway 17A interchanges.
- Eight-Lane with the Reference Concept Highway Improvements – Same as the 10-Lane Reference Concept but with the HOV/transit lanes removed between the Steveston and Highway 17A interchanges.

In addition to travel time and vehicle operating cost savings, any improvements to the Tunnel will result in reliability benefits. The current Crossing sees significant variability in travel times due to accidents, vehicle stall, etc. To estimate reliability benefits, travel time information was gathered for the region and the average uncertainty in travel times was calculated. Then, with any improvement in capacity, an estimate in travel time reliability reduction was estimated. The 10-lane Reference Concept results in an additional $509 million in NPV of user benefits. The six-lane 'Do Minimum' scenario achieves approximately 36% of these reliability benefits as it provides a capacity improvement in the off-peak direction. The eight-lane 'Do Minimum' scenario achieves 46% and the eight-lane with the highway improvements achieves 98% of the full build option, similar to the travel time and vehicle operating cost savings.

Replacing the Crossing only in the short term would provide improvements that are "right sized" for the Corridor context and aligned with the forecast of traffic. Remaining Corridor improvements can be provided in the longer term.

Table A provides a summary of the travel time and reliability benefits as a proportion (%) of the 10-lane Reference Concept for the other options that were analyzed.

The six and eight lanes 'Do Minimum' scenarios serve 87% and 91% of the 10-lane Reference Concept traffic volumes. The eight-lane 'Do Minimum' scenario achieves approximately half of the benefits (travel time and reliability) of the 10-lane Reference Concept while the eight-lane with highway improvements, achieves close to 100% of the benefits of the 10-lane Reference Concept. In terms of timing, the short-term need would be to replace the Crossing ('Do Minimum' scenario) and then provide the Corridor improvements (Reference Concept) for the longer term. This would provide improvements that are "right sized" for the Corridor context and aligned with the forecasts of traffic. Further, the Corridor improvements can be staged over time and added as congestion trigger points are reached.

Table A Summary of travel time and reliability benefits

Project Option	Lane Configuration	Future Traffic Volume (2045 AADT)	2045 PM Peak Travel Times (mm:ss)		Travel Time and Operating Cost Benefits (NPV $ 2018)	Reliability Benefits (NPV $ 2018)
			North-bound	South-bound		
4-Lane Do Nothing	2/2 General Purpose Off Peak 3/1 General Purpose Peak Counter Flow	74%	31:30	35:00	0%	0%
6-Lane Do Minimum	3/3 General Purpose	87%	16:10	33:50	42%	36%
8-Lane Do Minimum	4/4 General Purpose	91%	15:10	32:30	50%	46%
8-Lane Reference Concept	4/4 General Purpose	99%	13:25	17:30	95%	98%
10-Lane Reference Concept	4/4 General Purpose + 1/1 HOV/Bus	100%	13:20	17:00	100%	100%
Summary Metric		**128,400**	**-**	**-**	**$1,734 million**	**$509 million**

3.3.6 Forecast Uncertainty

The central case, or base case, traffic forecasts presented in the previous section are based on several assumptions and estimates of future economic and travel behaviour conditions. Variations in these assumptions and forecasts are expected and they will result in changes to the traffic forecast. Such variations may concern any one of several factors, for example different employment growth, different fuel price forecasts, or different economic outcomes.

The central case provides a vision of the future that is based on today's knowledge, calibrated model parameters and a set of reasonable future assumptions and estimates regarding the direction and magnitude of change in the years to come. If the future could be predicted with absolute certainty, it would be possible to define the demand levels for the Highway 99 Corridor associated with particular economic conditions at specific points in time. But, clearly, this is not the case. Whilst 'best estimates' of future demand levels can be made, even with the most sophisticated forecasting techniques, the future cannot be predicted with absolute certainty.

Given that uncertainty exists, it is beneficial to identify principal uncertainties that would have a significant impact to the central case traffic forecasts. For a more formal business case that would lead towards more investment-grade traffic forecasts, a risk analysis should be undertaken to quantify this uncertainty. Decisions can be greatly informed by this type of analysis and quantification, as the range in which vehicle demand levels are most likely to fall can be identified. Thus, the risk associated with the forecast traffic level can be judged and quantified. Rather than carry out a comprehensive risk analysis, the following (Figure N) identifies the principal uncertainties that would have an impact to traffic levels.

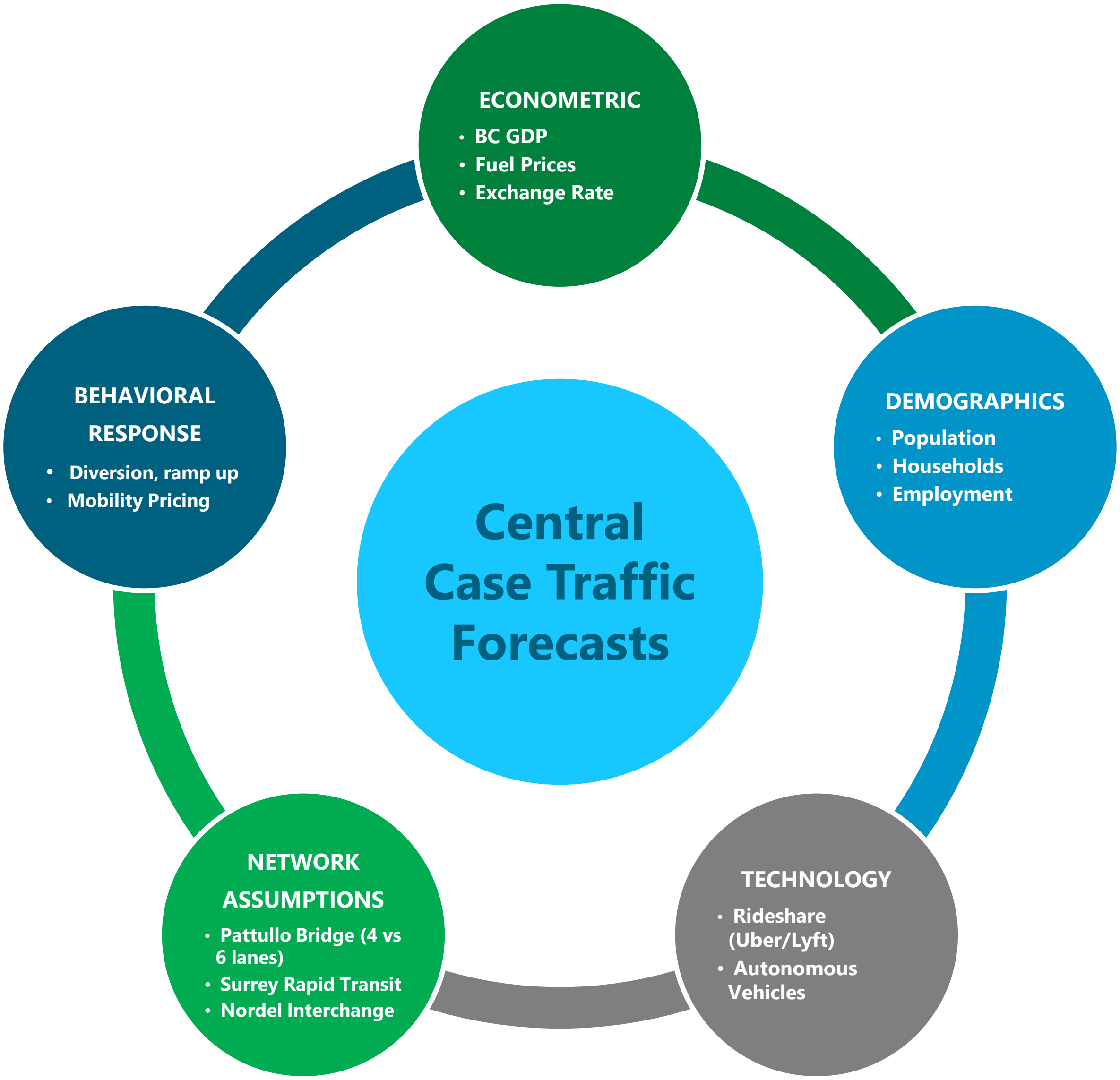

Figure N Principal uncertainties affecting central case traffic forecasts.

The traffic forecasts that have been developed are the most likely given current policy, pricing, travel conditions and projections of key explanatory variables for the future. Given these assumptions, however, there is likely more downside risk than upside risk; meaning that it is more likely that future traffic will be less than predicted. Economic conditions are generally good these days with BC GDP growing at approximately 3% annually. There is no certainty that this trend will continue at this rate over the next several decades. Fuel prices have risen substantially over the past couple of years, but there is no indication that they would drop significantly over the forecast horizon.

Tolls were removed on the Port Mann Bridge and Golden Ears Bridge recently, but the region just completed a comprehensive review of Mobility Pricing options, which could negatively affect traffic volumes on the Crossing. If ridesharing services rapidly increase market share in Metro Vancouver, there is a high likelihood of vehicle occupancies increasing, which would result in fewer vehicles on the region's roadways. Finally, other network elements such as a six lane Pattullo Bridge could draw traffic away from the Highway 99 Corridor. It is difficult to envision significant upside factors for future traffic on the Crossing with the exception of trucking, which would grow significantly with the development of Roberts Bank Terminal 2 and associated logistics facilities in the area south of the River.

3.3.7 Regional Context

The Project fits into a larger regional context and should reflect the larger goals and targets identified in the long-term plans for the region. The current Regional Transportation Strategy (RTS) developed by TransLink in 2013 sets out a long-term vision through the 2045 horizon year. A list of priority initiatives in support of this vision were identified in the 10-Year Vision, developed by the Mayors' Council in 2014, which is anticipated to be delivered in a series of phases as funding becomes available. Some key targets in the RTS involved designing the transportation system to support 33% shorter driving distances and a 50% active mode share target by the 2045 horizon year.

Although replacing the existing Tunnel with a higher capacity Crossing is in contrast with the vehicle kilometres travelled (VKT) and sustainable mode share targets set out, there are other elements of the RTS that do apply.

The removal of most congestion in the Project Corridor with the Reference Concept is supportive of many goals stated in the RTS, such as:

- Making travel more reliable;
- Increasing transportation options;
- Making it easier and less stressful to get to work and school;
- Giving us more time for doing the things we love;
- Ensuring businesses continue to prosper with better access to more workers and more markets;
- Making living, working and doing business in this region more affordable;
- Giving people better access to more jobs and more opportunities; and
- Making our roads safer.

A six or eight lane option is more compatible with the RTS than the 10-lane Reference Concept. Both scaled down options still provide significant relief to congestion, but at the same time provide an incentive for high occupancy vehicle and transit travel. Further, any future forms of travel demand management or mobility pricing would help ensure that a six or eight lane option performs at optimal traffic levels.

The Review, as noted above in Section 0, recommends the Province consider changing the original functional criteria of "Eliminate queuing at any time to 2045," which would:

- Enable the Crossing scale to be reduced to six or eight lanes to be more compatible with the RTS;
- Accommodate the majority of the future traffic forecast;
- Permit staging of highway improvements; and
- Provide some degree of "future proofing" against the expected technological and related societal changes that are occurring.

3.3.8 Review Findings

The Review determined that the traffic forecasts and analysis completed by the Project were carried out using sound judgement and traffic engineering/travel demand modelling principles accepted in industry at that time. The traffic forecasts result in reasonable estimates within the accuracy of the models available at the time.

The traffic re-forecasting completed by the Review using the updated RTM3 model predicted slightly greater volumes of traffic consistent with the improvement made to the model and are a reliable prediction for future traffic. Further, the distribution of travel through the Corridor was generally consistent with the Project findings.

The Review found that TransLink's revised RTM3 model is a reliable tool to be used for future traffic forecasting.

The Review found that it is essential that in planning for any changes or modifications either at the AFB or the Crossing that that the traffic analysis explicitly assess the impact of those changes on the other crossing and ensure that the solution of one perceived problem does not generate another. By way of example, the Review and the Project both identified that the Crossing and the AFB behave as couplet; working together to move the traffic. Congestion and/or capacity changes at either crossing directly affects the other. The Project estimated that there would be a 17%

increase in daily traffic at the AFB in 2045[46] as a result of diversion of traffic from a tolled Crossing. The Review estimated that for the un-tolled Reference Concept, approximately 22.5% of the 2045 Traffic would be as a result of diversion from the AFB.

The Review has estimated that a new six lane or eight lane Crossing, both with minimum highway Corridor improvements, can accommodate 87% and 91% of the forecast 2045 traffic, respectively. In both cases, the travel time in the peak directions would be 15 minutes to 17 minutes greater than the Reference Concept in 2045; very similar to what is experienced today. In both cases, the non-peak direction would experience almost no delay.

Planning for changes or modifications either at the Alex Fraser Bridge or the George Massey Crossing must assess the impact of those changes on the other crossing and ensure that the solution of one perceived problem does not generate another.

Eliminating all congestion is known to induce traffic, provides no incentive for SOV to shift to other modes of transportation, and provides no basis for mobility pricing because there is no congestion to value and price. Some delay is consistent with all other major crossings in the region.

[46] British Columbia Environmental Assessment Office. (2017, January 19). *George Massey Tunnel Replacement Project Summary Assessment Report* [Report]. Retrieved from https://projects.eao.gov.bc.ca/api/document/589cd664a029d5001d2ed3e4/fetch

As explained in *Exploring New Approaches to Reducing Congestion*[47]:

> *Reliable travel times can be more important than congestion delays. Urban areas will always experience a certain degree of congestion. That the demand for transportation exceeds capacity and delays occur is part of life in a major city, and must be accepted to a certain degree. However, there comes a point at which the length and in particular the unreliability of travel times becomes a major burden to individuals and businesses. Many people may accept a certain level of delay as long as they know how long the delay is likely to be. The problem occurs when the actual delay is longer than our expectations, and when journey times vary so much that we are unable to reliably predict when we will arrive.*
>
> *Given this situation, individuals tend to remember the worst delays, and often adjust their travel times to account for them. This leads to loss in other productive time, family time, or recreation time because they are accounting for variances which only occur sporadically. Therefore, reducing the variance of travel times can have the effect of improving average journey times, with only small reductions in total journey times.*

It is estimated that a new six lane or eight lane Crossing, both with minimum highway improvements, can accommodate 87% and 91% of the forecast 2045 traffic, respectively.

Figure O on the following page illustrates how variance in travel time is viewed.

The Project achieved maximum user and reliability benefits by eliminating all delay time by providing essentially free flow capacity. The previous studies and recommendations made for improving the Crossing discussed in Section 2.5 had the primary objective of improving reliability.

[47] Mobility Pricing Independent Commission. (2017, October). *It's Time - Moving around Metro Vancouver: Exploring New Approaches to Reducing Congestion* [Report]. Retrieved from https://www.itstimemv.ca/uploads/1/0/6/9/106921821/its_time_e1_research_report_-_moving_around_metro_vancouver_-_oct_24.pdf

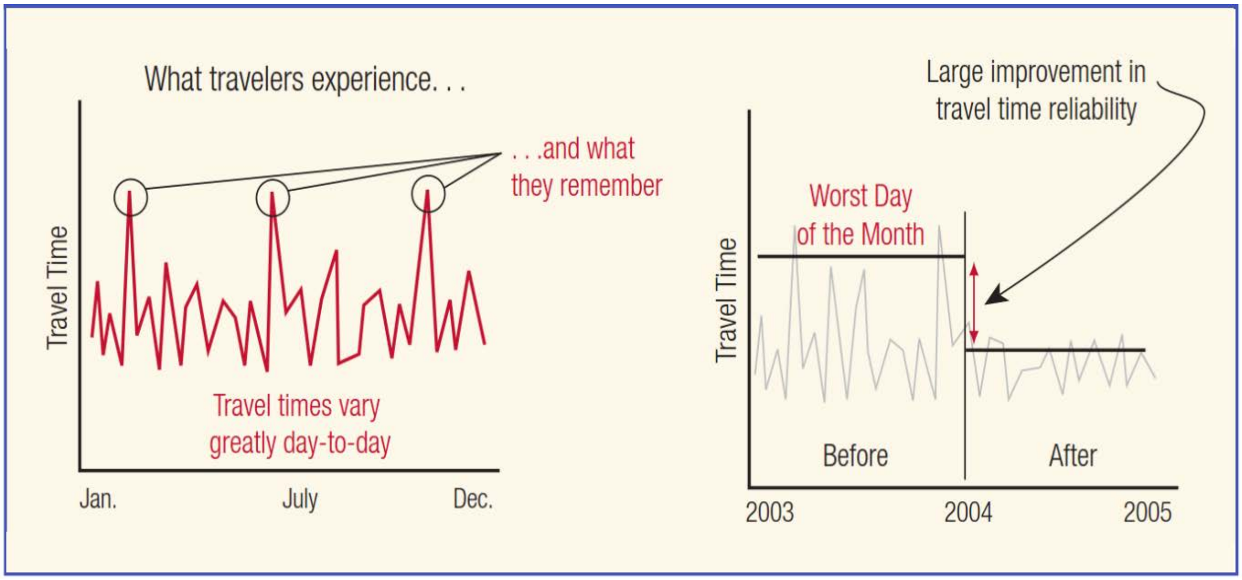

Figure O Impacts of improvement in travel time reliability[48].

A six lane 'Do Minimum' scenario Crossing or an eight lane 'Do Minimum' scenario Crossing will achieve the majority of the reliability benefits project benefits in 2045. Both scenarios can handle the majority of the 2045 predicted traffic but with some delay in peak direction; not inconsistent with the other Lower Mainland crossings.

3.4 Highway and Bridge Review

3.4.1 Reference Concept

The Reference Concept design requirements for the bridge and highway are described in the documents provided in the *George Massey Tunnel Replacement Project, Request for Proposals (RFP)*[49], dated October 4, 2016. Specific reference has been made to *Schedule 4 - Design and Construction; Part 2 Design and Construction Requirements, Article 1 – Laning and Geometrics Criteria and Article 3- Structural Design Criteria*.

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[48] US Department of Transportation, Federal Highway Administration. (2006). *Travel Time Reliability: Making It There On Time, All The Time* [Report]. Retrieved from http://www.ops.fhwa.dot.gov/publicaitons/tt_reliability/index.htm

[49] British Columbia Transportation Investment Corporation. (2016, October 4). George Massey Tunnel Replacement Project, Request for Proposals [RFP]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/10/Request-for-Proposals-Oct-2016.pdf

The Review has not checked the design in detail but has assessed that it generally achieves the stated requirements and complies with current design standards and practices.

In this regard, the following discussion describes, based on the Review, opportunities to optimize the Reference Concept, that while perhaps not achieving all of the functional criteria for the Project, are worthy of consideration.

3.4.2 Bridge

The bridge general arrangement and concept design resulted from the two Goal 6 functional criteria identified in Section 3.2.1:

6. **Goal: Enhance the environment.**
    a. Functional Criteria:
        i. Provide a clear span structure, with no piers in the Fraser River; and
        iii. Construct Project within existing corridor and reduce footprint of Project infrastructure.

The bridge main cable span is approximately 660 m in length with 300 m long back spans. There are 18 cables at each main pier in a harp type arrangement (see Figure P)[50]. The back spans have pier supports that function to reduce deflections from unbalanced live load on the main span. The main span cross section is a large, 50 m wide steel box girder that accommodates the 10 vehicle lanes. It is 4 m deep with orthotropic top and bottom flanges (see Figure Q).

The approach spans, including the back-cable spans, are shown as four concrete segmental box girders per span. The concrete box girders, while supporting the approach deck, also have a relatively large mass, which assists in the design to counteract potential uplift from a fully loaded main cable span. As the girders have a top flange that is the full width of the bridge, the permanent cast-in-place concrete deck can be constructed with minimal impact to the River traffic below.

To reduce traffic impacts on the existing highway during girder erection, it was assumed that the girders would be erected span-by-span using a traveller; a construction method used locally on the Millennium and Evergreen SkyTrain lines as well as the above-grade section of the Canada Line.

[50] George Massey Tunnel Replacement Project. (2016, October 20). *All Proponents Information Meeting* [Presentation].

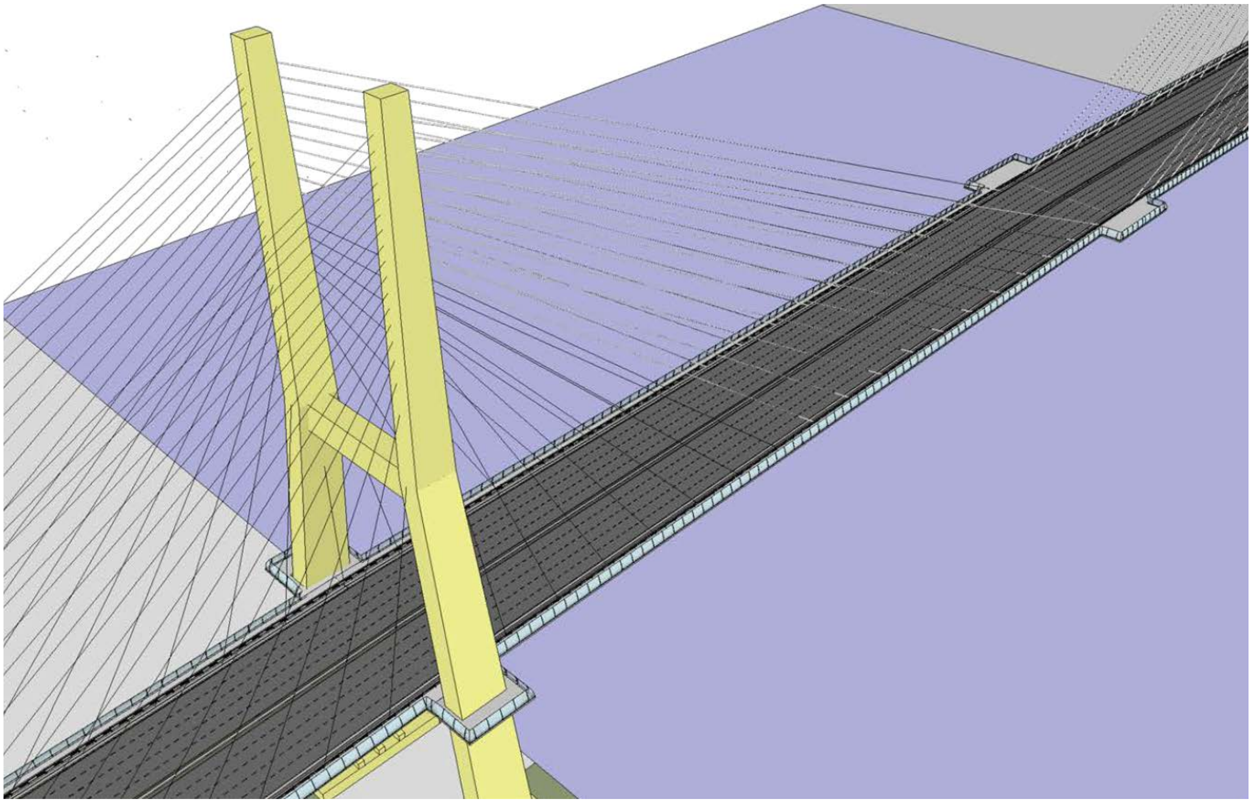

Figure P Schematic of the Reference Concept bridge[50].

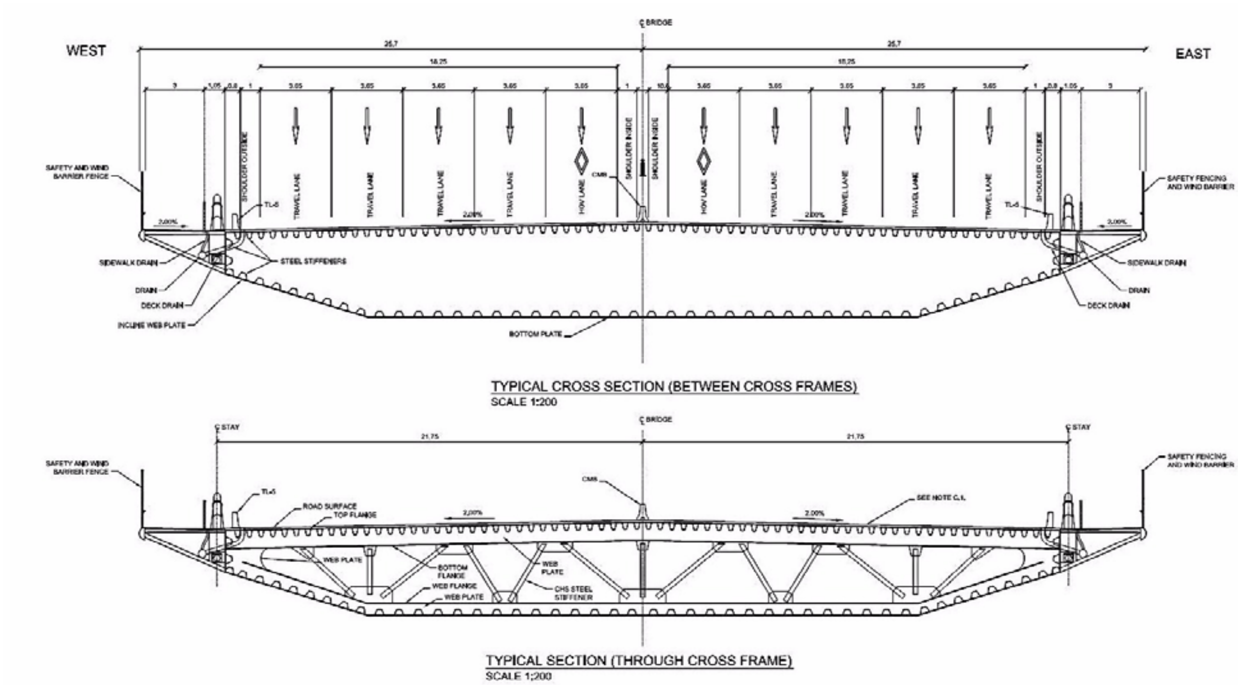

Figure Q Cross section of the Reference Concept bridge deck showing laning[50].

The Reference Concept steel box girder for the main span is appropriate given the main span length. Executed properly, it is a well-tested structural system. Given the size and mass of each individual section, the local steel fabrication industry may be challenged, and as with other large steel structures, international fabrication may be the lowest cost.

Constructing the new Crossing on the existing highway alignment, while minimizing the impact on adjacent properties, creates added complexity that influences the bridge design requirements and the construction efforts, which are anticipated to result in significantly greater costs than if an alignment offset from the existing highway and Tunnel was utilized.

This approach would allow for a wider choice of structural systems, such as steel I-girders, that have less mass. Other advantages include more flexibility in span length resulting in fewer substructure elements and potentially less piers on the approach structures. Further, with an offset alignment, the risks in constructing over traffic and in proximity to the existing Tunnel are reduced and traffic management is less challenging.

It is considered that a revised alignment of the bridge would provide a material cost saving to the Project; provided sufficient land can be obtained and impacts on adjacent developments can be adequately mitigated.

> Constructing the new Crossing on the existing highway alignment, while minimizing the impact on adjacent properties, is anticipated to result in significantly greater costs than if an alignment offset from the existing highway and tunnel was utilized.

To avoid the environmental impacts related to building in, and adjacent to, the River, the main piers for the Reference Concept are located well inshore of the existing shoreline resulting in the bridge main span length of 660 m. At this length, there are significant uplift forces generated on the back spans under full live load on the main span and low load on the back spans. A 660 m span requires a more sophisticated structural arrangement than was used on other cable-stayed bridges in the Lower Mainland such as the AFB and Port Mann Bridge, which have span lengths of 465 m and 470 m (see Figure R), respectively; and which were constructed with relatively simple and easy to fabricate longitudinal I-girder and transverse floor beam systems.

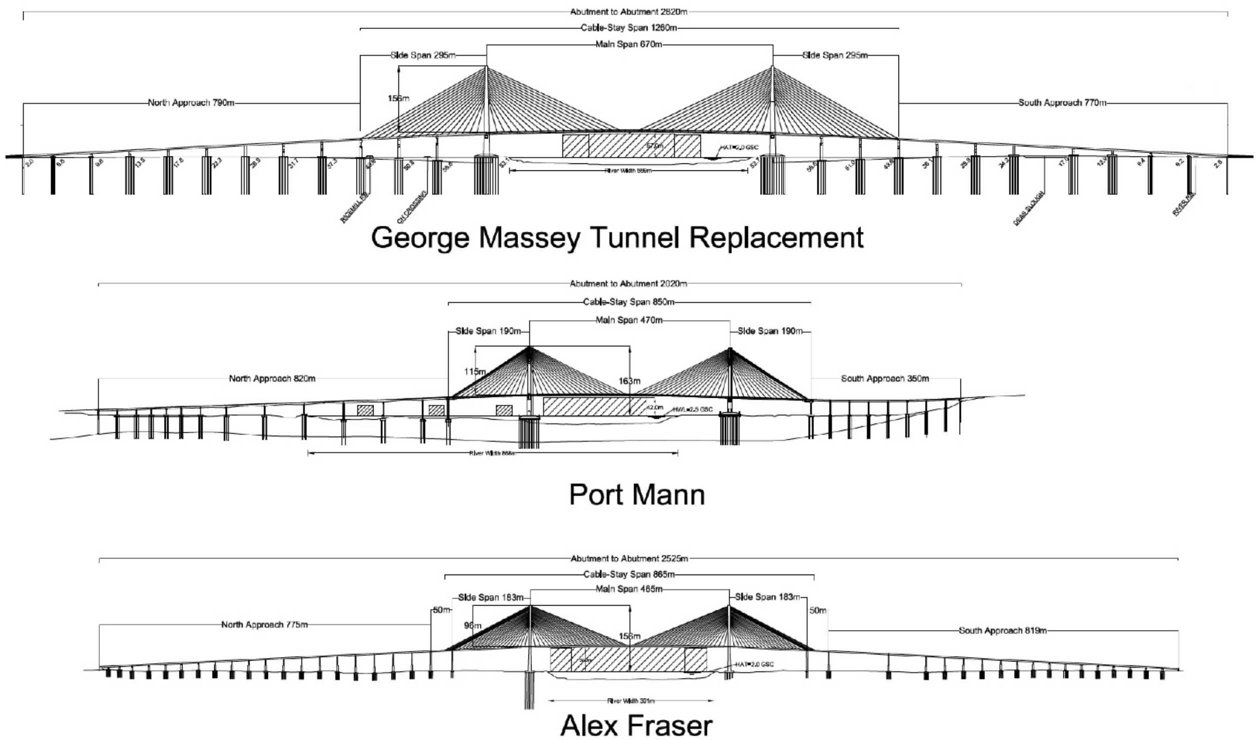

Figure R Comparison of main span lengths between GMTR Bridge, Port Mann Bridge, and Alex Fraser Bridge[50].

If the main piers were moved closer together to shorten the span to 550 m, the complexity and cost of the bridge would be reduced. It is recognized that environmental implications would need to be considered and mitigated. The other major crossings of the North Arm of the River have faced a similar challenge and successfully mitigated the impacts.

Using the minimum vertical curve K Factor of 80 allowed by the specified design criteria (as opposed to the 90 used in the Reference Concept) lowers the profile of the bridge approaches by about 1 m and correspondingly reduces the total length of the approach structures by approximately 120 m with corresponding cost savings.

The traffic forecasting modelling described in Section 3.3 demonstrates that there is the opportunity to reduce the number of lanes for the crossing from the originally specified 10 lanes, correspondingly reducing the cost of the Crossing, while still providing a reasonable level of service for the forecast horizon.

The combined effect of the proposed design adjustments described above will have a significant impact on the overall Project cost. The Review considers that cost reductions associated with the bridge in the order of $500 million, or more, may be achievable.

3.4.3 Highway and Interchange

3.4.3.1 HOV / LRT & Median Transit Provision

The Reference Concept included a substantial investment for present and future transit improvements along the Highway 99 Corridor; primarily by providing HOV/transit lanes adjacent to the median, which would at some point in the future could accommodate LRT (see Figure S). In conjunction with the lanes, centre median transit stops were to be provided at the Highway 17A Interchange and at the Steveston Highway Interchange (see Figure T). Access to, and from, the transit stops required the inclusion of multi-use pathways in the interchange design to allow for pedestrians and cyclists to have safe access to, and from, those stations.

The two additional HOV/transit lanes necessitate longer span overpasses over Highway 99, and a two-lane free-flow fly-over across the highway for buses at Bridgeport Road to reach the Bridgeport Canada Line Station.

The MoTI 2009 Highway 99 (King George Highway to Oak Street Bridge) Corridor Assessment report noted the limited benefits of median stops and the related high cost of ramps to eliminate buses having to cross multiple lanes of traffic to exit the highway. At that time, MoTI considered the construction costs related to the median transit stops would exceed the total cost of shoulder side bus lanes over the entire corridor and recommended against median transit lanes.

Elimination of the median HOV/transit provisions and maintaining the existing shoulder side bus lanes with provisions for queue jumping would:

- Substantially reduce the complexity and cost of the Steveston Highway and Highway 17A Interchanges;
- Remove two under utilized lanes from the crossing; and
- Allow for staged highway expansion and overpass reconstruction, based on need.

With these alterations, it is expected that the Project cost would be substantially reduced; potentially in the order of the $500 million originally estimated by the Project. A more detailed discussion of the cost benefit of the HOV/transit provisions is provided in Section 3.6.

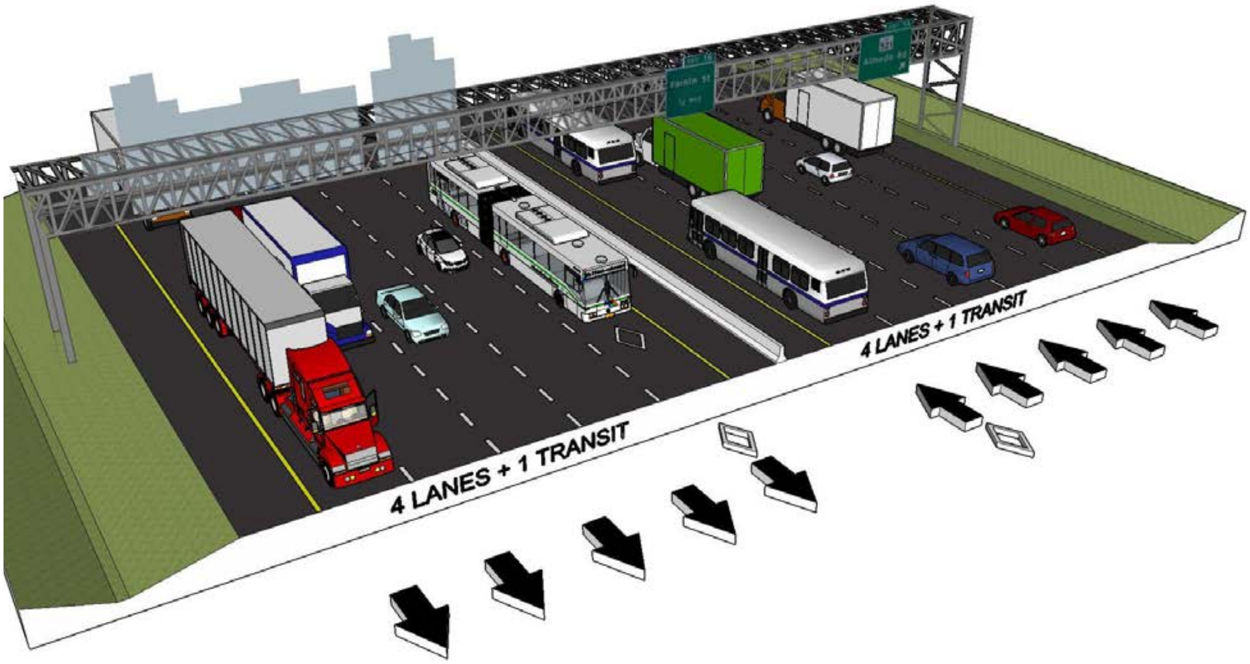

Figure S GMTR schematic of the proposed Reference Concept laning with transit lanes at the median[50].

Figure T GMTR rendering of the proposed centre median transit stop at Steveston Highway Interchange[50].

3.4.3.2 Highway Improvements

The user benefit analysis described in Section 3.3.5 determined 45% of the Project benefits to 2045 are derived from the proposed Reference Concept highway improvements over the entire Corridor. The highway improvements are, therefore, deemed a necessary and integral component of the Project. However, the short-term need is expansion of the Crossing.

The benefit analysis also determined that both a six and an eight-lane Crossing achieve a significant percentage of the user benefits with only improving the Steveston Highway Interchange, initially creating the opportunity to reduce the Project scope and completing the additional highway improvements on an "as needed" or on a "as funding is available" basis.

Conceptually, in a phased approach, Highway 99 north of the Steveston Highway Interchange and south of the Highway 17A Interchange would be three GP lanes each way with a bus shoulder lane. With elimination of the counterflow, there is sufficient pavement already in place. If the Crossing was eight lanes, the additional two lanes could initially be designated bus lanes with the expectation that in the future they would be designated as GP lanes when demand levels reach a trigger point. This phased approach would require continuing with sub-standard clearances at the existing overpasses and the divided lanes and narrow shoulders at the Highway 17A Interchange.

Further detailed planning and traffic modelling is required to assess the impacts and benefits (if any) of phasing highway improvements over a longer time span.

3.4.3.3 Steveston Highway and Highway 17A Interchanges

The Reference Concept designs for the Steveston Highway and Highway 17A Interchanges were constrained by the Project objective to minimize the footprint of the interchanges to avoid using additional agricultural or park lands and impacts to the adjacent commercial development.

The four northbound and three southbound GP lanes at Steveston Highway Interchange and four lanes northbound and southbound at Highway 17A Interchange, plus two HOV lanes and two transit lanes through the interchanges, the median transit stations, and the free flow directional ramps dictate the large scale and related cost of both interchanges (see Figure U and Figure V).

Figure U GMTR rendering of the proposed Steveston Highway Interchange[50].

Figure V GMTR rendering of the proposed Highway 17A Interchange[50].

The highest directional ramp at the Steveston Highway Interchange is approximately 17 m (without parapets) above Highway 99 below. Similarly, the Highway 17A Interchange has a directional ramp approximately 17 m above Highway 99. With existing overpass top of pavement being in the order of 7 m above Highway 99, having a three-level interchange higher above the surrounding terrain creates an imposing structure that is not compatible with the suburban/agricultural surroundings.

While the interchange design works well to achieve the project objectives, substantial foundation work is required to support the large elevated structures, given the geotechnical and seismic design requirements.

The requirements for upgrading City of Richmond roads to be consistent with a new 10-lane highway were not fully resolved, nor desirable or achievable given the footprint of surrounding developments.

The potential negative impact of the "free-flow" highway off-ramps entering the current City of Richmond road network, particularly along Steveston Highway where there are traffic signal-controlled intersections just off the highway at No. 5 Road and Sidaway Road, were modelled by the Project. It was estimated that the vehicle queues off highway would be acceptable based on the forecast traffic, albeit under tolled conditions which saw traffic levels below that of today.

The City of Richmond has confirmed that the requirements for upgrading City roads to be consistent with a new 10-lane highway were not fully resolved, nor desirable or achievable given the footprint of surrounding developments. There is the potential that the increased traffic volumes due to the elimination of tolls may exacerbate the impact to the Richmond road network.

Setting aside the above discussion, the existing Steveston Highway Interchange is currently congested with poor service levels. Regardless of the new Crossing chosen, this interchange needs to be improved. A principal factor is the existing two-lane overpass over Highway 99. During peak periods the overpass restricts traffic flow to the east and west, adding to congestion at both the south and north bound accesses to Highway 99. Further congestion results from the lack of a double left onto Steveston Highway westbound from the Highway 99 northbound off-ramp causing queues to back up onto the highway. Previous planning by MoTI had included a twinning of the overpass to improve east west traffic flow.

The City of Richmond has confirmed that there are no plans to widen or expand Steveston Highway west of Highway 99 as there is no land available for an expanded right of way from the existing four lane cross section. The City does have a plan to widen Steveston Highway to four lanes east of Highway 99, however this requires that the overpass be replaced or twinned.

The existing overpass presently has substandard overhead clearance (4.5 m vs. 5.5 m specified), no shoulders or bike lanes, and only a sidewalk on the north side. Assuming a bridge is the preferred Crossing solution, maintaining the 5% grade on the bridge approaches will further reduce the clearance by approximately 0.5 m. Additionally there is only sufficient space for three through lanes with narrow shoulders in each direction between the existing overpass piers.

With the main bridge lane reductions described above; the elimination of the free flow ramps; and removal of the centre median transit stops as discussed in Section 3.5, the proposed Steveston Highway Interchange could be substantially simplified. Figure W below shows a new five lane overpass at the Steveston Highway Interchange. This would be a "minimum improvement" that would substantially reduce the scale of the overpass while providing adequate functionality.

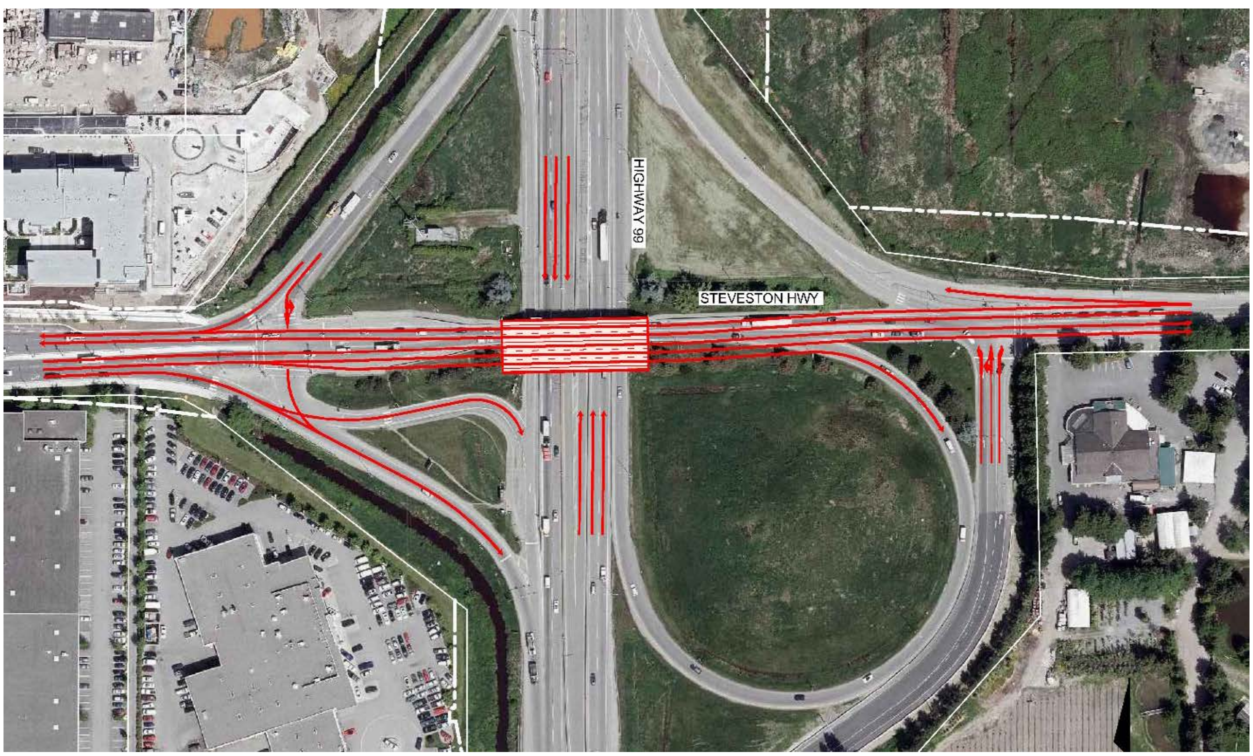

Figure W Potential five Lane Overpass at the Steveston Highway Interchange.

Unlike Steveston Highway Interchange, twin bridges already exist over Highway 99 at Highway 17A Interchange although they both also have substandard vertical clearance of about 4.5 m. Three westbound lanes can only be accommodated if the existing arrangement with lanes split between two bridge spans is maintained. As with Steveston Highway Interchange, the reduced laning and elimination of center median transit stops, will allow for a significantly simplified interchange.

3.4.4 Review Findings

Based on the foregoing discussion the Review has determined that:

- The Reference Concept generally achieves the stated requirements and complies with current design standards and practices.
- There is significant opportunity to optimize a bridge Crossing design by utilizing an alignment offset from the existing highway and by reducing the bridge span by constructing the main piers in, or adjacent to, the River. This requires that the Province accept that the Project functional criteria; avoiding construction in the River and avoiding additional use of agricultural land would not be fully achieved.
- Eliminating the HOV/transit stations in the median provides the opportunity to significantly reduce the scale and visual impact of the Steveston Highway and Highway 17A Interchanges.

Eliminating the HOV/transit stations in the median provides the opportunity to significantly reduce the scale and visual impact of the Steveston Highway and Highway 17A Interchanges.

- There is an opportunity with a reduced lane Crossing to phase the highway improvements, other that at the Steveston Highway Interchange.

3.5 HOV/ Transit

The Tunnel is unique among Lower Mainland crossings because of its transit utilization (outside of the Skytrain crossings). The Tunnel serves the greatest number of bus routes and carries nearly three times the passenger volume of the AFB, the crossing with the next highest transit ridership crossing the Fraser River (see Table B). The Project reported that the during the morning rush hour, approximately 60% of trips to downtown Vancouver by residents of South Delta and South Surrey are made by transit. During the northbound morning rush hour buses comprise only 1% of traffic but carry approximately 17% of all Tunnel travellers[51].

The Project reported that HOV use through the Tunnel is greatest on weekends, accounting for 40 per cent of total vehicles and transporting 56 per cent of total passengers[51]. During weekdays, HOVs represent 10% to 17% of traffic through the Tunnel, carrying 16% to 25% of all passengers[51].

Transit and HOV traffic enjoy high utilization and obvious benefits in terms of the queue-jumper access to the Tunnel during periods of high congestion.

Table B South Arm bridges – average weekday bus volumes and ridership.

Crossing	No. of Bus Routes	Bus Volume	Passenger Volume
George Massey Tunnel	9	559	10,535
Alex Fraser Bridge	3	250	3,853
Pattullo Bridge	1	11*	350*
Port Mann Bridge	1	137*	2,500*
Golden Ears Bridge	1	75	735
Skybridge	N/A	230 trains per day**	51,000**
Note:	Data taken from the *2011 Translink Screenline Survey*, except as noted below: * Data taken from *Translink 2014 Bus Service Performance Review* (no PMB or PB buses in 2011) ** Based on *2015 Transit Schedule*		

[51] TransTech Data Services Ltd. (2014, October). *GMT Data Collection Program Fall 2014*.

3.5.1 Project HOV/ Transit Provisions

The Project addressed the HOV/transit requirements for the Project by providing dedicated HOV/transit lanes over the entire 24 km length of the Project Corridor and transit stations in the centre of the highway with possible future LRT capability.

The design was "future orientated" locating the HOV/transit lanes adjacent to the median and providing transit stops in the median at the major overpasses (Steveston Highway and Highway 17A). This arrangement would reduce the transit stop times for buses relative to the present situation where buses must exit and re-enter the highway.

The provisions for possible future LRT are consistent with other new major crossings and considered a Provincial objective; although undocumented. These provisions increased the complexity of the highway and interchange design by; requiring multi-use pathways for pedestrians, additional lanes at the median for buses, and transit only ramps at Highway 17A and Bridgeport Road.

Project transit improvements and tolling were intended to encourage a modal shift away from SOVs. However, in the case of an un-tolled, 10 lane, uncongested crossing HOV/transit use is unlikely to increase. As described above, the existing Highway 99 transit system is well used today and is considered by TransLink to be effective and efficient.

> Proposed on-facility transit lanes and corridor stations would achieve only incremental total transit time savings over the existing shoulder bus lane with off-highway pullouts, which are functioning well and have substantial capability for expansion.

The Review was advised by TransLink that it was consulted by the Project to provide guidance as to what a future orientated high capacity transit system should include and provided guidance as to what future HOV/transit provisions on a major highway would include. TransLink confirmed to the Review that the 2045 RTS did not contemplate an extension of LRT to south of the River along the Highway 99 corridor. The transportation modeling for the RTS in 2013 showed that it was unlikely that, even when future growth is considered, there would be sufficient population and demand to justify the capital investment. Further, the Project conducted an assessment of expanded rapid transit to the area south of the River and concluded that there was less ridership due to lower frequencies of service.

TransLink noted that the existing shoulder bus lane with off-highway pullouts, and queue-jumping access at the Crossing, is functioning well and has substantial capability for expansion. Proposed on-facility transit lanes and Corridor stations would achieve only incremental total transit time savings; however, the proposed direct ramps to the Bridgeport Canada Line Station would improve both travel time and reliability.

Given the above, the Review recommends that the Province may wish to consider eliminating the median HOV/transit provisions in favour of lower cost alternatives. It is recognized that the HOV/transit provisions are a desired Provincial objective. As will be discussed further in Section 3.6, the HOV/ transit provisions when assessed independently of the Project do not provide value for money. Elimination of the provisions will remove two lanes from the highway and provide the opportunity to reduce the complexity and cost of the highway improvements.

3.6 Business Case

The Project's business case estimated capital costs for the Reference Concept to be $3.5 billion in as-spent dollars, which represented approximately $2.0 billion in 2014 dollars, before allowing for interest during construction. To complete a cost / benefit calculation, the Project assessed benefits that included (see Table C):

- **Quantified user benefits** - including travel time, reliability and vehicle operating cost savings; traffic safety; and seismic risk reduction.
- **Unquantified user benefits** - including benefits to cyclists/pedestrians; benefits to future transit; and other unquantified benefits.
- **Economic development benefits** - including increased economic activity and employment, both during construction and in the longer-term.
- **Social, community and environmental benefits and considerations** - such as improved community connectivity; improvements to Deas Island Regional Park; improved emergency response capability; and restoration of the Fraser River shoreline.

The Project forecast an estimated NPV of user benefits at approximately $2.5 billion, and the NPV of economic development impacts is in the range of $1.6 billion. When compared to costs, these benefits represent a benefit-cost ratio of 2.1 :1, more than twice the Project costs.

Table C Present value of benefits and costs[10].

Component	$ millions at 2014 level
Net Project Costs	**$2,016**
Quantified User Benefits	
Travel Time Savings & Increased Travel Time Reliability	$2,154
Construction-related Traffic Delays	(-$26)
Cost of traffic loss due to tolling	(-$93)
Future-year bridge congestion	(-$24)
Sub-total	**$2,012**
Fuel Cost Savings Benefit	$183
Traffic Safety Benefits	$135
Seismic Risk Reduction Benefits	$192
Total Quantified User Benefits	**$2,522**
Net Present Value of User Benefits	**$505**
User Benefit-Cost Ratio	**1.2 / 1**
Economic Development Benefits	**$1,652**
Total User & Economic Development Benefits	**$4,173**
User & Economic Development Benefit-Cost Ratio	**2.1 / 1**

The $2.485 billion in Travel Time, Operating Cost Savings and Safety / Seismic Benefits included:

- The present value of time savings and reliability benefits calculated at $1,977 million, based on a 6% real discount rate;
- Vehicle operating cost savings resulting from more efficient travel speeds and avoided idling times of $182 million;
- Traffic safety benefits with a present value of $135 million; and
- Seismic risk reduction estimated to have a present value of $192 million in 2014 dollars, at a 6% discount rate.

For clarity, when comparing the Review's benefit analysis discussed in Section 3.3.5, the NPV benefits are 2018 values. The Project provided NPV values in 2014 values. The Review calculated total benefits (time saving, reliability and vehicle cost savings) for the Reference Concept totalling $2,239 million while the Project calculated a total of $2,159 million. The Review used a shorter operating life of 25 years versus the 35 years assumed in the Project business case. The difference between the two results are small. The main finding is that the Project benefit calculations match those of the Review.

The Project based the economic development benefits on the study *Impact of Vancouver-area Transportation System Investments*[32]. With the Reference Concept, the Project forecast that GDP growth would accelerate by approximately $13 million per year starting in 2021. By 2045 this was forecast to add an incremental $325 million in GDP growth. The present value of the incremental GDP is estimated at $1.652 billion.

The Project also noted, from a social, community and environmental perspective, the new bridge, when compared to the baseline scenario, provides additional unquantified benefits including:

- Benefits to pedestrians and cyclists;
- Benefits to transit users;
- Reduced local traffic congestion;
- Improved emergency response capability;
- Improved cross-highway agricultural and local community connections;
- Deas Island Regional Park enhancements;
- Environmental restoration/improvements to the river shoreline and land/marine habitat;
- Greenhouse gas reductions;
- Support of Metro Vancouver's projected growth in population and employment; and
- Support of TransLink's Regional Transportation Strategy.

The Project noted that benefit-cost outlook for the Project is favourable based solely on user benefits such as congestion relief and increased safety, even before considering economic development and job creation as well as benefits for cyclists/pedestrians and local community and recreational users.

3.6.1 Review Findings

Assuming sufficient capital is available, it can be beneficial to construct the infrastructure required to satisfy present needs and future needs at one time (e.g., assuming a reasonable planning horizon). If Project funds are constrained, the investment in future infrastructure and the time to when the infrastructure will be fully utilized (i.e., when the benefits will be realized) needs to be assessed. It is common practice to defer the construction of assets that won't be fully utilized for 30 or 40 years. In addition, the continued use or repurposing of existing assets (e.g., the existing Tunnel) must also be assessed before they are disposed.

To achieve the primary goals for the Project, the Project made decisions that reflect their interpretation of MoTI strategic objectives and acceptable solutions to meet the perceived needs or desires of adjacent communities and Project stakeholders; (refer to Section 3.2.1).

The Project completed the business case analysis for the Project on a holistic basis and demonstrated that the total estimated project cost could be supported by user tolls. Individual components of the Project, derived from meeting the Project's goals and functional criteria, were not tested separately on a value for money basis.

The Reference Concept scope may have been reduced if each major component of the Reference Concept considered necessary to satisfy the functional requirements for the Project was tested on a value for money basis.

The Reference Concept scope may have been reduced if each major component of the Reference Concept considered necessary to satisfy the functional requirements for the Project was tested on a value for money basis. This does not mean the Reference Concept developed is incorrect or inappropriately developed, only that other less comprehensive solutions may have been selected that could also have been interpreted to meet the Project's Goals.

For example, the Project advised that the estimated capital cost for the HOV/transit provisions were estimated at approximately $500 million. According to the traffic modelling (see Section 3.3), the HOV/transit provisions generate approximately 5% of the project user benefits. Using the capital cost estimated and the estimated user benefits, the Review calculated the present value and benefit cost ratios for this provision alone using a discount rate of 6%:

- Discount Rate 6%
- Present Value of Costs ($ M) -$422
- Present Value of Benefits ($M) $132
- Net Present Value ($M) -$290
- Benefit Cost Ratio 0.31

The NPV is negative, and the benefit cost ratio is substantially less than one. At the 6% discount rate, the user benefits would have to increase from 5% to 16% of the total Project benefits to create a breakeven result. Alternatively, if the benefit level is kept constant at 5% then the initial capital cost would have to decrease to $143 million to create a breakeven.

Based on the above, the decisions to add the HOV/transit provisions was to fulfill the noted Provincial objective, which could be funded through the toll revenue. When examined on its own, it does not provide value for money. It is recognized that, on occasion, governments must make societal investments with benefits that cannot be assessed based only on financial analysis.

The Review recommends, particularly in the absence of tolls, that future planning should examine the major project components in detail on a value for money basis.

The Review has not examined each of the opportunities to reduce the scope and scale of the Reference Concept but recommends, particularly in the absence of tolls, that future planning should examine the major project components in detail on a value for money basis. It is recognized that eliminating any of the noted provisions on the basis of "value for money" may not be consistent with Provincial societal objectives and may therefore be unacceptable to the Province.

MoTI's Guidelines for Preparing MoTI Business Cases, *Appendix 4 – Option Evaluation Guidelines for MoTI Business Cases*[52] notes:

> *Economic Development Account - This is not a straightforward account. The Highway Planning & Programming Branch's Manager, Economic Analysis must be contacted if the economic development account is thought to apply to any project under consideration. Refer to Appendix 1 for the appropriate MoT contact person.*
>
> *This account does not apply to a project unless it results in B.C. being a beneficiary in terms of:*
>
> *1) a net increase in employment*
>
> *2) a positive impact on private sector investment*
>
> *3) a positive impact on productivity*
>
> *4) a positive impact on GDP and tax revenues*
>
> *5) a positive impact on trade*
>
> *The business case must explain how the project will result in these positive net benefits. Quantitative analysis is preferred but if this is not possible, a qualitative analysis is necessary.*

The Guidelines go on to say:

> *Comparing the net benefit stream to the base case will answer the question "what would happen if this project does not go ahead?" In most cases there would be no impact on the provincial economy.*

The Guidelines provide an example of where Economic Development Benefits would apply:

> *An example of a project which had positive economic development benefits was the Coquihalla Highway project, because it had a pronounced impact on capital investment and employment activity in the Thompson-Okanagan region.*

[52] British Columbia Ministry of Transportation and Infrastructure. (2018). Highway Planning and Programming Publications [Website]. Retrieved from http://www.th.gov.bc.ca/publications/planning/index.htm

Federal guidelines[53] suggest the same:

> *Economic activity should only be included in the estimation of effects if it would not have occurred in the economy at large in the absence of the project. It would take an exceptional set of circumstances to warrant the explicit inclusion of any macroeconomic benefits in a BCA.*

The Review met with MoTI to discuss the business case. MoTI confirmed economic development benefits would not typically be included in a business case for a Project of this magnitude.

MoTI practice is to plan projects to the minimum requirements to meet project needs and assess incremental improvements on a value for money basis. MoTI acknowledged this process is not always followed on larger projects. It was also observed that the method of calculating economic development benefits is based on the capital investment; the more spent the greater the benefits. The inclusion of these benefits, if improperly considered, can mask project economics.

The Project, as shown in Table C, recognized the limitations of the economic development benefit analysis and correctly showed the Project user benefit cost analysis as well as the economic benefit analysis separately. However, it is shown that the two benefits combined to achieve a 2.1:1 benefit cost ratio.

The Review recommends, in accordance with the Provincial and Federal Guidelines that the Project be assessed initially only on user benefits, which in the case of the Project analysis resulted in a positive cost benefit ratio of 1.2:1. The Review further recommends the inclusion of the economic development benefits be confirmed for future iterations of the Project.

As explained in Section 3.3, the Review finds that travel time and vehicle operating costs estimated by the Project to be comparable to the Review's RTM3 estimate, if not conservative. The Review finds the safety and seismic benefits to be reasonable and agrees that with 10 lanes the Project has a benefit/cost ratio greater than 1.0.

[53] Transport Canada. (1994, September). Guide *to Benefit-Cost Analysis in Transport Canada* [Guide]. Retrieved from http://data.tc.gc.ca/archive/eng/corporate-services/finance-bca-122.htm

3.7 Retrofit of the Existing Tunnel

The Tunnel Expert Panel described, in detail in Section 3.8.1, stated that, in its experience, very few tunnels have been removed. In Europe, the objective is to re-use the existing infrastructure whenever possible. The Panel suggested considering the re-use of the Tunnel.

Given the above, the Review has assessed the potential for retaining the Tunnel for continued use as one component of a new Crossing.

Concerns that have been raised regarding the on-going use of the Tunnel include its:

- Seismic vulnerability;
- Limited laneway geometry;
- Aging lighting and ventilation systems; and
- Lack of access for cyclists and pedestrians.

These issues were assessed by the Project and it was concluded that the Tunnel would not become part of the new Crossing; instead it would be de-commissioned and partly removed after the construction of the new Crossing.

The Review Team met with COWI to better understand the analyses completed through the years by COWI and to hear directly from the team who prepared the design of the Tunnel structural retrofit that was completed in 2006 and who also completed the design of the Tunnel geotechnical retrofit, which was never completed.

As the new tunnel and retrofitting of the existing tunnel were not progressed to a full concept design for the Project, there was no additional geotechnical analysis completed to estimate the extent of soil liquefaction at the Tunnel since the code requirements for design seismic event changed in the National Building Code of Canada in 2010 (NBCC 2010). To provide an opinion on the feasibility of either option, the Review completed concept level analyses to estimate the potential extent of liquefaction, which was used as an input into a concept design and cost estimate for retrofitting the Tunnel.

Detailed information on the history of the investigations and analysis of the geotechnical conditions at the Tunnel site, and the reference information that was utilized by the Review, is provided in Appendix F.

3.7.1 Benchmarking

The Tunnel Expert Panel workshop and independent Review investigations identified several tunnels that have been constructed in liquefiable soils in areas of high seismicity. Selected benchmark tunnels most relevant to the retrofit and re-use of the Tunnel as one component of the new Crossing are summarized below:

- **Posey & Webster Street Tubes, Oakland/Alameda, California.** The soils around these tubes liquefied in the 1989 Loma Prieta earthquake resulting in minor damage and some water leaking slowly into the tunnel. A major seismic retrofit of the tubes was completed in 2004 and the lighting in both tubes was upgraded in 2007. The primary seismic retrofit consisted of jet grout columns and stone columns.
- **BART Transbay Tube, Oakland, California.** This tunnel survived the Loma Prieta earthquake without damage. In a subsequent retrofit, fill was compacted to reduce the risk of liquefaction. A major interior retrofit involved installing heavy steel plates at various locations inside the tube. Further seismic retrofitting is planned, consisting of a new steel liner and higher-capacity pumps.
- **Kobe City Tunnel, Japan.** This tunnel survived the M6.9 Kobe Earthquake in 1995 without damage while still under construction.
- **Maastunnel, Rotterdam, Netherlands.** A large scale structural renovation of the 75-year-old tunnel is currently underway. A fire life-safety upgrade will bring the tunnel into compliance with new Dutch tunnel regulations, including modern ventilation units installed beyond the endpoints of the main tunnel as, similar to the Tunnel, there is not enough height within the main tunnel tubes, but this location provides sufficient ventilation to meet modern design standards (see Figure X). The retrofit will also address concrete decay and will extend the service life for at least 50 years (see Figure Y).
- **Midtown Tunnel, Portsmouth, Virginia.** The Midtown Tunnel was one of three tunnels in the Portsmouth area that were rehabilitated as part of a much larger project, called the Elizabeth River Tunnels Project, that was completed in 2017 and also included the construction of a new ITT. The rehabilitation work on the Midtown Tunnel included:
  - Removal of suspended ceilings;
  - Replacing existing transverse with longitudinal ventilation;
  - Fire-life safety and lighting upgrades (see Figure Z);
  - Concrete repairs (spalls and cracks);
  - Electrical rehabilitation and upgrades; and
  - Miscellaneous signage, painting and repairs.

Figure X New mechanical systems that form part of the retrofitting of the Maastunnel currently underway[54,].

Figure Y Retrofitting of the Maastunnel currently underway[55].

[54] Mooijaart, B. (2018, May 2). Alle software van de Maastunnel succesvol getest. *Grond/Weg/Waterbouw* [Magazine]. Retrieved from http://www.gww-bouw.nl/software-maastunnel-succesvol-getest/
[55] Rdam Onderweg. (2018, June 11). *Rotterdam Onderweg - afl 34 - 11 juni Maastunnel* [Video]. Retrieved from https://www.youtube.com/watch?v=gdmGEtSGc64

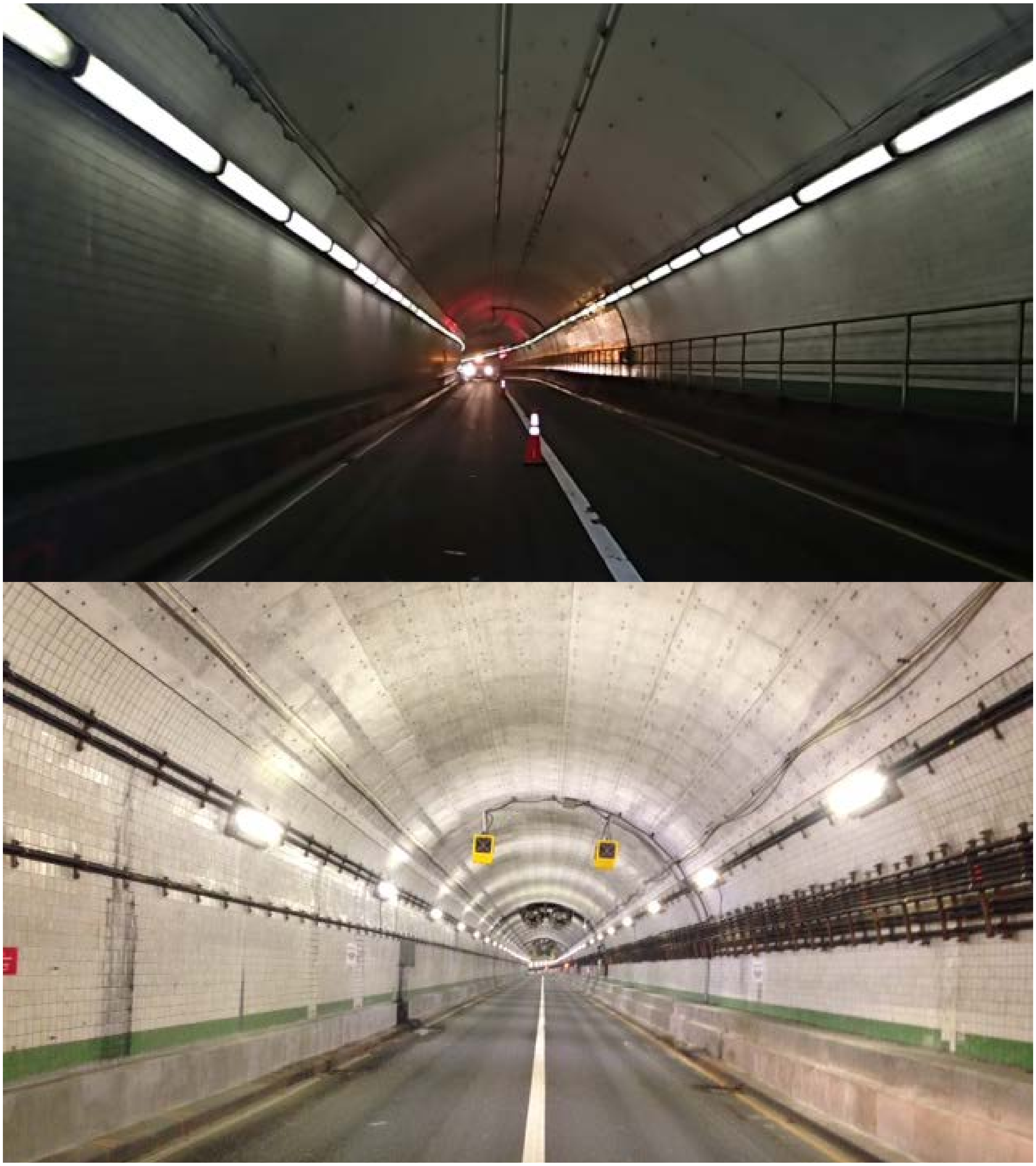

Figure Z Midtown Tunnel lighting upgrades before (above) and after (below)[56].

[56] Elizabeth River Tunnels (2015, March 5). *The Elizabeth River Tunnels Project* [Slide Presentaton].

3.7.2 Project Analysis of Options with the Existing Tunnel

The *Review of Replacement Options* report presents the overall scoring comparison of the five scenarios considered by the Project[7]. Scenarios that involved re-use of the Tunnel (Scenarios 1, 4a, 4b, and 5) all scored lower than the two options that did not include re-use of the Tunnel (Scenarios 2 and 3).

Table D presents the evaluation scores for Scenarios 2, 3, 4a and 4b with emphasis (**blue text**) on those Project Goals where the scores for a bridge or tunnel were markedly different in the categories including: improve safety, support trade and commerce, and enhance the environment.

Table D Selected results of Project Scenario evaluations[7].

Project Goal	Scenario 2 New Bridge	Scenario 3 New Tunnel	Scenario 4a GMT + New Bridge	Scenario 4b GMT + New Tunnel
Reduce congestion	5	5	5	5
Improve safety	**5**	**4**	**1**	**1**
Support trade and commerce	**5**	**3**	**2**	**2**
Support increased transit on Hwy 99	5	5	5	5
Support options for pedestrians & cyclists	5	5	5	5
Enhance the environment	**3**	**2**	**4**	**2**
Total Score	**28**	**24**	**22**	**20**
Achievement of Project Goals	**90%**	**80%**	**60%**	**60%**
Risk Profile	**Medium**	**High**	**Medium-High**	**Medium-High**
Cost ($ millions)	**$3,500**	**$4,300**	**$3,550**	**$4,050**

Review of Table D and the tables in the *Review of Replacement Options* report shows that the comparatively low scores that related to re-use of the Tunnel were based on the following:

- **Seismic concerns.** The Tunnel could not be upgraded to acceptable seismic standards;
- **Safety concerns.** The geometric constraints of the Tunnel could not be overcome and would represent ongoing safety concerns;

- **Environmental concerns.** Working in the River would have a significant impact on the River during construction;
- **Trade and Commerce.** For scoring purposes, re-use of the Tunnel pushed the new bridge or tunnel into an offset alignment with consequent impact to agricultural lands in Richmond and Delta; and
- **Construction Risks.** Working around the Tunnel is considered high risk and the need to work in the construction windows increases schedule risk.

Options analysis is challenging because identifying impacts and quantifying their respective importance is subjective. The Review understands that the above are legitimate concerns for the Project; however, based on the current state of practice for tunnel design and construction, it is considered that some of the previous scoring for Scenarios 4a and 4b may be unduly low. When re-evaluated, there is potential that the re-use of the Tunnel may be viewed as a more attractive option than was previously determined. Comments on each of the above concerns regarding the re-use of the Tunnel are presented below.

Seismic Concerns

Present day seismic design is based on a 1 in 2,475-year return period event. It is stated that the Tunnel, even after a retrofit, would not meet modern seismic standards[7]; however, the required Tunnel retrofit to achieve acceptable performance in a 2,475-year seismic event has never been formally assessed. The analysis by others to date was based on a 475-year event because that was the design earthquake at the time the work was done. Based on a high-level analysis undertaken by the Review (Section 3.7.3 and Appendix F), discussions with the COWI team that completed previous retrofit studies and upgrades, and supported by benchmarking (Section 3.7.1 and Section 3.8.1), and the Tunnel Expert Panel, retrofitting the Tunnel for life safety in a 475-year or for a 2,475-year seismic event is expected to be technically feasible; however, whether it is cost effective to undertake the retrofit must be assessed separately.

Scenario 4b did not consider that GI provided for a new tunnel constructed adjacent to the Tunnel could potentially be designed to also improve the seismic performance of the Tunnel. This idea is supported by the Tunnel Expert Panel and by the analysis completed for this Review.

Safety Concerns

The previous work only considered re-use of the Tunnel to provide four highway traffic lanes and safety scores were significantly downgraded. Although the tunnel lane geometry is less than the modern preferred design standards for new structures, it exceeds the minimum requirements for maintaining existing roadway structures. The elimination of counterflow alone will result in safety improvement.

In addition, there are several further measures that could be undertaken to improve the safety in the retrofitted Tunnel:

- Revise procedures for first responders. In other jurisdictions, first responders' standard procedure is to enter blocked tunnels in the direction opposite to traffic flow to attend to emergencies. The narrowness of the lanes and the lack of shoulders may not downgrade safety as much as previously thought.
- Provide only two wider traffic lanes with wide shoulders, i.e. one lane in each tube.
- Remove ballast concrete from the roadway floors and place equivalent ballast in the ventilation tubes to provide additional height over the traffic lanes, as suggested by the Tunnel Expert Panel. Alternatively, restrict tunnel use to lower height vehicles to eliminate safety risks due to poor vertical clearances.
- Increase visibility by means of paint, tiled walls, and/or improved lighting, which was studied by DMD & Associates Ltd. in 2013 and found to increase the light level in the tunnel by approximately 200%[21].

Environmental Concerns

The environmental impact of retrofitting the Tunnel is of short duration (construction period only) whereas many of the environmental impacts of a new bridge (noise, shading, and visual) remain in perpetuity. The impact of shading on the Deas Island Regional Park, the adjacent housing complexes, and the bridge approaches combined with the large construction footprint of a bridge, may not have been adequately considered in the comparative scoring. In addition, working in the River is required if the Tunnel is to be removed as is proposed for all scenarios where the Tunnel is not re-used.

Working in fish bearing rivers is done in an environmentally sensitive manner on many tunnel projects locally and internationally. There are appropriate mitigations available (see Section 3.8.1.4).

Every other existing River crossing required construction in the River. The proposed new Pattullo Bridge replacement is also planned to require construction in the River[57].

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[57] The Province of British Columbia. (2018, February). *Pattullo Bridge Replacement Project – Project Overview* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/331/2018/02/Project-Overview.pdf

The Review is of the opinion that the negative view of environmental impacts of retrofitting the Tunnel in the evaluation relative to other crossing alternatives is overstated and has not adequately taken into consideration that environmental mitigation and compensation measures can as a minimum offset the impacts.

Trade and Commerce

It is possible that the relative negative influence on agricultural lands, with consequent negative effect on agricultural trade and commence[7], may have been overstated. As noted in Section 3.4.2, there are significant construction cost and safety benefits that could be achieved by construction of the new Crossing off the existing alignment; which may require use of some additional agricultural land and which would require mitigation.

Construction Risks

Construction risks associated with working around the Tunnel can be managed. Many mitigations are available including separation walls, use of vibration free construction methods, and the use of a curved tunnel alignment to increase the lateral distance between a new tunnel and the Tunnel, as suggested by the Tunnel Expert Panel. Tunnels, by their nature, are frequently required to be constructed within strict timing windows and tunnel construction has been successfully completed in similar sensitive locations (Section 3.8.1.4) and often adjacent to existing structures (Section 3.8.1.7).

3.7.3 Concepts to Retrofit the Tunnel for Improved Seismic Performance

The 2009 COWI study (described in Section 2.3.2) was undertaken as a scaled comparison to earlier work. The study was based on 2D analysis only and the tunnel cross-sections selected for analysis represented the worst conditions, in terms of riverbed profile, over the length of the tunnel. The riverbed profile varies over the length of the tunnel and the worst-case profiles occur over relatively short lengths and are constantly changing due to the dynamic nature of the riverbed.

A detailed analysis of the displacements that the Tunnel can tolerate, without life safety damage and with consideration of the variation of soil characteristics and riverbed slope profiles along the tunnel length, was not done. A 3D analysis of the tunnel response to a seismic event that considers the variation of the riverbed surface along the length the tunnel has the potential to show that the Tunnel, in its current state, may provide life safety protection in a larger earthquake than previously estimated.

Previous COWI design work was based on the Tunnel being the only crossing at this location and, therefore, the use of the MoTI Seismic Retrofit Design Criteria for lifeline bridges subject to a 475-year design seismic event (the relevant design event in the early 2000s) was appropriate.

Seismic upgrade requirements are typically judged on a case by case basis, considering cost versus benefit. On the assumption that the retrofit of the existing Tunnel was to be included as a component in a new Crossing, the Province could consider accepting a lower seismic performance for the existing Tunnel than for the new part of the Crossing, which would be designed to meet the MoTI lifeline criteria. Very few crossings in the Lower Mainland meet current seismic performance criteria in a 2,475- year event. If a Tunnel retrofit is combined with a new adjacent tunnel, the foundation preparations for the new tunnel will likely inherently improve the seismic performance of the Tunnel.

For a 475-year seismic event, the Review considered multiple retrofit options: the previously designed *Part 2 - Ground Improvement Retrofit*, the recommendations put forward by the 2007 VE team, and an independently developed concept. Details on these previous studies and the independently developed concept are provided in Appendix F.

The Review found that there is a potential that the *Part 2 - Ground Improvement Retrofit* may not be adequate based on current state of practice and would have to be supplemented with additional measures to provide the desired stability in the 1 in 475 year RP seismic event. The VE Study recommendations have merit and should be analysed in detail as part of any future retrofitting program.

Retrofitting the Tunnel for acceptable performance in a 475-year seismic event is technically feasible based on analysis by the Review Team, which is supported by benchmarking and discussion with international experts.

Based on the concept independently developed by the Review, discussions with the COWI team that completed previous retrofit studies and upgrades, which is supported by benchmarking (Section 3.7.1) and by the Tunnel Expert Panel, retrofitting the Tunnel for acceptable performance in a 475-year seismic event is expected to be technically feasible. A similar concept to the above to provide life safety protection in a 2,475-year event may also be feasible using longer piles and deeper GI over an increased width.

3.7.4 Review Findings

The Review, within the limitation of the work described above, believes that structurally retrofitting of the Tunnel is technically feasible, which creates the opportunity to incorporate it as one component of a new Crossing and recommends that it be examined in greater detail. Whether the Tunnel would provide four lanes of capacity or two lanes will depend upon the acceptability of the existing narrow lane widths.

The estimated order of magnitude costs to retrofit the tunnel to an improved seismic standard (1 in 475 year event or 1 in 2475 year event) will be in the range of $250 million to $300 million, not including the potential synergies that would be achieved with a new tunnel Crossing.

A more comprehensive geotechnical and structural analysis is necessary to confirm these findings.

The decision to retain or dispose of the Tunnel needs to consider the following additional factors:

- The costs to remove and dispose of the asset; which were notionally estimated by the Project to be approximately $50 million depending upon the extent of demolition;
- The environmental impacts associated with its removal combined with the impacts already expended by the original construction;
- The risks related to the removal process; and
- The inherent value of the asset if constructed today recognizing that it is feasible to extend the service life substantially.

3.8 New Tunnel Crossing

As was noted in Section 2.5, the recommendation that a new tunnel Crossing be constructed to supplement the capacity of the existing Tunnel was made repeatedly over several years prior to 2012 when full replacement of the existing tunnel was announced by the Province. Since 1959 when the existing tunnel was opened as one of the first concrete ITTs in the world, tunneling technology has significantly advanced and is being used in a variety of environmentally and technically challenging locations.

To assess the feasibility of a new tunnel crossing in the context of the constraints of the Crossing location, the Review completed benchmarking of similar ITT projects globally and convened a Tunnel Expert Panel to discuss the relevancy and applicability of those projects, and other projects that the Panel had been involved in. The full report on the benchmarking and Tunnel Expert Panel discussion prepared by BGC Engineering Inc. is provided in Appendix C.

The Review, jointly with the Tunnel Expert Panel, identified eight key criteria and considerations that would likely determine the feasibility and practicality of a new ITT for the new Crossing:

1. Strong ground motion from the design seismic event.
2. Seismically induced liquefaction of deep foundation alluvium, which was separated out from strong ground motion because some locations included in the benchmarking review had strong ground motion but were not situated in liquefiable soils.
3. Strong channel current during construction that would affect the ability to place tunnel segments.
4. Environmental sensitivity of dredging and in-water work.
5. Short in-water construction windows.
6. Requirements for deep sea vessel navigation and channel access during construction.
7. Proximity of new construction to existing structures.
8. Required tunnel width (lanes).

Several of these criteria were identified during the Project options analysis as reasons why a new bridge is preferable over a new tunnel.

Two options for a new tunnel have been considered in this review: ITT and bored tunnel. A discussion on the applicability of each tunnel type is outlined in Section 3.8.2. There have been several recently completed and currently ongoing bored tunnelling projects in Metro Vancouver to replace aging water conveyance and outfall structures. These new tunnels are all designed as critical infrastructure projects that comply with current code requirements for seismic design similar to what a road tunnel would be required to comply with.

3.8.1 Tunnel Expert Panel Review

The Tunnel Expert Panel was convened to review:

- The Project requirements;
- Experience with ITTs as a particular means of tunnel construction; and
- The relevance of past experience with respect to the primary challenges and requirements of the Project.

The panelists were chosen to represent experience on the Pacific Coast of North America as well as global experience. They were identified to be independent from past work related to the Tunnel and its potential replacement. The North American experts brought valuable experience with North American contracting means and methods, local site conditions and construction, and bored tunnel alternatives, whereas experts from the United Kingdom and Netherlands brought global experience and perspective. The Panel members were:

- **Mr. Jonathan Baber, CEng.** Project Director. Metros & Civil, Account Leader International Metros/Highway Tunnels, Mott MacDonald; United Kingdom. Jonathan is recognised as a world expert in the field of immersed tube tunnels, a field in which he has worked for over 25 years. Jonathan is currently the Animateur of the International Tunnelling and Underground Space Association (ITA) Working Group 11 (WG11) for immersed and submerged floating tunnels.
- **Mr. Hans de Wit, M.Sc.** Managing Director Tunnel Engineering Consultants (TEC)/Leading Professional Tunnels, Royal HaskoningDHV; Member of International Tunnel Association Working Group 11: Immersed and Floating Tunnels Netherlands. Hans has worked in many national and international immersed tunnel projects as a Senior Designer, Design Leader and Consultant and is also a lecturer in Immersed Tunnels at the Delft University of Technology and for the ITA.
- **Mr. Bob Bittner, PE.** President, Bittner-Shen Consulting Engineers, Inc.; USA. Bob is a professional engineer with 49 years of experience in construction engineering and project management on major marine construction projects world wide. Bob was the President of the Deep Foundation Institute from 2013 to 2014 and Chair of the Marine Foundation Committee of the Deep Foundation Institute from 2003 to 2008.
- **Mr. Doug Grimes, P.Geo., PMP.** Lead Associate, McMillen Jacobs Associates; Canada. Doug has a master's degree in geological sciences with over 25 years of experience in technical roles, including several bored tunneling projects in Metro Vancouver.

More than 20 ITT projects were considered as part of the workshop. A primary resource used to obtain data on the ITT projects was a publication by ITA-WG11, a working group dedicated to immersed and floating tunnels.[58] These projects will be discussed in this section to support the opinions of the Tunnel Expert Panel in relation to the eight key criteria identified in Section 3.8.

[58] International Tunnelling and Underground Space Association. (2018). *Working Group 11: Immersed and Floating Tunnels Publications* [Website]. Retrieved from https://about.ita-aites.org/publications/wg-publications/content/16/working-group-11-immersedand-floating-tunnels

3.8.1.1 Strong Ground Motion During a Seismic Event

Tunnels are inherently suitable for resisting ground motion from earthquakes as these structures experience less amplification of ground motions due to being buried. Precedent ITT projects in areas with potentially strong ground motion from seismic activity include:

- **Aktio-Preveza Tunnel, Greece.** The tunnel survived a moderate earthquake located on the Ionian Sea approximately 120 km from the tunnel one year following tunnel completion.
- **Coatzacoalcos Tunnel, Veracruz, Mexico.** The tunnel survived two moderate earthquakes soon after completion in September 2017 (Central Mexico earthquake and Chiapas earthquake). Movements were recorded, but were quite small, and an inspection showed no damage. The tunnel was reopened one day later.
- **Kobe Tunnel, Japan.** The tunnel survived the Hannshin Earthquake of 1995 while under construction.
- **BART Transbay Tube, Oakland, California.** This tunnel survived the Loma Prieta earthquake without damage.
- **Posey & Webster Street Tubes, Oakland/Alameda, California.** The soils around these tubes liquefied in the 1989 Loma Prieta earthquake resulting in minor damage and some water leaking slowly into the tunnel.

It is also noted that there are approximately 25 more ITTs in Japan, all of which have been designed to withstand strong ground motion. Ground motion for ITTs is mitigated through structural design, built-in ductility through jointing at appropriate intervals (element length, typically around 100 m to 125 m), and robust sealing solutions at element joints (specifically gaskets, which are common solutions to seal and protect the immersion joints between elements).

ITTs are considered to be highly applicable to the Project with respect to strong ground motion. Drawing upon their considerable experience, the Tunnel Expert Panel was not aware of any poor performance or tunnel flooding from seismic events, and it is estimated that there are approximately 30 ITTs around the world in seismic areas.

The Tunnel Expert Panel stated that segmental tunnels are designed to withstand earthquakes up to approximately magnitude 9.2, and that monolithic tunnels (only one element, and with no intermediate joints) are designed to withstand earthquakes stronger than magnitude 9.2. ITT designers are comfortable with the solutions that exist to address the strong ground motions required to be designed for at the Crossing.

3.8.1.2 Seismically Induced Liquefaction

There are several precedent ITT projects that were constructed in areas with liquefiable soils and used GI as mitigation, including:

- **Aktio-Preveza Tunnel, Greece.** The tunnel is underlain by approximately 15 m of liquefiable soil and GI was stone columns.
- **Coatzacoalcos Tunnel, Veracruz, Mexico.** GI consisted of removing and replacing a few meters of liquefiable soil.
- **Marmaray Tunnel, Istanbul, Turkey.** GI was compaction grouting for this tunnel, which has a tunnel bottom located approximately 70 m below the water surface and is underlain by 15 m of liquefiable soil.
- **Posey & Webster Street Tubes, Oakland/Alameda, California.** GI consisted of a combination of jet grout columns and pipe pile stone columns on both sides of the tunnel.
- **Shenzhen-Zhongshan Crossing, China.** GI for the tunnel, which is under construction, is a dense grid of sand compaction piles.

Similar to the review of strong ground motion, it was noted that several of the approximately 25 ITTs built in Japan have been designed to address soil liquefaction.

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- GI can be done to approximately 30 m depth below ground surface with routine methods.
- GI using stone columns has a high to medium applicability for the Crossing. There are a variety of techniques for the installation of stone columns that can be considered when the level ground modification required is fully understood.
- GI using compaction grouting had a medium applicability. Compaction grouting is appropriate for deeper soil layers but not the soil layer close to the surface due to potential heaving of the adjacent existing Tunnel.
- Soil sub-excavation and replacement had a low applicability due to the required depth of the liquefiable zone. and proximity to the existing Tunnel.
- A tie down anchoring system, commonly used for offshore platforms, may be applicable for resisting tunnel upward heave during liquefaction in the absence of other mitigation techniques.
- Cut-off walls constructed on either side of the tunnel to contain soil movement during liquefaction are a potential solution to reduce the effects of liquefaction. Such a wall could have a dual purpose on the side of the new tunnel adjacent to the existing Tunnel to limit the footprint of the new construction.

3.8.1.3 Strong Channel Current

Precedent ITT projects installed in waterways with a strong current include:

- **Marmaray Tunnel, Istanbul, Turkey.** The tunnel crosses the Bosporus Strait that has a strong discharge current.
- **Oosterweel Tunnel, Antwerp, Belgium.** The tunnel crosses the River Schelt, which has tidal currents and river discharge.
- **Coatzacoalcos Tunnel, Mexico.** The tunnel crosses the River Coatzacoalcos, which has tidal and river discharge currents (see Figure AA).
- **Limerick Tunnel, Ireland.** The tunnel crosses the River Shannon, which has tidal and river currents.
- **Kennedytunnel, Belgium.** The tunnel crosses the River Scheldt, which has up to 3 m/s tidal and river currents. Tunnel immersion was done near neap tide at 1.5 m/s.

Figure AA Coatzacoalcos Tunnel in Mexico being placed in the River Coatzacoalcos[59].

[59] World Highways. (2015, April). *Mexico: underwater tunnel in Latin America* [Article]. Retrieved from http://www.worldhighways.com/categories/road-highway-structures/features/mexico-underwater-tunnel-in-latin-america/

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- ITTs have a high applicability for installation in river currents similar to, and greater than, those at the Crossing.
- ITTs have been installed in river and marine environments with currents stronger than those experienced at the Crossing (approximately 2 m/s).
- ITT installation methods in current employ robust upstream and downstream anchoring systems for the installation equipment and tunnel elements.
- Lowering tunnel elements parallel to current direction and then turning the element near the bottom of the lift has been used to overcome flows 3 m/s or greater. This technique is not likely applicable at the Crossing. A specialist subcontractor experienced in lowering ITTs would be required for that part of the work.
- The length and depth of tunnel elements would need to consider the effect of current during installation. Given that currents in the River are not that fast, it is expected that the geometry of the Crossing will dictate the element length. Tunnel section lengths of approximately 100 m to 150 m are common and appear reasonable at the Crossing.

3.8.1.4 Environmental Sensitivity of Dredging and In-Water Work

Precedent ITT projects installed in areas with environmental sensitivity issues include:

- **Marmaray Tunnel, Turkey.** The tunnel is located along a significant fish migration route.
- **New Tyne Tunnel, Newcastle, UK.** Dredging restrictions were implemented during construction to avoid interference with fish migration.
- **Limerick Tunnel, Ireland.** The tunnel is located in a pristine estuary with no dredging windows permitted during fish migration periods (see Figure BB).
- **Bjorvika Tunnel, Oslo, Norway.** Tunnel construction was completed around blockages of the river during fish migrations. Construction techniques were used to contain contaminated bed sediments during dredging.
- **Marieholm Tunnel, Gothenburg, Sweden.** Now under construction, this tunnel must work around periods with no dredging and immersion during fish migration seasons.

Figure BB Limerick Tunnel located under the River Shannon near Limerick, Ireland[60].

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- ITTs have a high applicability in environmentally sensitive areas such as the Crossing.
- Environmental habitat concerns and mitigation measures are typical of ITT projects.
- Common issues include fish spawning, shell fish and bird habitats with construction windows for fish movement, restrictions on dredging, and adjustments to methods to reduce siltation.
- No projects were identified where an ITT option was discounted because environmental impacts could not be mitigated to meet regulatory requirements.
- While fish tend to avoid disturbances, monitoring fish movements during construction combined with specific mitigation measures during the trench excavation and tunnel installation are common. Side scan sonar to monitor fish movement, and bubble curtains to keep fish away are suitable mitigation techniques.

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[60] Strukton Immersion Projects. (2018). *Limerick Tunnel* [Website]. Retrieved from http://www.struktonimmersionprojects.com/projects/limerick-tunnel---ireland/

- Silt curtains would likely not be applicable due to the reversing tidal currents.
- Suction dredging is a favourable method for trench excavation as the effluent can be managed to not create turbidity. The River navigation channel is maintained annually using suction dredging equipment.
- Excavation with a closed clamshell dredge is also a potentially suitable trench excavation method to limit sediment spill and are often used in sensitive areas.
- Resource information on this topic can be found in ITA-WG11 Immersed Tunnels in the Natural Environment[57].

3.8.1.5 Short In-Water Construction Windows

Precedent ITT projects installed in areas with construction window constraints include:

- **Marmaray Tunnel, Turkey.** One tunnel element was immersed per month.
- **Bjorvika Tunnel, Oslo, Norway.** No work could occur in the water from July to November. The tunnel elements were immersed every four weeks.
- **New Tyne Tunnel, UK.** Dredging was only permitted from November to February. One tunnel element was immersed every two weeks at neap tide.
- **Piet Hein Tunnel, Amsterdam, The Netherlands.** One tunnel element was immersed every one to two weeks.
- **Oresund Link, Denmark.** One tunnel element was immersed per month.
- **Coatzacoalcos Tunnel, Mexico.** Tunnel elements were only placed during the dry season at a rate of one tunnel element every two weeks.

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- An ITT would have high applicability with respect to conforming to available construction windows.
- The time required for ITT element placement normally ranges between one per week and one per month.
- ITT placement should be completed by a specialist contractor familiar with the appropriate techniques.
- Fabrication of tunnel elements does not require unusual skills and can be completed by experience by local contractors.
- Limiting the tunnel element length to approximately 100 m would be appropriate for the Crossing. That element length is more manageable and will mitigate schedule risk.

- Element construction in the pre-excavation for the tunnel approach way was used for the Limerick Tunnel (see Figure CC) and could have applicability for the Crossing.
- Tunnel elements can be constructed remotely and towed or shipped to the staging area if a suitable fabrication facility cannot be found close to the Crossing. Some projects have successfully towed elements hundreds of kilometres from the fabrication drydock location to the tunnel site. For example, the Bjorvika Tunnel contractor towed elements 600 km through the North Sea off the coast of Norway.
- Approximately three to four years would be required for the ITT construction including, design, site preparation, ground improvement, element casting, tunnel finishing works (including tunnel systems and installations) and instream works. Development of a tunnel element fabrication facility would take about one year, while design is being done.
- Given the conditions and the length of the Crossing, a single tunnel could likely be placed within one construction season, during the current winter construction window at the Crossing. It was noted that the original Tunnel was placed within a five-month period.

Figure CC Tunnel elements being fabricated in approach to ITT crossing[61].

[61] International Tunnelling and Underground Space Association. (2018). *Limerick Tunnel* [Website]. Retrieved from https://cases.ita-aites.org/search-the-database/project/157-limerick-tunnel

3.8.1.6 Deep Sea Vessel Navigation and Channel Access During Construction

Precedent ITT projects installed across busy navigable channels include:

- **Wijkertunnel, The Netherlands.** The tunnel is located at Amsterdam Port's entrance.
- **Elizabeth River Tunnels, Norfolk, USA.** The US Navy had access requirements during construction, which included rapid construction demobilization.
- **Hong Kong Zhuhai Macao Link, China.** The tunnel is located in a busy access channel to the port of Hong Kong and Guangzhou. The project could not block the navigation channel and was restricted to a 400 x 400 m^2 working zone during tunnel element immersion (see Figure DD).
- **BART, San Francisco.** The tunnel is located near the ports of Oakland and Alameda.
- **Blankenburg Tunnel, Rotterdam, The Netherlands.** The tunnel is located along the main access route to the Port of Rotterdam and ships passed by the site during construction while immersed tunnel elements were on temporary supports.
- **Caland Tunnel, Rotterdam, The Netherlands.** The tunnel is located on a busy, narrow (240 m wide) waterway in the Port of Rotterdam.
- **Oosterweel Tunnel, Antwerp, Belgium.** Ships passed by the site during construction while immersed tunnel elements were on temporary supports.
- **Coatzacoalcos Tunnel, Mexico.** Ships were permitted to pass over the tunnel elements immediately after immersion.

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- ITTs have high applicability for installation within navigable channels.
- The floating construction plant for an ITT project typical occupy approximately 50 m of a crossing at any time. Anchorages can require an additional 50 m. Additional channel width is required during the placement of tunnel elements.
- If there is insufficient width within the crossing area for the use of conventional ship style anchors, specialized fixed point anchoring platforms may be required; an approach which is more expensive but may be needed for a new ITT at the Crossing.

Figure DD Tunnel element being placed in a busy navigable channel for the Hong Kong Zhuhai Macao Link in China[62].

- Site preparation work frequently occurs within navigable channels while ship traffic is passing. Contractors will select appropriate equipment to facilitate being able to move out of the navigable channel as required to provide clearance for large vessels. For the New Midtown Tunnel that is part of the Elizabeth River Tunnels project, the equipment used to place the immersed tube tunnel elements was required to demobilize in a few hours with minimal notice if US Navy vessels were required to exit the area in an emergency.
- During tunnel element placement, shipping channels have often been shut down, or have posted lower required speeds, at least for large vessels. This restriction or closure might be for two or three days, normally a weekend planned well in advance. Transport Canada has a well-established system for instream works within navigable waters and planning well in advance with Transport Canada would be important. Advanced planning with shipping authorities is standard practice on ITT projects.

[62] Hong Kong-Zhuhai-Macao Bridge. (2016, October 24). *Element No.33(E33) has connected to the East island* [Website]. Retrieved from http://en.cccchzmb.com/P28-6466.biz

3.8.1.7 Proximity of New Construction to Existing Structures

The panel was aware of several ITTs that have been constructed adjacent to existing structures, including (see Figure EE):

- **Elizabeth River Tunnels, Norfolk, USA.** The tunnel has a curvilinear horizontal alignment to provide separation with an existing, adjacent ITT.
- **Second Coen Tunnel, Amsterdam, The Netherlands.** The tunnel was constructed adjacent to an existing ITT.
- **Second Benelux Tunnel, Rotterdam, The Netherlands.** The tunnel was constructed adjacent to an existing ITT.
- **BART, San Francisco.** The tunnel passes below the San Francisco to Oakland Bay Bridge, approximately 80 m from one of the bridge foundations.
- **New Tyne Tunnel, Newcastle, UK.** The tunnel was constructed beside an existing bored tunnel.
- **Hampton Road Expansion, Virginia, Chesapeake Bay Area.** The tunnel is planned to be constructed beside an existing ITT.
- **Shatin-Centre Metro Link Hong Kong.** The cross harbor section of the tunnel was constructed adjacent to the existing Western Harbor Crossing ITT.

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- ITTs have a high applicability for construction next to existing structures.
- Mitigation measures include:
    - Alignment adjustments, such as a horizontal curve (Elizabeth River Tunnels),
    - Cut off walls (Second Coen Tunnel), and
    - Adjusting the alignment such that dredging a trench for a new ITT does not intersect adjacent tunnel protective structures (Second Benelux Tunnel).
- ITTs have routinely been constructed next to existing structures, such as the bottom of a new ITT tunnel being constructed within 1.5 m of a 100-year-old transit tube (Boston Central Artery Tunnel), and the Second Coen Tunnel (Netherlands) was constructed 13 m from the first Coen Tunnel.

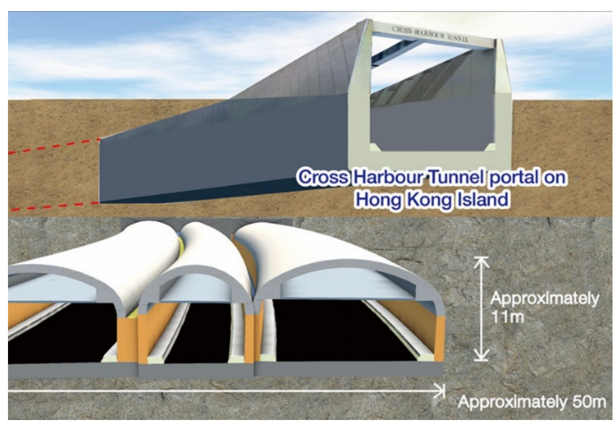
(a) Elizabeth River Tunnels, Norfolk, USA

(b) Second Coen Tunnel, Amsterdam, The Netherlands

(c) Second Benelux Tunnel, Rotterdam

(d) New Tyne Tunnel, Newcastle, UK

(e) Hampton Road Expansion, Virginia, Chesapeake Bay Area



(f) Shatin-Centre Metro Link Hong Kong

Figure EE Various examples of immersed tube tunnels constructed adjacent to existing tunnels.

- Tunnel approaches may require sheet piles to contain excavations.
- Press-in sheet piles (separation walls) could be considered to isolate a new ITT from the Tunnel.
- Sonic methods for installing pipe piles for the soil replacement stone column ground improvement technique would reduce vibration and mitigate settlement below the Tunnel.
- A horizontal curve is the most practical solution to separate a new tunnel from the Tunnel.

3.8.1.8 Wide Tunnels with Multiple Lanes

The Tunnel Expert Panel discussed five examples of tunnels that are approximately 50 m wide and support eight lanes of traffic with one project that is moving to construction that has a width of 60 m and supports 12 lanes, as indicated below:

- **Hong Kong Zhuhai Macao Link, China.** This tunnel is nearly completed construction and, at its widest section, will have 12 lanes and a width of over 60 m width. The standard section will have eight lanes and will be over 50 m wide)(see Figure FF, Figure GG, and Figure HH).
- **Drecht Tunnel, Dordrecht, The Netherlands.** This tunnel is 50 m wide with eight lanes.
- **Second Benelux Tunnel, Rotterdam, The Netherlands.** This tunnel is 45 m wide with tubes for vehicles, LRT, and pedestrians and cyclists.
- **Kennedytunnel under the river Schelt, Antwerp, Belgium.** This tunnel is 48 m wide with tubes for vehicles, LRT, and pedestrians and cyclists.
- **Bjorvika Tunnel, Oslo, Norway.** This tunnel has six lanes and is 45 m wide.

On basis of their personal experience and the benchmarked projects, the Tunnel Expert Panel made the following observations and recommendations:

- The applicability of ITTs is high for single tunnel widths up to 50 m, sufficient for eight lanes of traffic and utility spaces.
- ITTs wider than 50 m require supplemental design provisions and structure to provide sufficient torsional stiffness during transportation.
- Wider elements will require larger equipment, and larger construction and staging areas, and may require internal walls for stiffness or support.
- The tunnel for the Hong Kong Zhuhai Macao Link project will be 60 m wide, setting a new precedent for single elements.

Figure FF Tunnel element being fabricated for the Hong Kong Zhuhai Macao Link in China[63].

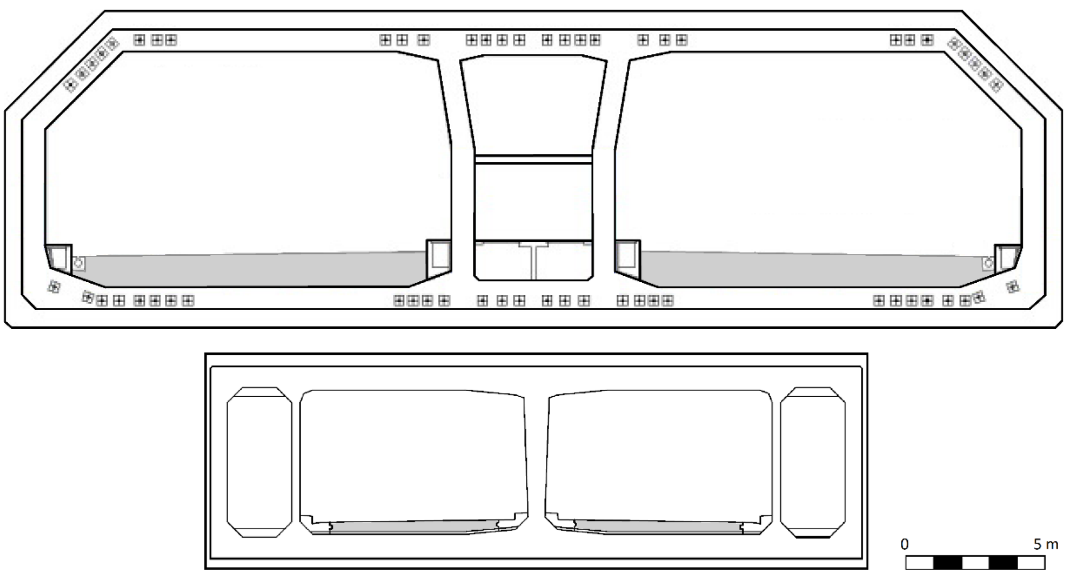


Figure GG Comparison of the size of the Hong Kong Zhuhai Macao Link tunnel (above) to the Tunnel (below).

[63] Li, K., Li, Q., Wang, P., Fan, Z. (2015, August). Durability assessment of concrete immersed tube tunnel in Hong Kong-Zhuhai-Macau sea link project. *27th Biennial National Conference of the Concrete Institute of Australia*. Retrieved from https://www.researchgate.net/publication/274084563_Durability_assessment_of_concrete_immersed_tube_tunnel_in_Hong_Kong-Zhuhai-Macau_sea_link_project

Figure HH View inside a completed tunnel tube with three driving lanes and a shoulder for the Hong Kong Zhuhai Macao Link in China[64].

3.8.1.9 Other Topics Reviewed Panel

Upon concluding the discussion of key criteria with the Tunnel Expert Panel, other topics deemed important to the project were briefly discussed and are summarized in this section.

Bored Tunnel Option

The panel considered the construction a bored tunnel as an alternative to a new tunnel or a bridge. This topic is further discussed in Section 3.8.2.2.

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[64] The Government of the Hong Kong Special Administrative Region. (2018, January 20). *Latest situation of Hong Kong-Zhuhai-Macao Bridge Hong Kong Link Road* [Press release]. Retrieved from https://www.info.gov.hk/gia/general/201801/20/P2018011901035.htm

Conceptually, two 17 m diameter bored tunnels, with two lanes stacked per tunnel (eight lanes total), constructed approximately 30 m below grade beneath the River, a depth assumed to be below zones of liquefaction would be required. The increased depth combined with maintaining the 5% specified grade results in a significantly greater length of tunnel than for an ITT. Another technical issue is constructing the boring entrance and exit portals in large excavations adjacent to the highway.

Operation and Maintenance of a New ITT

An ITT would have operation costs of on-going pumping, lighting (which is now low power LED) and ventilation. The panel concluded that, based on their experience, the operating costs of an ITT would not be more than a bridge. An ITT would be about 1.2 km shorter than a bridge, and there are normally only small amounts of pumping required during rain events, but relatively minimal pumping requirements otherwise.

Retrofitting of George Massey Tunnel

The Tunnel Expert Panel noted that the Maastunnel in Rotterdam, an ITT older than the Tunnel, is still in service and stated that retrofitting the existing Tunnel should be considered. It was understood by the panel that one of the issues is the current height of the roadway tubes within the Tunnel. The panel suggested that ballast material under the roadway could be moved into the maintenance tubes at the sides to provide more roadway height or provide modern ventilation units within the roadway tubes.

Cost Considerations

No cost estimates were prepared or evaluated as part of the Tunnel Expert Panel workshop. The experience of the Panel is that a cost of 750 to 1,500 Euros (approximately $1,100 to $2,300 Canadian) per cubic meter of tunnel is typically used at the earliest stages of feasibility evaluation.

3.8.1.10 Expert Panel Findings

Eight key considerations and criteria were identified as most important to evaluate the suitability of a new ITT crossing at the Crossing. Though no single past or current project served as a benchmark for all eight key considerations, there were between six and 13 existing benchmark projects discussed for each. The Panel believes even more projects could be identified.

The Tunnel Expert Panel's opinion was that the conditions of the Project site and the needs of the Project are similar to those that have been addressed within successful past design and construction experience with ITTs. Based on the Panel's opinion, it is recommended that a more thorough exploration of an ITT Crossing be considered. Additionally, the possible suitability of a bored tunnel (or two) was discussed, and this idea appears warranted, though Section 3.8.2.2 suggests that, when compared to an ITT, the benefit may be in terms of other criteria, rather than cost.

The Tunnel Expert Panel's opinion was that the conditions of the Project site and the needs of the Project are similar to those that have been addressed within successful past design and construction experience with immersed tube tunnels.

3.8.2 New Tunnel

There were several Project Goals provided in the *Review of Replacement Options* report that indicated that a tunnel would not provide the same benefits as a bridge. The following sections discuss these project goals as they relate to both an immersed tube tunnel option and a bored tunnel.

3.8.2.1 Immersed Tube Tunnel

The Review's review of the global state-of-the art of ITT construction discussed above has provided sufficient supportive expert opinion and industry data to demonstrate that an ITT would be a reasonable solution for an expanded Crossing. A new tunnel could fully replace the existing Tunnel or be added to increase existing capacity. The feasibility of upgrading the existing Tunnel has been discussed previously in section 3.7. This section assesses the extent to which an ITT achieves the stated Project Goals.

The Project Goals identified in the *Review of Replacement Options* report will be discussed sequentially.

Reduce Congestion

The Review agrees with the Project that a new tunnel will provide the same level of congestion reduction as a new bridge following project completion.

During construction it is expected that a new tunnel will cause fewer traffic delays. The length of the new tunnel would be slightly greater than the Tunnel and installed on an alignment adjacent to the existing highway. While some adjustment to the existing highway adjacent to the new tunnel portals would occur, for the most part the highway will continue to function without being impacted by construction activities. The bridge is significantly longer with approaches that extend from Steveston Highway to Highway 17A; and that were planned to be constructed over the existing highway. It is expected that this would require significant traffic management and construction zone slowing resulting in additional congestion during the construction period.

Improve Safety

The Project assessed that a new tunnel will have reduced safety in comparison to a bridge. There is no evidence that a new tunnel designed to modern standards will have a decreased level of safety in comparison to a new bridge. A new tunnel will have sophisticated ventilation systems to efficiently remove smoke from fires, will have sprinkler systems to counteract fires before emergency responders can arrive on the scene, and will have separated corridors to allow drivers to escape and first responders to gain access with a barrier between them and the danger.

There is no evidence that a new tunnel designed to modern standards will have a decreased level of safety in comparison to a new bridge.

Support Trade and Commerce

The Project assessed that the alignment of a new tunnel will significantly impact agricultural lands in Richmond and Delta, reducing overall farm production. Recently completed ITT projects around the globe have demonstrated that new tunnels can be constructed beside existing tunnels with curvilinear alignments in the horizontal direction to provide reasonable separation between tunnels in the water crossing and will have exit locations that are close to the existing highway minimizing the impacts on agricultural land. (see Figure II for an example plan arrangement and Figure EE showing close proximity of tunnel end points adjacent to existing tunnels).

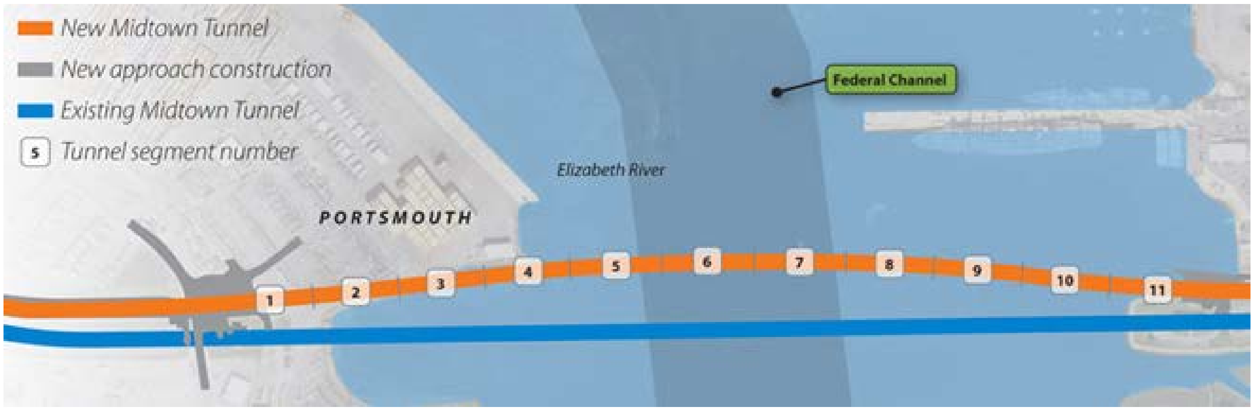

Figure II Example curvilinear ITT horizontal layout to minimize upland land impacts at the Elizabeth River Tunnels – Second Midtown Tunnel Project[65].

Support Transit on Highway 99

Dedicated transit lanes could be provided through a new tunnel, with integrated connections to transit stops at the Steveston and Highway 17A interchanges. In addition, a tunnel cross section with multiple tubes would allow for flexibility to change lane uses (SOV, HOV, transit only, LRT) or allow for counterflow during peak periods to reduce the total number of lanes required for a new crossing to meet current and future forecasted demands.

Support Options for Pedestrians and Cyclists

The Project stated that the travel experience for pedestrians and cyclists would be inferior in a tunnel to that of a bridge. Any loss of views that would occur by having a tunnel rather than a bridge for pedestrians and cyclists to enjoy is offset by the elevation change being substantially less for a tunnel compared with a bridge and that a tunnel protects pedestrians and cyclists from rain and snow. And for cyclists, a tunnel will require less energy to cross as momentum will be built up on the downhill portion to carry into the uphill portion; and the overall Crossing length is significantly shorter.

[65] Kenyon, P. (2014, December 2). Sinking the concrete elements at Midtown. *Tunnel Talk* [Article]. Retrieved from https://www.tunneltalk.com/Midtown-Tunnel-02Dec2014-Sinking-the-first-elements-for-the-Norfolk-Portsmouth-immersed-tube-tunnel.php

Enhance the Environment

The Project stated that construction of a new tunnel would have a significant impact on the Fraser River and Deas Island Regional Park for several years during construction and several seasons in the river. There does not appear to be any environmental or public space advantages to a bridge in comparison to a tunnel.

Metro Vancouver, the government entity responsible for Deas Island Park, has expressed concern that the Bridge will have a negative environmental impact due to shading.

The shorelines on either side of the main channel that would be impacted and restored by tunnel construction are currently engineered riprap that were constructed at the same time as the existing tunnel and offer minimal marine habitat. These shorelines could be restored with improved structures that have marine habitat features incorporated into them.

The dredging and rock placement required for placing the tunnel elements in the River would cause similar impacts to what was proposed for the removal of the existing tunnel following completion of a new bridge.

> The shorelines on either side of the main River channel that would be impacted by tunnel construction offer minimal marine habitat. These shorelines could be restored to have marine habitat features incorporated into them.

Risk Profile

The Project stated that experience is limited in the Lower Mainland to be able to construct an ITT. The contractors based in the Lower Mainland have significant experience constructing large concrete floats (original Okanagan Lake Floating Bridge, replacement William R. Bennett bridge, multiple BC Ferries terminals, Nanaimo Cruise Ship Terminal) and large concrete caissons (Deltaport, Centerm, Fairview Terminals, Lynnterm), which are similar to large tunnel elements. The Tunnel expert Panel stated that tunnel construction could be completed with primarily local skills and resources. Only the tunnel placement will require international expertise.

The Project stated that there is a unmitigable risk to the integrity of the existing Tunnel as a result of excavation for a new tunnel or that there is an unmitigable risk to the integrity of the new tunnel during decommissioning of the existing Tunnel. There are multiple methods to mitigate potential loss of integrity to the existing Tunnel, or new tunnel during construction and multiple international examples of new tunnels being constructed adjacent to existing tunnels, as noted in Section 3.8.1.7.

The Project assessed that construction windows and navigation requirements in the River could cause a prolonged construction schedule for a new tunnel over several years. The production rate of recently completed ITT projects globally under similar environmental, navigation, river current, and seismic design constraints demonstrates that it is feasible to construct an ITT in the same schedule as a bridge.

There are multiple options available for a casting location for the tunnel elements, including but not limited to: a nearby location along the River that could be restored with increased marine habitat features following use; in the approaches to the new tunnel (see Figure CC), and at multiple drydocks within a 600 km radius of the site, which is the international precedent for tunnel element towing distance. The drydock in Aberdeen, WA that was built for the fabrication of the floating pontoons for the SR 520 floating bridge replacement project near Seattle is currently owned by the State of Washington and sitting idle.

A new immersed tube tunnel is cost competitive with a bridge and could provide additional cost savings if it was combined with retrofitting the existing Tunnel.

Cost

The Project estimated that the cost of a new ITT would be greater than a new bridge. Based upon the information provided during the above described Tunnel Expert Panel workshop, the cost of an ITT is expected to be competitive with a bridge. Further, there are potential additional cost savings opportunities if a new tunnel was combined with retrofitting the existing Tunnel.

3.8.2.2 Bored Tunnel

The Review requested McMillen Jacobs Associates, who participated in the Tunnel Expert Panel, to review the feasibility of a bored tunnel concept as an option for a new Crossing. The complete findings are appended to the Tunnel Expert Panel Report in Appendix C.

Similar to ITTs, there are many international precedents for bored tunnels with both ITTs and bored tunnels included in options analyses for new crossings.

The conclusion reached by the Review is that the bored tunnel option is more costly than a bridge or an ITT with the same capacity but that it has the least environmental impacts of any option. Further, it was determined that a bored tunnel option may not be feasible for the Project because of the geometry of the bored tunnel.

With acceptable traffic grades to get under the liquefiable soils in the River, the tunnel end points are too close to the existing interchanges for safe traffic flow unless substantial excavation is completed. This issue is exacerbated when the traffic is in two levels within the tunnel and must also transition back to the same plane approaching the interchanges. As can be seen in Figure JJ that compares the generalized vertical alignments of bridges, ITTs, and bored tunnels, a bored tunnel would typically be as long as a bridge but also requires additional distance if the roadway is stacked in two levels.

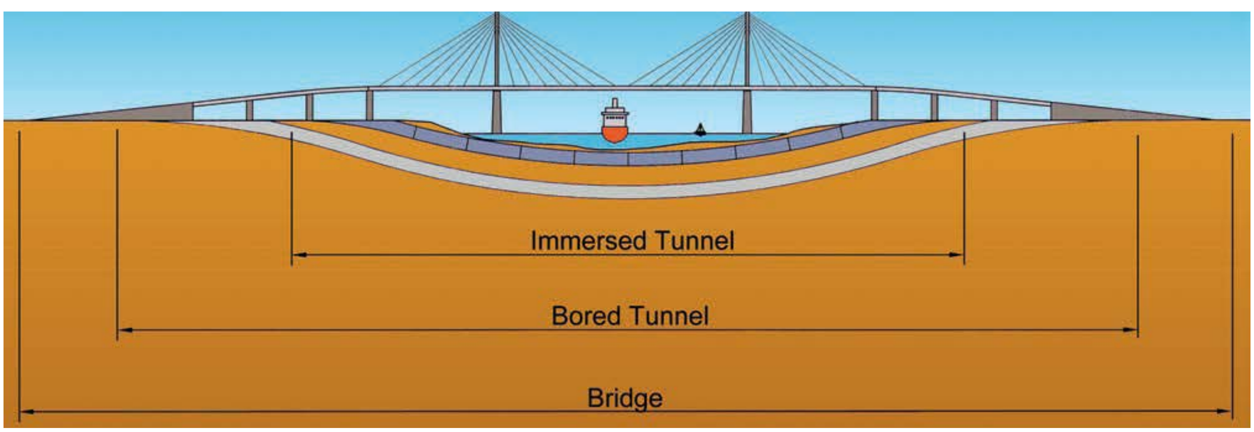

Figure JJ Comparison of typical vertical alignments of bridges, ITTs, and bored tunnels[66].

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[66] De Wit, J.C.W.M., Van Putten, E. (2012, April 12) Immersed Tunnels: Competitive tunnel technique for long (sea) crossings. Under City 2012 Dubrovnik [Conference Proceedings]. Retrieved from http://tec-tunnel.com/wp-content/uploads/2012/11/UC2012-paper-immersed-tunnel-De-Wit.PDF.pdf

A bored tunnel option would provide the least environmental impacts of any of the available options for replacement of the Crossing as it would bypass Deas Island completely and would have no visual impacts.

3.8.3 Review Findings

An ITT crossing option is feasible and may result in increased benefits and cost savings in comparison to a new bridge when such options as staged development and utilizing existing infrastructure initially is considered. There are several international precedents where ITTs have been selected over other options and successfully constructed in similar conditions including environment, seismic conditions, and proximity of adjacent structures.

The Review recommends that a feasibility design study be completed with the support of recognized international experts in ITT design and construction. The feasibility design studies for both the existing tunnel and the new tunnel should be completed together to further assess the benefits of utilizing the existing tunnel; i.e. a new six lane tunnel with a retrofitted existing tunnel with safety improvements.

3.9 Stakeholders and the Environment

The following sections discusses concerns regional stakeholders had regarding the Project and its impact on local communities and the environment.

3.9.1 Project Engagement

The Project completed a phased public and external consultation program to support Project planning and development. This included:

- **Phase 1.** Understanding the Need (November to December 2012) – Focused on understanding the need and potential constraints to develop the Project scope and design requirements.
- **Phase 2.** Exploring the Options (March to April 2013) – Based on Phase 1 consultation results and preliminary technical work, Phase 2 sought input on the draft Project scope and Goals, five potential replacement scenarios and on the criteria to evaluate these options.
- **Phase 3.** Project Definition Report (December 16, 2015 to January 28, 2016) – Sought feedback on the full Project scope and business case, including Project Goals, design features, benefit and cost analysis, draft performance evaluation/Project success measures, and tolling to fund the Project.

The Phase 3 *Consultation Summary Report*[67] provides a high-level summary of feedback from all sources, including stakeholder meetings, open houses, feedback form respondents and written submissions. The Project reported the following findings:

- General support for the Project overall and for the proposed transit, cycling and pedestrian measures, capacity improvements and interchange improvements.
- Concerns were raised about potential increased traffic congestion at the Oak Street Bridge and, to a lesser extent, other River North Arm crossings.
- Concerns about Tunnel decommissioning and the potential effects of increased marine traffic/industrialization of the River if the Tunnel is removed.
- Support for a future rapid transit with some suggesting expanded transit improvements should be completed instead of the Project.

The Project found residents of Delta and Richmond were more likely to be supportive of the Project as compared with Vancouver residents, who were more likely to suggest the Project was not required.

The interests of stakeholders and Indigenous Peoples are summarized in the Working Group comments submitted on the *George Massey Tunnel Replacement Project Application for an Environmental Assessment Certificate* that were considered in the EAO's referral to the Ministers for decision[11].

3.9.2 Stakeholder Concerns

The Review finds all levels of government agree that congestion at the Crossing needs to be addressed[68] and are supportive of Project functions, including:

- Improving access for cyclists and pedestrians;
- Improving resiliency to seismic events;

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[67] George Massey Tunnel Replacement Project. (2016, March). Phase 3 – Project Definition Report - Consultation Summary Report. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/04/Phase-3-Consultation-Summary-Report-March-2016.pdf

[68] TransLink. (2013, June 14). *Regional Transportation Strategy - Draft Strategic Framework for Consultation* [Report]. Retrieved from https://www.translink.ca/~/media/documents/plans_and_projects/regional_transportation_strategy/draft_strategic_framework_for_consultation.ashx

- Adding capacity with better geometry;
- Allocating capacity to trucks and HOV/transit;
- Providing capacity for today and tomorrow; and
- Improving access to the Hwy 99 corridor (e.g. improving Steveston Highway Interchange).

Some local governments, including Delta, are supportive of the Reference Concept as summarized in the *Project Summary Report*[46]:

- Reducing traffic congestion for Delta commuters;
- Addition of more lanes and ability to accommodate future rapid transit and light rail; and
- Creating opportunities to pedestrians and bikes that currently do not exist.

While supportive of some project functions, other regional (i.e., the Mayors Council on Transportation, TransLink, and Metro Vancouver) and local (i.e. the City of Richmond) governments have requested the Province consider changes to the Reference Concept, reasoning that the scope and scale of bridge and highway improvements did not align with regional planning, community planning and regional transportation objectives[69]. Concerns are outlined in the Summary Report[67]:

> *Richmond expressed several areas of concern, which included:*
>
> - *Traffic, including: impacts to local road systems; potential increased congestion at the Oak Street Bridge; the rationale for a 10-lane bridge versus 8-lane bridge; and MOTI's traffic modelling assumptions used in the Application;*
> - *Drainage concerns, including from the new bridge;*
> - *Potential adverse effects to agriculture and land use;*
> - *Potential effects to the Richmond Nature Park and Garden City Lands;*
> - *Project design and visual effects, particularly related to the new Steveston interchange;*
> - *Potential increased noise and decreased air quality as a result of GMTR in nearby residential areas;*
> - *Downloading of major expenditures onto local governments for road improvements;*

[69] Metro Vancouver. (2016, June 29). *Metro Vancouver Releases Impact Assessment of George Massey Tunnel Replacement Project* [Press release]. Retrieved from http://www.metrovancouver.org/media-room/media-releases/regional-planning/445/Metro%20Vancouver%20Releases%20Impact%20Assessment%20of%20George%20Massey%20Tunnel%20Replacement%20Project

- *A request for a net gain of Environmentally Sensitive Areas and Riparian Management Areas; and*
- *Interest in there being a federal EA of GMTR.*

Metro Vancouver expressed several areas of concern, which included:

- *Insufficient consideration of alternatives to a 10-lane bridge;*
- *Lack of integration of GMTR into the regional growth strategy and transportation network;*
- *Ecological disruption to the Fraser River estuary, an important habitat for salmon and birds;*
- *Impacts to Metro Vancouver infrastructure, including water mains and sewer lines;*
- *Recreational and ecological disruption on Deas Island Regional Park;*
- *Downloading of major expenditures onto local governments for road improvements;*
- *Negative effects on transit ridership and affordability;*
- *Insufficient consideration of climate change and air quality;*
- *Lack of transparency and consultation with respect to design and business case; and*
- *Interest in there being a federal EA of GMTR.*

3.9.3 Draft Project Considerations

Three draft key design considerations for the Project from November 2012[70] were not carried forward as primary Project Goals:

1. **Alignment with Community, Regional and National Objectives** – including concentrating growth in designated areas and providing access to regional town centres.
2. **Community Livability** – including property, visual and noise impacts, as well as community access.
3. **Cost** – including capital cost, technical viability, time to implement and impacts to road users during construction.

[70] George Massey Tunnel Replacement Project. (2012, November). Planning for the Future – Phase 1: Understanding the Need – Consultation Discussion Guide [Brochure]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2012/11/George-Massey-Tunnel-Replacement-Project-Discussion-Guide.pdf

3.9.3.1 Alignment with Regional Objectives

A perceived lack of alignment with regional and community plans is cited as one of the primary concerns with respect to the Reference Concept. With respect to alignment of regional objectives, Metro Vancouver noted two principal concerns[71]:

> ***A) Potential for Induced Vehicle Travel and Emissions in the Near-Term***
>
> *A new facility having expanded vehicle capacity could induce more vehicle trips. Inducing more vehicle trips runs counter to established regional objectives. TransLink's newly adopted Regional Transportation Strategy Framework establishes two regional targets:*
>
> - *To make half of all trips by walking, cycling, and transit; and*
> - *To reduce the distances people drive by one-third.*
>
> *Metro Vancouver has established ambitious greenhouse gas reduction targets and air quality objectives.*
>
> *An expanded facility might:*
>
> - *Unleash pent up travel demand (travelers who may be adverse to sitting in traffic may decide to take more trips in the future as a result of the improved travel times and safety),*
> - *Shift travelers from transit or carpooling to single-occupant vehicles, or*
> - *Change travel patterns (travelers who were used to taking an alternate route, such as the Alex Fraser Bridge, may switch over to the new facility via the South Fraser Perimeter Road).*
>
> *An expanded facility without additional complementary measures to discourage single occupant vehicles and to encourage carpooling, transit, and cycling would indeed be deficient and short-sighted. Unfettered access could easily result in a congested facility. Further, an expanded facility may simply move the "bottleneck" further downstream or upstream.*

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[71] Metro Vancouver. (2013, October 9). Greater Vancouver Regional District Transportation Committee [Agenda]. Retrieved from http://www.metrovancouver.org/boards/Transportation/Transportation-October_9_2013-Agenda.pdf

B) Potential for Unanticipated Land Use Changes in the Long-Term

Reducing travel time expands the catchment area for a given travel time budget. Improvements to accessibility are capitalized in land markets. The improved access to lands, be it residential, commercial, industrial, or agricultural, could have a distributional effect on shifting growth from one area to another. This is an uncertainty that the Regional Growth Strategy never explicitly considered in the population and employment forecasts. It is unclear what basic demographic assumptions the Ministry has been using to justify the proposed capacity on the bridge. It is also unclear what assumptions have been made about plans by Port Metro Vancouver to expand container throughput capacity at Roberts Bank, and to better utilize available marine terminal capacity at Fraser Surrey Docks.

The City of Richmond has concerns about how future increased traffic in Richmond will be accommodated by the existing municipal road network, especially if increased congestion from longer queue lines northward towards the Oak Street Bridge results in drivers exiting Highway 99 sooner to use the municipal road network. Specific concerns were raised over increased use of Steveston Highway in both east and west directions from Highway 99 and primary north-south routes that are located west of Highway 99, such as No. 3 Road.

3.9.3.2 Community Livability

The City of Richmond expressed concerns regarding the impacts from the replacement interchange proposed for Steveston Highway. Specific concerns include visual and noise impacts due to the height of the interchange and resulting impacts on nearby residential and commercial properties (see Figure U for a rendering of the proposed interchange).

3.9.3.3 Value for Money

With respect to cost, Metro Vancouver, in announcing it did not support the Reference Concept[69], expressed concern that the project had not considered "the investment of $3.5 billion in funding towards the new bridge against other alternatives that would achieve Project goals, but would better align with Metro 2040 and enhance the proposed investments included in the TransLink Mayors' Council 10-Year Vision."

In a report, TransLink notes:

> *Times are tight. In addition to an array of operating and maintenance demands, many communities within the region have reasonable and pressing ambitions to expand the transportation system, to keep pace with growth, achieve our shared goals for livability and economic prosperity. In that context, we must affirm that we are providing maximum value from our existing assets and that we work with our partners to make new investment decisions in a more integrated way, considering all possible solutions on an equal footing. For example, when seeking to resolve a traffic chokepoint, we will compare demand management solutions on par with strategies to increase capacity. We will give equal consideration to all of the modes. We will assess capital budget decisions along with operating budget decisions.*

3.9.4 Environment, Agriculture and Communities

The environmental, agricultural and community considerations related to any option to improve the Crossing are important. Existing structures in the River have been allowed to promote the growth of habitat and interact with various terrestrial and marine species since they were constructed nearly 60 years ago. There is also a farmland adjacent to the Corridor, with a significant portion protected as part of the Agricultural Land Reserve (ALR).

As stated previously, it is not the purpose of this Review to revisit decisions made by the environmental assessment process, the ALC review, or by other statutory decision makers. When considering alternative options for the Crossing, the Review has considered the effect on the environment and agricultural lands.

The Project was subject to an Environmental Assessment on the basis that the Project would include dismantling of an existing shoreline facility that would entail direct physical modification of foreshore and submerged land, and modification of a public highway over a continuous distance greater than 20 km. The Review notes that the area of the main River channel that would have been avoided by keeping the bridge piers on land was identified as having medium or low habitat value (see Figure KK). The proposed bridge would have disturbed areas of shoreline with high habitat value as it spanned over Deas Slough.

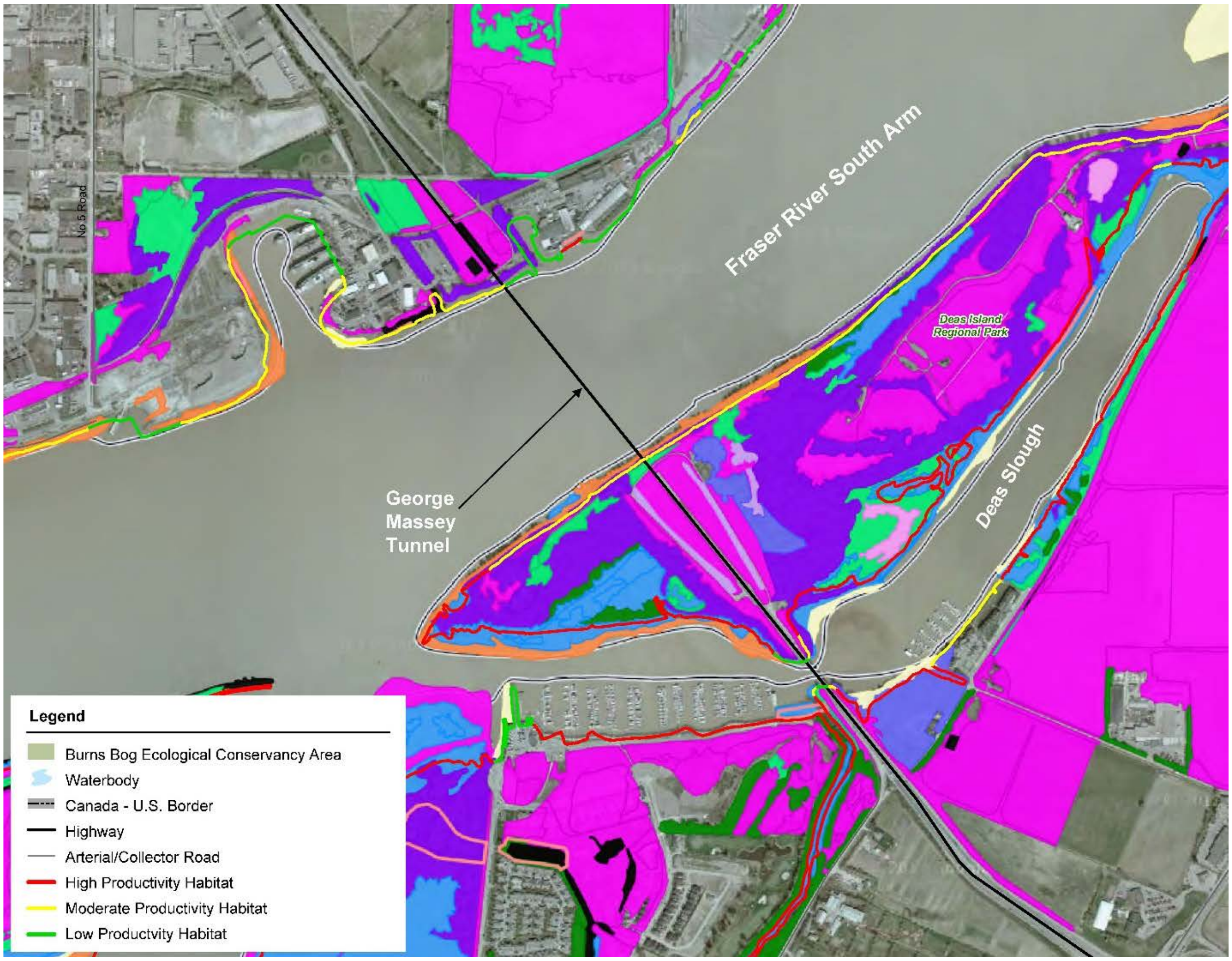

Figure KK Fraser River Estuary Management Program Habitat Inventory[11].

3.9.4.1 Preservation of Agricultural Lands

The Reference Concept results in a net addition of land within the proposed Corridor that could be used for agricultural purposes after completion of the Project.

The City of Richmond is concerned about the pressure to industrialize agricultural land upstream of the Crossing along the River if a new Crossing is a bridge and the existing Tunnel is decommissioned.

In 2009, the Port of Vancouver purchased land in the City of Richmond upstream of the existing tunnel that is currently within the ALR[72]. The Port of Vancouver indicated that land within the ALR that is currently not being used for farming could be considered for industrial port use[73] .

The Summary Report completed by the EAO notes[46]:

> *Concerns were raised by members of the public and Aboriginal groups regarding the decommissioning of the Tunnel, asserting that removal of the Tunnel would facilitate large-scale, capital dredging of the Fraser River in the future to allow for an expansion of marine traffic.*

The Port of Vancouver has released a statement that the potential removal of the existing tunnel "would have no bearing on the port authority's plans to manage increasing trade on the Fraser River"[74] The statement went on to confirm that "the port authority has no plans to further deepen the Fraser River to accommodate larger vessels."

Metro Vancouver also expressed concerns on the pressures that such an increase in capacity could place on farmland: *"The result may be increased pressures for land use conversion, including the conversion of agricultural and industrial land.*[75]"

3.9.4.2 Further Industrialization of the Fraser River

The Summary Report completed by the EAO notes[46]:

> *During the EA, Aboriginal groups, including Musqueam Indian Band, also raised concerns that due to relatively short fisheries windows in the Fraser River, any potential in-river construction activities that have the potential to impede access to Aboriginal fishing would be serious.*

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[72] Nagel, J. (2012, January 26). Port's hunger for farmland a 'declaration of war'. *Richmond Review*. Retrieved from http://www.richmond-news.com/news/port-s-hunger-for-farmland-a-declaration-of-war-1.1912429
[73] Gyarmati, S. (2013, February 8). The ALR at 40. *Delta Optimist*. Retrieved from http://www.delta-optimist.com/news/the-alr-at-40-1.456781
[74] Vancouver Fraser Port Authority. (2018). *George Massey Tunnel Replacement* [Website]. Retrieved from https://www.portvancouver.com/about-us/topics-of-interest/george-massey-tunnel-replacement/
[75] Metro Vancouver. (2016, June 14). *George Massey Tunnel Replacement Project – Analysis of Regional Impact* [Items released from closed meeting]. Retrieved from http://www.metrovancouver.org/boards/GVRD/RD_2016-Jun-24_RCL.pdf

> *They expressed concerns that the level of detail of MOTI's marine access management plan included in the Application, did not give them confidence that Aboriginal fisheries would not be affected. During the EA, at the request of EAO, MOTI submitted an outline of the proposed marine access management plan.*
>
> *During the EA, the public and Aboriginal groups raised concerns regarding the effectiveness of fish habitat offsetting and proposed fish habitat enhancement opportunities, risk of underwater noise effects on fish, and that least-risk timing windows do not take into account upstream migration of adult salmon.*

3.9.5 Environmental Assessment Certificate

An EAC was issued on February 8, 2017. In the accompanying announcement, the Province noted[76]:

> *Key findings that assisted ministers in concluding that no significant adverse effects are likely to occur from the project include:*
>
> - *The design of a clear span bridge across the Fraser River to avoid instream footprint effects on fish and fish habitat;*
> - *Tunnel decommissioning would not result in changes to the size of vessels using the Fraser River; and*
> - *Analysis that indicated the project would eliminate congestion delays and idling at the tunnel, providing relief for a number of local Richmond roads.*

3.9.6 Review Comments

The preceding summary has been provided for context as to the benefits of the Project and the concerns of the various stakeholder groups. This has assisted the Review in focussing on the more salient components of the Reference Concept and was considered throughout the Review process.

[76] Province of British Columbia. (2017, February 9). *George Massey Tunnel Replacement project granted Environmental Assessment approval* [Press release]. Retrieved from https://news.gov.bc.ca/releases/2017ENV0011-000293

4 Principal Findings and Recommendations

The following provides a categorically organized summary of the Review's principal findings and recommendations, as described in detail within Sections 2 and 3 of this report. Categories are listed in the following order:

Project Needs, Objectives and Functional Criteria

The George Massey Tunnel

Traffic Modelling and Forecasting

Highway and Bridge Review

HOV/ Transit

Business Case

New Tunnel Crossing

CONCLUDING RECOMMENDATIONS

CATEGORY - Project Needs, Objectives and Functional Criteria

Findings

- The Reference Concept achieved the requirements of the Project functional criteria and technical criteria within the total Project context and with the understanding that it was a concept only, and not a fully optimized final design.
- The Project planning and integration with the local communities would have been better served by the inclusion of the following three key design considerations as principal Project Goals:
  - *Alignment with Community, Regional and National Objectives* – including concentrating growth in designated areas and providing access to regional town centres.
  - *Community Livability* – including property, visual and noise impacts, as well as community access.
  - *Cost* – including capital cost, technical viability, time to implement and impacts to road users during construction.

Recommendations – *see next page*

Recommendations *(for Project Needs, Objectives, and Functional Criteria)*

It is recommended that formal trade-off studies and present value analysis be completed on each of the major project components to confirm they result in value for money. MoTI confirmed (Section 3.6.1), confirmed its practice is to plan projects to the "minimum requirements to meet project needs and assess incremental improvements on a value for money basis."

It is recommended that the Province re-evaluate appropriateness of the criteria to "eliminate queuing at any time to 2045," which resulted in the 10 lane Reference Concept and its related impacts and costs.

It is recommended that the Reference Concept solution of "median transit lanes and stations" and the criterion to "Provide convenience of transit by improving infrastructure" be re-evaluated by the Province in favour of maintaining the existing transit provisions and reducing the number of traffic lanes from 10 to a maximum of eight.

It is recommended that the criteria to: (i) Provide a clear span structure with no piers in the River; and (ii) Construct project within existing corridor and reduce footprint of project infrastructure be re-evaluated given the opportunity to substantially de-risk the construction of the project and reduce the capital cost.

CATEGORY - The George Massey Tunnel

Findings

- Based in the Review's pre-feasibility analysis (Section 3.7), the opinion of the ITT experts supported by benchmarking (Section 3.7.1 and Section 3.8.1), and the opinion of the designers of the *Part 2 - Ground Improvement Retrofit* (Section 3.7.1), constructing the GI necessary to retrofit the Tunnel for life safety in a 475-year or in a 2,475-year seismic event is expected to be technically feasible.
- The previously designed *Part 2 - Ground Improvement Retrofit* may not be adequate for 475-year performance based on current state of practice due to liquefaction in the silty materials below the previously identified liquefiable sands. Consequently, a change to the scope of the previous GI program may be required.
- The GI necessary for the Tunnel retrofit will require significant construction work in the River, requiring agency and stakeholder approval.
- The deficiencies in the Tunnel lane geometry, limited overhead clearance, and the concrete deterioration in the approaches, while important to be considered, are not so severe to necessitate not retaining the Tunnel.
- If the Tunnel was thoroughly rehabilitated, in a similar fashion to the Midtown Tunnel (see Figure Z) and the counterflow function removed, many of the current safety concerns could be mitigated.
- The estimated order of magnitude costs to retrofit the Tunnel to an improved seismic standard (1 in 475 year event or 1 in 2475 year event) will be in the range of $250 million to $300 million (total project cost), without the consideration of the potential synergies that would be achieved with a new tunnel Crossing (Section 3.7.4).
- It is important to note that the total Project cost to upgrade the Tunnel may exceed the cost to provide an equivalent level of capacity in a completely new structure. The inherent value of the asset, if it was to be constructed today, combined with the demolition costs for removal if not retained should be considered in any cost benefit evaluation.

Recommendations

It is recommended that a comprehensive feasibility study be completed to confirm the scope and cost to upgrade the Tunnel.

CATEGORY - Traffic Modelling and Forecasting

Findings

- The traffic modelling and forecasting completed by the Project and the various models used were developed using sound judgement and traffic engineering/travel demand modelling principles accepted in industry at that time.
- The Project traffic forecasts were reasonable estimates within the accuracy of the models available at the time.
- TransLink's RTM3 traffic forecasting model is a reliable and suitable model for future traffic forecasting within the Highway 99 corridor.
- The RTM3 produced forecasts for the 2030 and 2045 year horizons were approximately 10% greater than the Project forecasts, consistent with the improvements made to the model (Section 3.3.4.3).
- The majority of traffic growth to 2045 for the Reference Concept (approximately 22.5% of total traffic) was traffic diverted from the AFB (Figure L in Section 3.3.4.3).
- The 10 lane untolled Reference Concept has surplus traffic capacity in 2045 based on estimated lane utilizations (Section 3.3.4.4).
- Approximately 50% of the Reference Concept user benefits are derived from the Highway 99 Corridor improvements and 50% from the new Crossing (Section 3.3.5).
- The highway improvements are an essential component of the Project to achieve the full user benefits.

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Findings *(Traffic Modelling and Forecasting, continued from previous page)*

- The Review analyzed a range of options for the Project to assess the opportunity the implications to traffic capacity, user benefits and travel time if the number of Crossing lanes was reduced and the highway improvements were phased. As a percentage of the Reference Concept benefits (Table A in Section 3.3.5):
    - The six GP lane "Do Minimum" concept accommodates 87% of the 2045 traffic, and achieves 42% of the travel time and operating cost benefits and 36% of the Reliability benefits;
    - The eight GP lane "Do Minimum" concept accommodates 91% of the 2045 traffic and achieves 50% of the travel time and operating cost benefits and 46% of the reliability benefits; and
    - The eight GP lane with full highway improvements concept accommodates 99% of the 2045 traffic and achieves 95% of the travel time and operating cost benefits and 98% of the reliability benefits.

- For the six GP lane and eight GP lane "Do Minimum" concepts, travel times in the peak directions would be 15 minutes to 17 minutes greater than the Reference Concept in 2045; very similar to what is experienced today. In both cases, the non-peak direction would experience almost no delay (Section 3.3.5).

- The Review acknowledges that both the traffic models used by the Project and the new RTM3 used by the Review are based on historical traffic behaviour. As such, future forecasts are a best guess based on known travel conditions observed today. There is inherent uncertainty given technological change (i.e., autonomous vehicles and ride sharing services) that could significantly impact travel demand and efficiency of highway operations (i.e., highway capacity, vehicle occupancy) (Section 0).

- Future traffic modelling and infrastructure planning for the Crossing need to consider the couplet behaviour of the Crossing and the AFB to ensure there are no unintended consequences at the AFB.

Recommendations – *see next page*

Recommendations *(Traffic Modelling and Forecasting)*

As noted above, it is recommended that the Province consider changing the original functional criteria of "Eliminate queuing at any time to 2045" to allow a reasonable level of queuing at peak periods. This enables the 10 lane Reference Concept to be reduced to six or eight lanes, which would:

- Be more compatible with the RTS;
- Accommodate the majority of the future traffic forecast;
- Permit staging of the highway improvements; and
- Provide an incentive for HOV and transit use and allow any form of mobility pricing to manage future traffic volumes.

Both scaled down options still provide significant relief to congestion, but at the same time provide an incentive for high occupancy vehicle and transit travel. Further, any future forms of travel demand management or mobility pricing would help ensure that a six or eight lane option performs at optimal traffic levels.

Eliminating all congestion is known to induce traffic, provides no incentive for SOV to shift to other modes of transportation, and provides no basis for mobility pricing because there is no congestion to value and price. Some delay is consistent with all other major crossings in the region. Both a six or an eight-lane option can handle the majority of the 2045 predicted traffic but with some delay in peak direction; not inconsistent with the other major crossings in the region.

CATEGORY - Highway and Bridge Review

Findings

- The highway and bridge components of the Reference Concept achieve the stated requirements and comply with current design standards and practices
- The Reference Concept bridge steel box girder design for the main span is appropriate given the main span length. Executed properly, it is a well-tested structural system. Given the size and mass of each individual section, the local steel fabrication industry may be challenged, and as with other large steel structures, international fabrication may be the lowest cost.
- The Review found that the requirements for upgrading City of Richmond roads to be consistent with a new 10-lane highway were not fully resolved with the City.
- The Steveston Highway Interchange requires substantial upgrading and recommends that it is a required component of any future project. (Figure V in Section 3.4.3.3).
- Reducing the number of highway lanes to six or eight, combined with the elimination of the median transit stations, will significantly reduce the scale and complexity of the Steveston Highway and Highway 17A interchanges and will permit phasing of Highway 99 improvements (Section 3.4.3.1). The Project capital cost would be substantially reduced, potentially in the order of the $500 million originally estimated by the Project for the HOV/transit provisions.
- A new tunnel Crossing, relative to a bridge, more readily facilitates staging of Highway 99 improvements (Section 3.4.4).

Recommendations

It is recommended that the Province consider not mandating the two principal functional criteria that defined the bridge (no construction in the River and maintaining the existing highway alignment) to allow greater flexibility in the bridge design with the potential to achieve in excess of $500 million in capital cost savings (Section 3.4.2).

CATEGORY - HOV/ Transit

Findings

- The Project Goal to "Support increased transit on the Highway 99 corridor" and related functional criteria was derived in the context that the Crossing would be tollled, reducing overall traffic utilization (Section 3.5) and the incentive to use transit would be increased. In the absence of tolls, the 10 lane Reference Concept provides no incentive for further transit use.
- The location of the HOV/transit provisions at the highway median provided for the possible future installation of an LRT system on the Corridor. Initially, the transit stations would be utilized by the existing buses; incrementally reducing the total corridor transit times for the buses.
- The existing bus lane with off highway pullouts combined with queue jumping access at the crossing, is functioning well and has substantial capability for expansion.
- Possible LRT along the Highway 99 Corridor is not currently in the RTS and it is unlikely that even with future population increases there would be sufficient demand to justify the capital investments.
- The MoTI 2009 Highway 99 (King George Highway to Oak Street Bridge) Corridor Assessment report noted the limited benefits of median stops and the related high cost of ramps to eliminate buses having to cross multiple lanes of traffic to exit the highway and recommended against median transit lanes (Section 3.4.3.1).
- The HOV/transit provisions are estimated to provide only 5% of the total project user benefits (Section 3.3.5). Based on the Project's estimate of $500 million for the Reference Concept transit, the provisions have a substantially negative net present value and do not deliver value for money (Section 3.6).

Recommendations

It is recommended that the Province consider eliminating the median HOV/transit provisions in favour of maintaining the existing bus shoulder lanes and off highway transit stops. The Review acknowledges that this recommendation may not be consistent with Provincial societal objectives and may therefore be unacceptable to the Province.

CATEGORY - Business Case

Findings

- The Review agrees with the Project's calculation of user benefits and the resulting positive cost benefit of 1.2. The Review notes that the user benefits would increase incrementally based on the RTM3 traffic forecasts which are approximately 10% greater than the Project forecasts (Section 3.3).

Recommendations

It is recommended that future planning should be completed in accordance with MoTI practice: identifying the minimum solution and then assessing incremental improvements separately on a value for money basis. It is recognized that eliminating any of the noted provisions in the Reference Concept on the basis of "value for money" may not be consistent with Provincial societal objectives and may, therefore, be unacceptable to the Province.

CATEGORY - New Tunnel Crossing

Findings

- An ITT is a feasible and cost competitive solution for the Crossing and would provide similar benefits to a bridge.
- There is the potential that an ITT could provide a more beneficial alternative when all factors are re-considered.
- The cost of a new ITT is expected to be competitive with a bridge.
- A bored tunnel would be more costly to construct than either a bridge or an ITT and would have greater traffic management requirements. The bored tunnel would have the least environmental impacts as it would pass under Deas Slough and would not require GI immediately adjacent to the River. The Review does not recommend further consideration of a bored tunnel.

Recommendations

It is recommended that a comprehensive feasibility study be completed to confirm the scope of an ITT Crossing.

It is recommended that international experts in ITT design and construction be engaged to participate in the ITT feasibility study.

It is recommended that the ITT feasibility study be completed in conjunction with the feasibility study for the Tunnel retrofit as the design and construction considerations are similar.

CONCLUDING RECOMMENDATIONS

As described throughout this Report, the planning for the Project was completed based on the identification of Project needs and the functional criteria to provide a comprehensive solution. The resulting Reference Concept achieves the functional requirements, resulting in a Project that maximized quantifiable user benefits had a positive benefit cost ratio.

The Reference Concept was prepared with functional criteria that were expansive and avoided adverse effects that might otherwise have been mitigated, or compensated, for. As such, the resulting Reference Concept is an all-encompassing solution. Most groups agree with improvements to reliability at the Crossing, however, the scope and scale of the Reference Concept remains a concern to many.

The Review has highlighted specific functional criteria, which if modified, could result in a reduced Project scope and cost savings, while still providing increased capacity and reliability. These changes would better align the Project with regional transportation and community planning goals and would likely result in broader acceptance of the Project.

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CONCLUDING RECOMMENDATIONS *(continued)*

It is the Review's opinion and recommendation that the Province should re-examine the Project needs and functional criteria to facilitate a Project that:

- Provides capacity to improve current reliability and reduce future congestion to levels consistent with other crossings in the Lower Mainland;
- Provides transit infrastructure that is appropriate based on regional transportation planning;
- Respects the environment by including necessary mitigation and compensation measures to allow for alternative Crossing designs that may include a shorter bridge span, retrofit of the Tunnel, or a new ITT; and
- Respects the need to maintain agricultural and park lands by including necessary mitigation and compensation measures to allow for lower risk, alternative interchange and Crossing designs that are less imposing and better reflect the surrounding lands and communities.

The Review recommends that the Province complete a new comprehensive feasibility study that would initially re-visit the Project Goals and functional criteria addressing the findings and recommendations in this Review. The feasibility study should consider:

- Allowing for congestion to be reduced, but not eliminated;
- Allowing the new tunnel or bridge Crossing to be located off of the existing highway alignment;
- A more detailed consideration of adding new capacity in the form of a tunnel;
- The reuse of the existing Tunnel;
- Maintaining and improving the existing shoulder bus transit system;
- Allowing construction in the River with suitable mitigation and compensation measures; and
- Allowing for some encroachment on agricultural and park lands with suitable mitigation and compensation measures.

Appendix A ITR Terms of Reference

INDEPENDENT TECHNICAL REVIEW
GEORGE MASSEY CROSSING

Terms of Reference – Nov. 1, 2017

Background

The George Massey Tunnel Replacement Project has been in pre-development, planning and procurement since 2012. Questions have been raised about the proposed bridge option, such as: how the improvements fit within the regional context; the need for 10-lane capacity; tunnel vs. bridge; magnitude of connecting infrastructure, etc. Public comments have been made about environmental, agricultural, port marine/truck impacts and imperatives and the need to ensure George Massey traffic modelling aligns with broader regional models.

The Ministry of Transportation and Infrastructure is proceeding with an independent technical review of the George Massey corridor. The review will focus on what level of improvement is needed in the context of regional and provincial transportation planning, growth and vision.

While this review is underway, the Province will engage with mayors from Metro Vancouver to gather their perspectives on the project, and to ensure that any plan for this crossing reflects their ideas and fits into the overall vision for the region.

Terms of Reference

The timeline for the independent review is expected to be six months.

The review will include the following:

1. **Review the technical objectives for George Massey crossing improvements;**
2. **Review the analysis and assumptions made for the Project;**
3. **Review and analyze previous information collected on considerations such as environmental, agricultural and port-related traffic (e.g., marine, trucks);**
4. **Undertake a technical review of safety, seismic and congestion issues for George Massey Tunnel;**
5. **Review the costs and technical requirements of a tunnel versus a bridge;**
6. **Identify improvements necessary to address safety, seismic and current congestion issues, including any technology limitations;**
7. **Review traffic models and, with TransLink, determine regional traffic model to be used for George Massey and other future regional traffic demand analysis;**
8. **Use the outputs from provincial, regional and local transportation planning and regional traffic modelling to validate the future traffic demand for the George Massey crossing;**

9. **Identify George Massey improvement options that meet technical objectives, including the size and capacity of the infrastructure, scope and cost.**

The review is not a reconsideration of decisions made by the environmental assessment process, the Agricultural Land Commission review or by other statutory decision makers.

The independent review lead must submit to the Minister of Transportation and Infrastructure a report by Spring 2018.

Resources

The lead will draw from the technical information developed by the Province and from Metro Vancouver municipalities. The lead may also obtain expert advice and analysis on any subject related to the review, which may include highway infrastructure design and construction, transportation planning and traffic engineering. Ministry of Transportation and Infrastructure staff will be available to support the review in ensuring procurement of independent expert advice.

Appendix B Abbreviations & Defined Terms

List of Abbreviations and Defined Terms

Abbreviations

Abbreviation	Description
%	Percent
1D	One dimensional
2D	Two dimensional
3D	Three dimensional
AADT	Annual average daily traffic
AFB	Alex Fraser Bridge
ALC	Agricultural Land Commission
ALR	Agricultural Land Reserve
ALRT	Automated light rapid transit
AM	Ante meridiem, meaning before midday
API	Application programming interface
ATIS	Advanced Traveller Information System
BART	Bay Area Rapid Transit
BAU	Business as usual (no change or improvement)
BC	British Columbia
BCTFA	BC Transportation Finance Authority
BGC	BGC Engineering Inc.

Abbreviation	Description
CA	Concession Agreement
Christiani & Nielsen	Christiani & Nielsen of Canada Ltd.
COWI	COWI North America, Ltd. (formerly Buckland & Taylor Ltd.)
EA	Environmental Assessment
EAC	Environmental Assessment Certificate
EAO	Environmental Assessment Office
FENCO	Foundation of Canada Engineering Corporation
g	Gravity
GDP	Gross domestic product
GI	Ground improvement
GMT	The existing George Massey Tunnel
GMTR	George Massey Tunnel Replacement
GP	General purpose
GSAM	Gateway Sub-Area Model
HOV	High occupancy vehicle
ITA	International Tunnelling and Underground Space Association
ITA-WG11	International Tunnelling and Underground Space Association Working Group 11for immersed and submerged floating tunnels
ITR	The Independent Technical Review of the George Massey Crossing completed by Stanley R. Cowdell of Westmar Advisors Inc.
ITT	Immersed tube tunnel
kg	Kilograms

Abbreviation	Description
km	Kilometres
LED	Light-emitting diode
LRT	Light rail transit
m	Metres
m^2	Square metres
M7	Magnitude 7 (for example) earthquake
MADT	Monthly average daily traffic
MAWDT	Monthly average weekday traffic
MAWET	Monthly average weekend traffic
mm	Millimetres
mm:ss	Minutes and seconds
McElhanney	McElhanney Consulting Services Ltd.
MoTI	BC Ministry of Transportation and Infrastructure
NBCC	National Building Code of Canada
NPV	Net present value
PM	Post meridiem, meaning past midday
RFP	Request for proposals
RP	Return period
RTM	Regional transportation model
RTM3	TransLink regional transportation model, phase 3
RTS	Regional Transportation Strategy developed by TransLink in 2013

Abbreviation	Description
SOV	Single occupancy vehicle
SME	Subject matter expert
TBM	Tunnel boring machine
UBC	University of British Columbia
UK	United Kingdom
USA	United States of America
VE	Value engineering
VKT	Vehicle kilometres travelled
WA	The State of Washington, United States of America
Westmar Advisors	Westmar Advisors Inc.

Defined Terms

Defined Terms	Description
Branch	BC Ministry of Transportation and Infrastructure Planning and Programming Branch
Concession	The contract between the Province and the selected proponent following the Request for Proposals, also called the Concessionaire, that governs the handing over of obligation from the Province to the Concessionaire the portion of highway to be operated and maintained.
Corridor	The overall Project corridor along Highway 99 that includes a crossing near the existing George Massey Tunnel
Crossing or George Massey Crossing	A crossing of the South Arm of the Fraser River located near the existing George Massey Tunnel that forms part of Highway 99

Defined Terms	Description
Environmental Impact Statements	A proponent is required to prepare an environmental impact statement that identifies and assesses the environmental effects of a project and the measures proposed to mitigate those effects, according to the environmental impact statement guidelines prepared by the lead regulatory agency.
Indigenous Groups	Groups that are connected with Indigenous people in BC[1].
ITR	The Independent Technical Review of the George Massey Crossing completed by Stanley R. Cowdell P.Eng.
K Factor	Horizontal distance required to achieve a 1% change in the slope of the vertical curve
Lower Mainland	Located in the southwestern corner of British Columbia, the Lower Mainland encompasses Vancouver and its surrounding area and the Sunshine Coast[2].
Park	Deas Island Regional Park
Project	The George Massey Tunnel Replacement Project
Project Description	The Ministry of Transportation and Infrastructure submitted a Project Description and Key Areas of Study document (Project Description) to the B.C. Environmental Assessment Office (EAO) to initiate the Pre-Application Stage of the B.C. EAA process. The Project Description provided Project-related information that allowed the EAO to determine whether the Project triggered a review under the B.C. Environmental Assessment Act.
Project Goals	The six key goals were identified for the Project based on the BC Ministry of Transportation and Infrastructure's mandate and results of consultation.

[1] Province of British Columbia. (2018). *British Columbia Ministry of Indigenous Relations and Reconciliation* [Website]. Retrieved from https://www2.gov.bc.ca/gov/content/governments/organizational-structure/ministries-organizations/ministries/indigenous-relations-reconciliation
[2] Statistics Canada. (2018). *B.C.'s Lower Mainland* [Website]. Retrieved from https://www150.statcan.gc.ca/n1/pub/11-402-x/2011000/chap/geo/geo02-eng.htm

Defined Terms	Description
Project Team	The team engaged by the BC Ministry of Transportation and Infrastructure to lead the development of the George Massey Tunnel Replacement Project
Proponent Teams	Teams that were form by the financing, construction, and engineering design industry to respond to the Province's shortlisting process for the Concession Agreement for the George Massey Tunnel Replacement Project. Three teams were chosen to respond to the Request for Proposals for the Project.
Province	Province of British Columbia
Reference Concept	The concept design included in the request for proposals for the George Massey Tunnel Replacement Project
Review	The Independent Technical Review completed by Stanley R. Cowdell of Westmar Advisors Inc.
Review Team	The team assembled by Stanley R. Cowdell of Westmar Advisors Inc. to assist him with completing the Independent Technical Review
River	The Fraser River
Terms of Reference	The scope of work prepared by the Province of British Columbia for the Independent Technical Review of the George Massey Crossing
Tunnel	The existing George Massey Tunnel
Tunnel Expert Panel	Panel of experts on tunnel design and development engaged by Westmar Advisors Inc. to assist with the Independent Technical Review

Appendix C Traffic Study Report

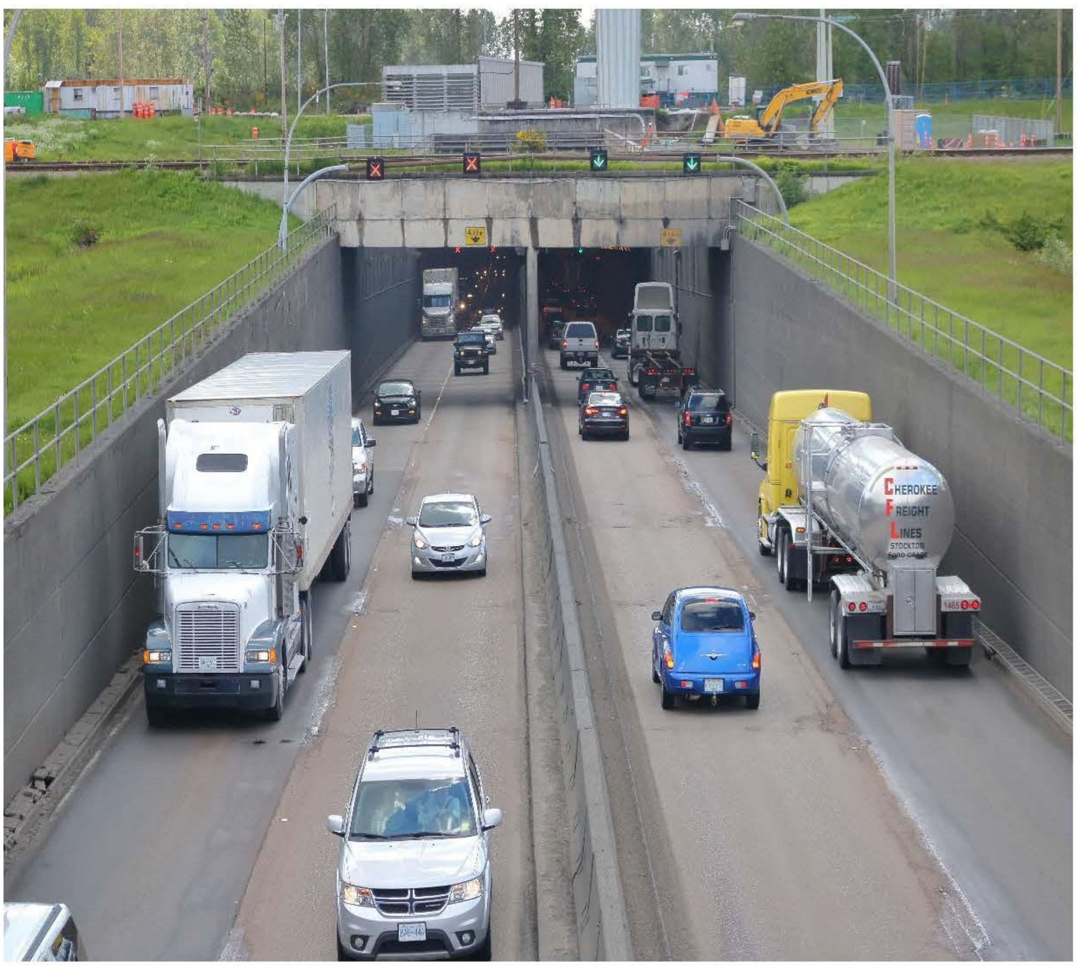
Ministry of Transportation and Infrastructure

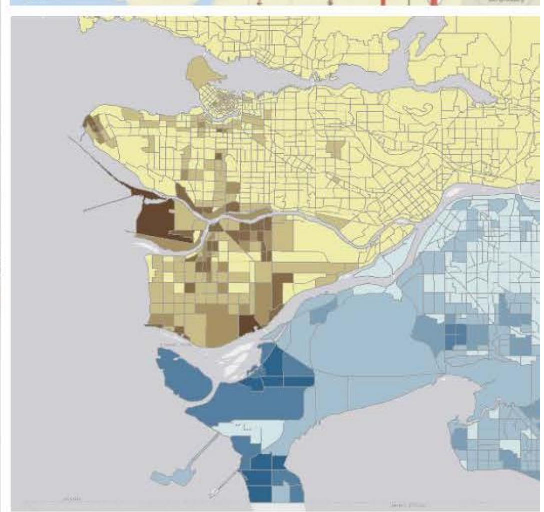
McElhanney

Traffic Technical Report

GEORGE MASSEY TUNNEL REPLACEMENT PROJECT – INDEPENDENT TECHNICAL REVIEW

June 2018 | Our File: 2121-00288-03





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June 27th, 2018

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Attention: Stan Cowdell, P.Eng., President

TRAFFIC TECHNICAL REPORT: GEORGE MASSEY TUNNEL REPLACEMENT PROJECT – INDEPENDENT TECHNICAL REVIEW

As requested, we have prepared a technical report summarizing a review of the George Massey Tunnel Replacement (GMTR) project traffic forecasts developed previously. This report summarizes the work done to date by the GMTR team to forecast traffic on the crossing and estimate user benefits. We have conducted an extensive validation of the Regional Transportation Model (RTM) within the study area and prepared updated traffic forecasts as well as estimates of user benefits.

We trust you will find this summary of our review and updated forecasts meets the requirements as set out in our scope of work. Please contact us if you have any questions or require any clarification.

Yours truly,
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EXECUTIVE SUMMARY

BACKGROUND / CONTEXT

The George Massey Tunnel (GMT) provides a significant ‘gateway’ facility for Metro Vancouver along the Highway 99 corridor connecting the US border, BC Ferries, deep sea terminals at Roberts Bank and communities on both sides of the Fraser River. Traffic volumes across GMT have remained relatively stable over the past few decades around 80,000 vehicles per day with significant congestion during the morning and afternoon peak periods. The neighbouring 6-lane Alex Fraser Bridge (AFB) has absorbed additional traffic volume growth since it has had spare capacity but is now also congested. Both the GMT and AFB crossings provide a couplet system linking both Highway 91 and 99 through Delta and Richmond. For longer distance trips, the choice between GMT and AFB is very close in terms of travel times. With both facilities experiencing significant congestion levels during peak times today, there is likely a level of traffic suppression occurring where people choose to not cross the Fraser River. This is a similar effect that happened when the AFB opened in 1986 or when the Golden Ears Bridge opened in 2009 and there was a significant ramp up in traffic volumes in the first few years of operation.

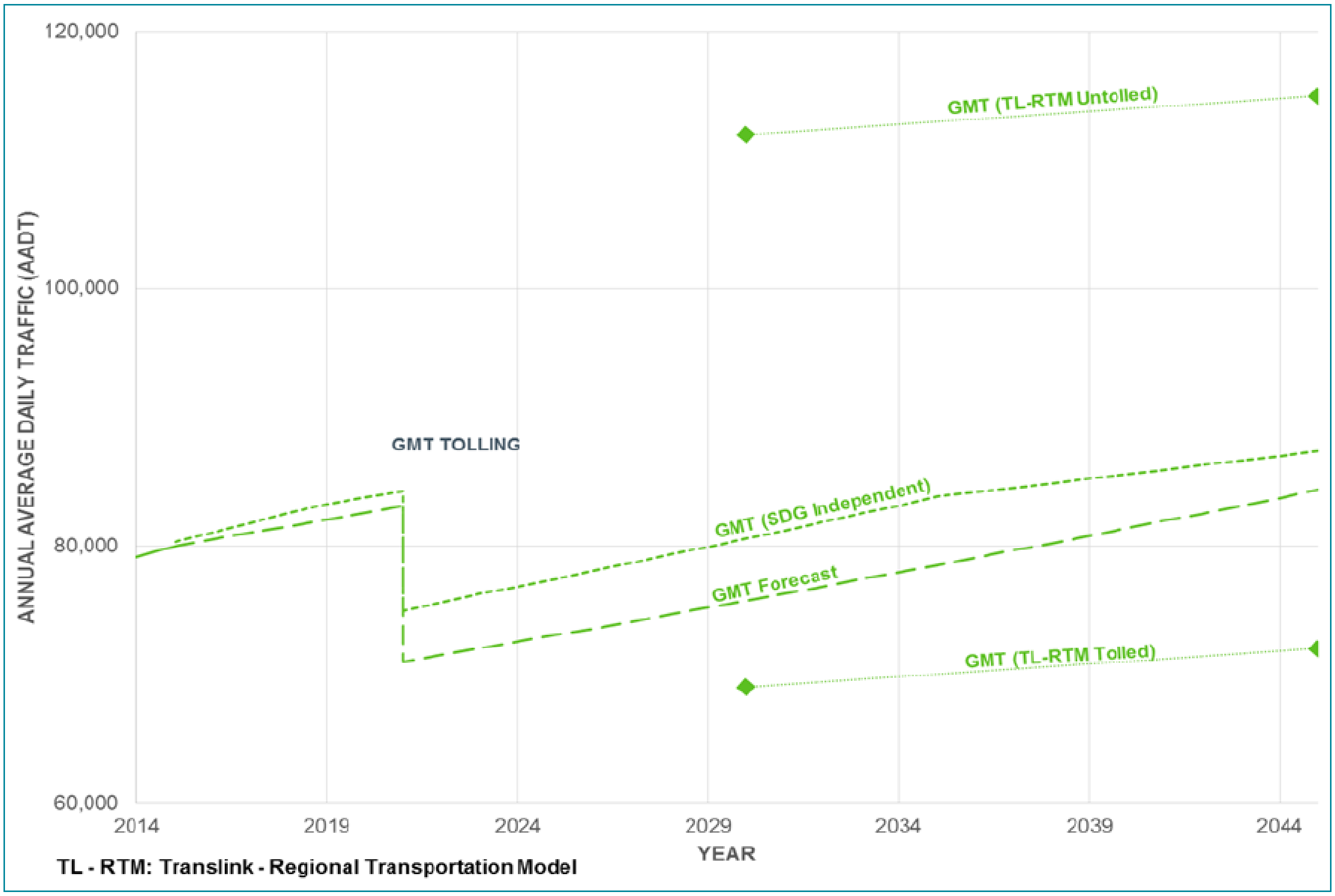
To accommodate the peak-oriented nature of traffic patterns, the GMT is operated with a counter-flow system (3 peak lanes + 1 off-peak lane) during peak times (morning and afternoon). The GMT/AFB couplet suffers from congestion and reliability issues with significant queuing during peak times, especially when incidents (accidents, vehicle stalls, etc) occur. Average northbound travel time along Highway 99 (from the Highway 91 interchange in Delta to the Highway 91 interchange in Richmond) is approximately 20 mins, which can vary up to 50 min. The northbound direction during the afternoon peak sees some of the highest delay times and variability in the region, with perhaps the exception of the Lions Gate Bridge which also operates with a counter-flow system.

The Metro Vancouver region is anticipated to grow by an additional million people by 2045, much of it occurring south of the Fraser River. The GMT is arguably the most critical and congested crossing of the south arm of the river with greater travel time and reliability issues than the other south arm crossings. The counter flow system, access improvements and highway shoulder bus lanes have all been put in place to help manage travel demand and congestion in this corridor. The current levels of peak congestion and reliability have necessitated a review of crossing options to address these issues. With anticipated economic development, the GMT crossing will need to be improved to support this growth and enable economic activity to occur on both sides of the crossing.

GMTR PROJECT TRAFFIC FORECASTS

As part of developing the GMTR business case, several methods to forecast traffic volumes were employed. **Figure 1** provides a summary of the range of previous traffic forecasts that were developed. The following describes how the GMTR Project estimated traffic impacts and future demand levels. In each case, the models were generally developed using sound judgement and traffic engineering/travel demand modelling principles accepted in industry at that time. As such, the traffic forecasts result in reasonable estimates within the accuracy of the models available at the time. Lack of base year validation within the study area corridor, however, was a deficiency in some of these previous attempts. In other words, there was limited information that provided a comparison of the modelled versus observed travel conditions (ie, traffic volumes, travel times, etc.) in the current year. This appears to be a deficiency in the project traffic forecasting that was undertaken.

Figure 1: Range of Previous GMTR Traffic Forecasts



Source: Figure 5.1-2, 5.1 Traffic, George Massey Tunnel Replacement Project – Part B, Traffic Assessment, Environmental Assessment Application, Ministry of Transportation and Infrastructure, July 2016.

GSAM

Regional traffic demand models have been applied to evaluate infrastructure investments in Metro Vancouver for many years. Developed as part of the BC Ministry of Transportation and Infrastructure (MoTI) Gateway Program in the early 2000's, the Gateway Sub-Area Model (GSAM) modelled the AM and PM peak period travel volumes through the 2031 horizon year. Each peak period was modelled independently and used to develop the benefits cases for projects such as the Port Mann Bridge (PMB) / Highway 1 Expansion, Pitt River Bridge, South Fraser Perimeter Road (SFPR) and Golden Ears Bridge (GEB). Variants of this approach were also used to evaluate the Canada Line and Evergreen Line regional rapid transit projects.

The GSAM was updated with additional detail for the GMTR project in 2013 where additional detail was added in the project corridor and contemporary information on land use, transit services and truck generators were provided to produce an updated base model. The model formulation was largely the same as the 2003 baseline, with some updates made to improve the response to tolling based on early experience with GEB and PMB operations.

RTM

Separately from the GSAM development, TransLink had developed the Regional Transportation Model (RTM) which modelled regional travel behaviour on a 24-hour basis and provided individual time slices for the AM and Midday time periods. This model was formulated using information from the 2011 TransLink Trip Diary and 2011 Census surveys. The trip diary survey includes a random sample of households that are asked questions about their previous days travel including trip origin/destination, time of day, trip purpose, trip mode, etc. The level of network detail was significantly less than the GSAM which had seen numerous updates over the previous decade in the Gateway project corridors. The behavioural complexity and level of disaggregation of the RTM was significantly more detailed than the previous peak-period focused models. An early development version of the regional model (Phase 0) was provided to the GMTR project for use in evaluating the project.

A PM time period was added to the Phase 0 snapshot for the project as a separate slice of the 24-hour demand, but was not integrated into the overall model formulation, leaving it fundamentally driven off of the AM and Midday time periods. A validation report that provides a comparison of modelled versus observed travel conditions for the modified model was not provided making it difficult to evaluate the appropriateness of the model for use on tolled facilities or the project corridor in general. There were significant issues identified in this model being overly sensitive to tolling in addition to the large levels of demand adjustment present in the base model calibration. Demand adjust is applied to the model matrices as an adjustment factor to force the model to fit observed traffic counts.

Congestion Throughput Model

The RTM's lack of a validation report to observed conditions prompted the creation of a congestion estimation model based on calibrating measured delay to tunnel throughput measured by the Ministry's Advanced Traveller Information System (ATIS) through Bluetooth sensor capture along the Massey corridor. This model was calibrated to the directly measured volume and delay information for an entire year and provided a link from the modelled delay to total annual delay based on direct measurement.

The throughput model appears to be well calibrated to observed conditions and provides some insight into how weekday volume and delays relate to total annual values in the Massey corridor which is very useful when expanding the peak period models to annual values, particularly for user benefits. The congestion values produced by this model are highly dependent on the traffic arrival patterns and per-lane throughput assumptions made when evaluating the project options in the future and are difficult to quantify as the model is directly estimated from observed conditions and not a separate theoretical model based on traffic engineering fundamentals. In other words, this model fits well to observed conditions today but there is no theoretical basis from traffic engineering principles to support the levels of congestion forecast in the future. Some benchmarking of future congestion levels would be helpful to validate the congestion throughput model.

Econometric Demand Model

An independent econometric model was commissioned as a comparator to the forecasts developed previously by the project team and estimates the change in travel demand based on indicative regional measurements such as GDP, population, employment and other regional indicators. Retention of demand after applying tolling was estimated from the limited experience on the Port Mann Bridge to that point in time. The elasticity in travel demand to these indicators can vary widely and is highly context dependent as it implicitly represents the availability of alternatives in the urban setting and are most appropriate to benchmark the long-term growth potential of travel demand into the future. A review of this model shows that the assumptions and approach were sound and the outcomes reliable given the availability of data at the time.

ITR - TRAFFIC FORECAST: PURPOSE & OBJECTIVES

The purpose of this study is to demonstrate the validation of the RTM3 within the Highway 99 corridor context and application for travel demand forecasting. The RTM3 is the latest available travel demand forecasting model that is suitable for application within the Highway 99 corridor. It has been recently updated and calibrated using latest available travel survey and traffic count information. Updated traffic forecasts for the GMTR were produced for various options for the 2030 and 2045 horizons. Consumer surplus calculations were then carried out to estimate user benefits in terms of travel time savings, vehicle operating cost savings and reliability benefits. The objective of this study is to demonstrate the effectiveness of each option to address congestion issues at the current GMT crossing. Key model outputs include traffic volume forecasts, components of traffic volume forecasts, travel time savings and vehicle operating cost savings and reliability benefits.

UPDATED TRAFFIC FORECASTS

Since the previous GMTR traffic forecasts and related business case was developed, an updated version of the regional transportation model (i.e. RTM3) has been developed and maintained by TransLink. This includes updates to land use inputs (population, households and employment), road and transit networks, and the formulation of the model. These refinements provide this tool with a higher level of detail and predictive capability for travel demand forecasting of major infrastructure projects. Recent application of the model to predict the traffic impact of toll removal on Port Mann and Golden Ears bridges, as well as ridership on the Evergreen Line, has shown that it is a reliable tool for travel demand forecasting of major infrastructure improvements. It is the latest available regional travel demand model and includes the more recent land use and network inputs.

Base Year Validation

Before forecasting future conditions, the base year model required extensive validation to ensure that it is replicating observed conditions. Off the shelf, RTM3 is calibrated and validated to regional traffic volumes, mode shares and travel patterns, and does not necessarily provide a sufficient level of detail and validation within a specific corridor such as Highway 99 or 91. Greater confidence in traffic forecasts is provided by ensuring that traffic volumes, trip distribution patterns and travel times are well represented for a specific facility. Various data sources were compiled to provide a set of validation metrics including automated traffic counts, ramp volumes (for trip distribution) and Google Maps API travel times. Some updates to network coding and model specification were required to fine tune the RTM3 within the Highway 99/91 study area. With these improvements, a sufficient level of model validation was achieved and provided a solid basis for developing the updated traffic forecasts.

Scenarios Analyzed and Key Assumptions

The following provides a summary of the various time periods, horizon years and network configurations that were modelled using RTM3:

- ***Land Use Horizons –*** The model was used to develop a 2017 base year and 2030 and 2045 future horizons. Land use forecasts for population, households and employment were based on Metro Vancouver’s officially adopted Regional Growth Strategy numbers.

- ***Time Periods –*** The RTM3 develops travel demand estimates on a 24-hour basis. Time slices from the model are then developed to provide estimates of travel demand for the morning peak hour (07:30-08:30), the midday period (12:00-13:00) and the afternoon peak hour (16:30-17:30). Note that these peak hours may not be the true peak, in which case time of day adjustment factors can be applied to represent this condition.

- ***Network Configuration –*** The model roadway network was updated for the following configurations:

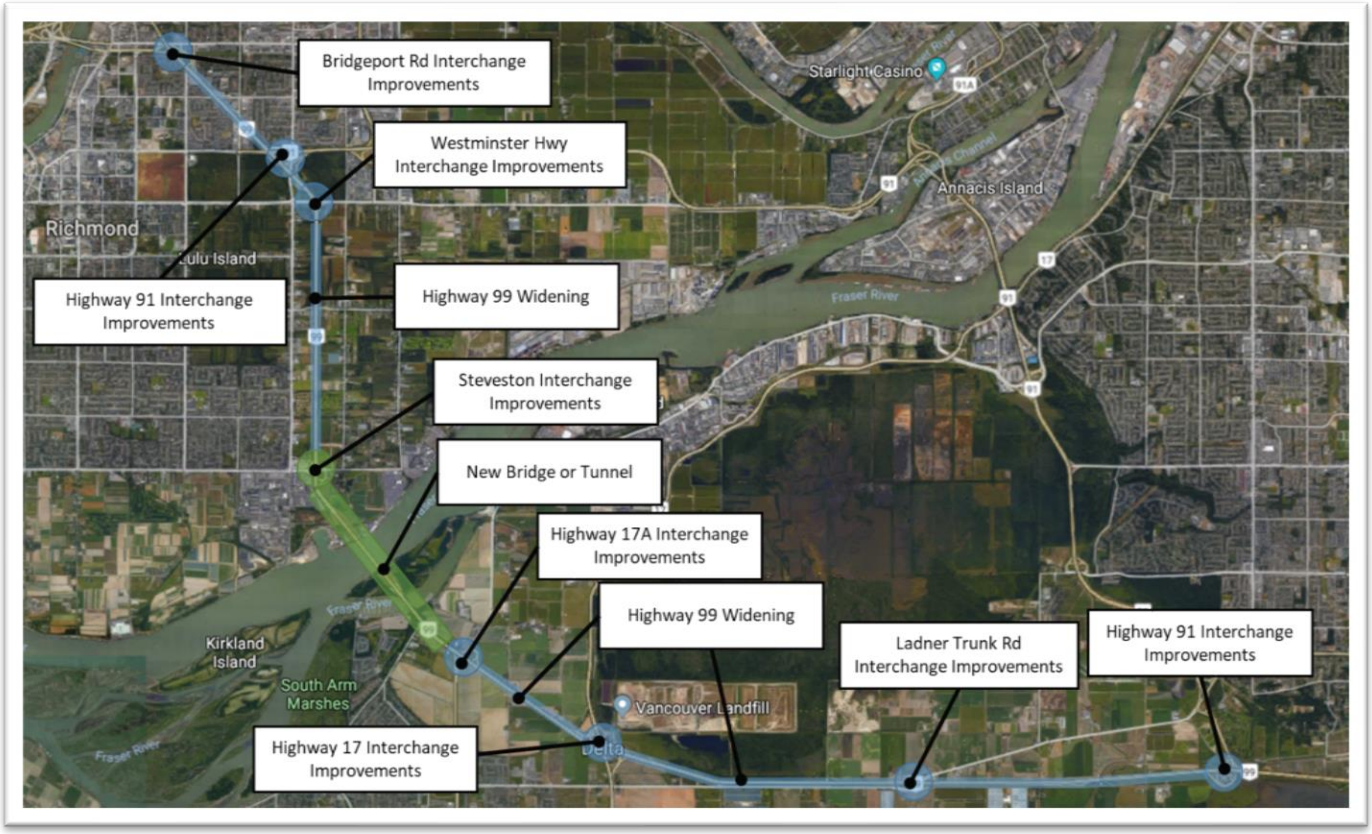
    - **Four-Lane Business as Usual (BAU)** – To represent a future business as usual which provides a basis for estimating travel time savings of any future improvement options.

    - **Six-Lane Do Minimum** – Provides a new six lane crossing of the Fraser River with no counter-flow operation. This includes improvements to the Steveston Highway interchange to accommodate higher traffic volumes accessing this municipal arterial.

    - **Ten-Lane Reference Concept** – This includes a new ten-lane crossing with extensive Highway 99 interchange and laning improvements as defined in the GMTR Reference Case.

These scenarios are illustrated in **Figure 2** which differentiates the ‘Do Minimum’ scenario in green and the ‘Reference Concept’ in blue. The Do Minimum includes the replacement of the crossing and improvements to the Steveston Highway interchange including the replacement of the two-lane Highway 99 overpass.

Figure 2: Extent of Do Minimum (Green) and Reference Concept (Blue) Improvements along Highway 99



Note: Do Minimum improvements are included in the Reference Concept.

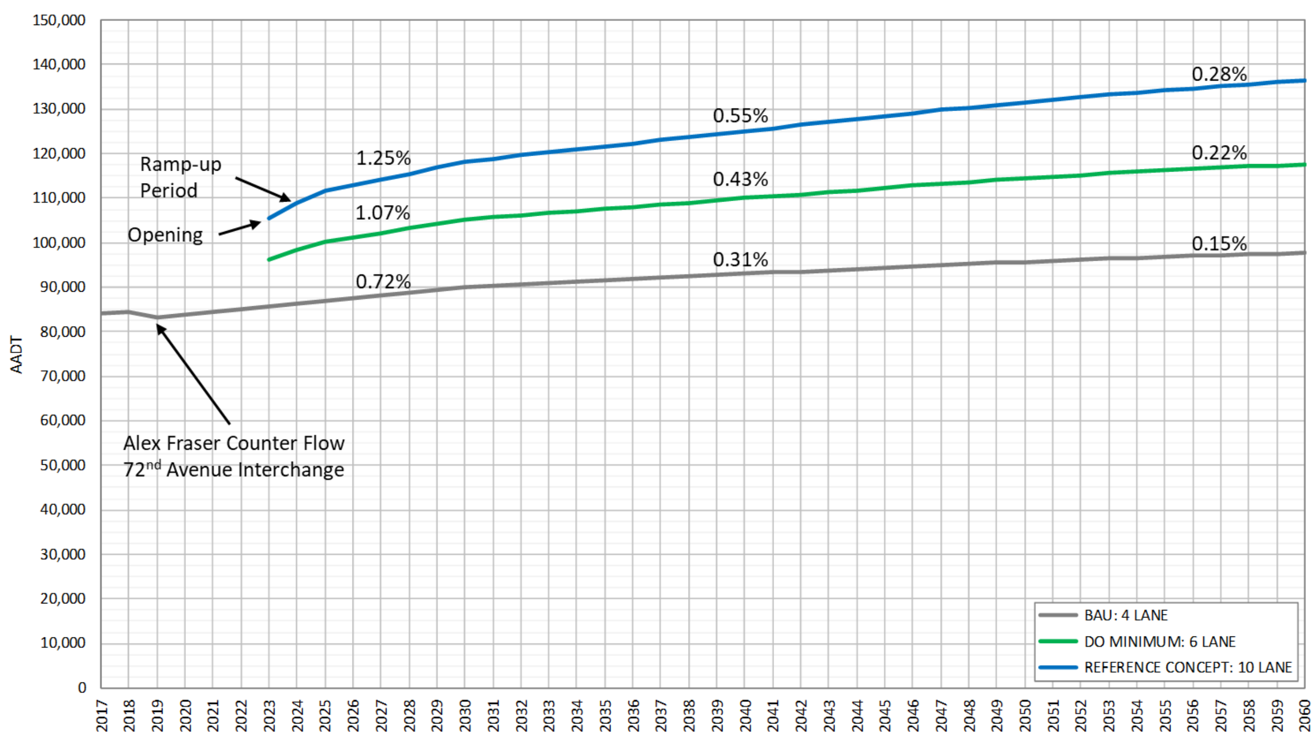
Other key model assumptions include the following:

- ***Other Relevant Infrastructure Improvements –*** Includes network improvements that have a high likelihood of occurrence (ie, funding committed or already underway) and a material impact to traffic using either Highway 91 or 99 within the study area. These include the following:
  - Alex Fraser Bridge Counterflow
  - Pattullo Bridge Replacement
  - 72nd Ave Interchange
  - 216th St Interchange
  - Surrey Light Rail Transit
- ***Special Traffic Generators –*** Includes expansion of Roberts Bank Terminal 2 which doubles container handling capacity at this deep-sea terminal.
- ***Pricing Variables –*** All economic variables are assumed to inflate at the same rate, such as incomes, value of time, fuel prices, parking, etc. No bridge tolls or mobility pricing options were included in this analysis.

Traffic Forecast Results

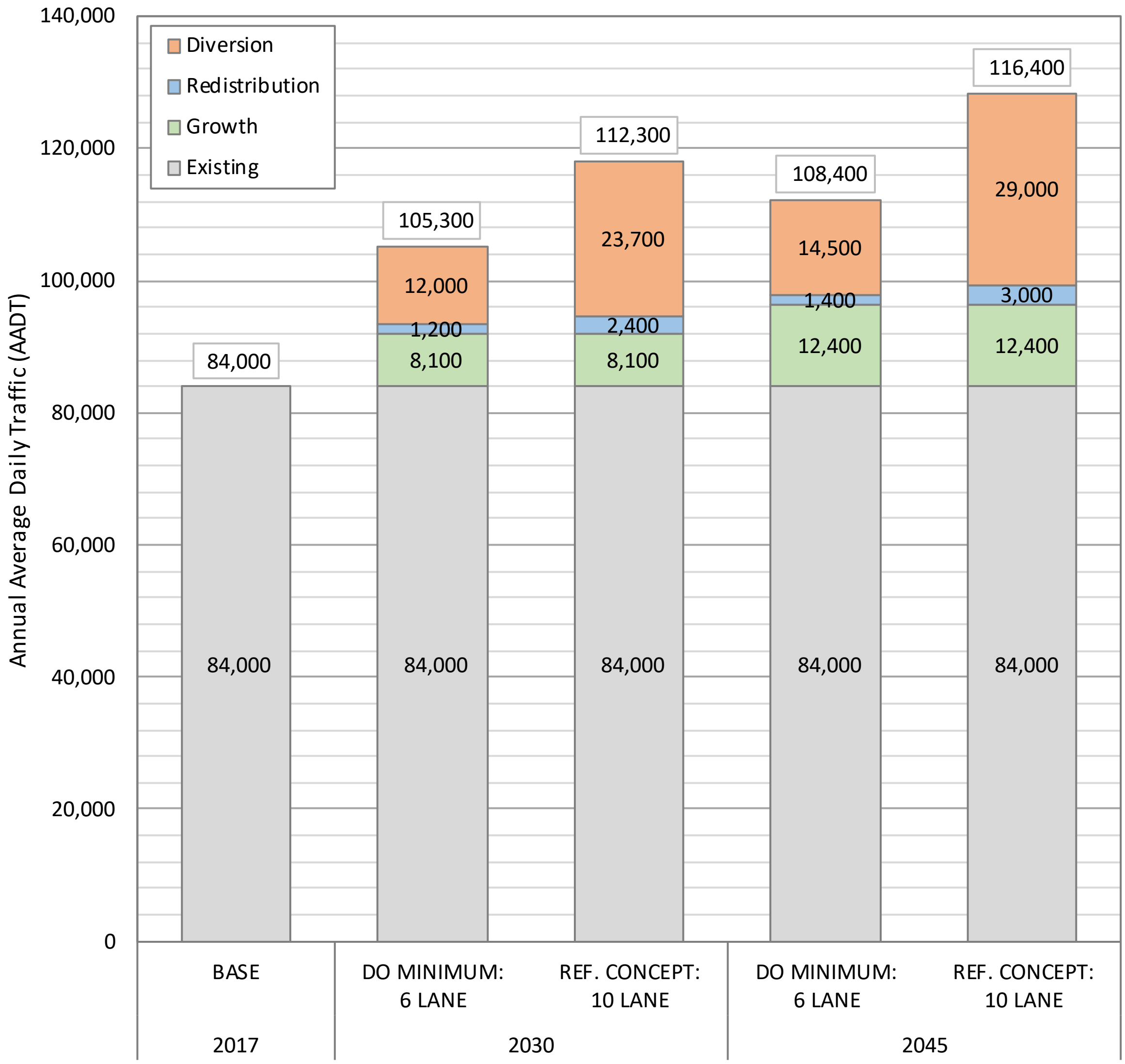
The RTM3 was used to develop updated traffic forecasts based on the growth and network assumptions. **Figure 3** below shows the traffic forecasts for the 4-Lane BAU, 6-Lane Do Minimum and 10-Lane Reference Concept expressed as average annual daily traffic (weekday and weekend). Note that there is a small decrease in GMT traffic volumes in 2019 with the opening of the Alex Fraser Bridge counterflow system. From opening day, the annual growth rates for the short, medium and long-term show that traffic initially grows fairly quickly, and then levels out over the long term. Capacity constraints in the 4-Lane BAU suppresses growth in traffic volumes, while any improvements provide travel time savings making the corridor more reliable and attractive. The 10-Lane Reference Concept grows to approximately 130,000 AADT in 2045, which is a similar volume that was carried on the 10-lane Port Mann Bridge just prior to toll removal in September 2017.

Figure 3: GMTR Updated Traffic Forecasts



The following chart (**Figure 4**) provides a breakdown of the components of the traffic forecasts for the 6-Lane Do Minimum and 10-Lane Reference Concept. Existing traffic is based on actual traffic count information today and forms the foundation for the traffic forecast. Growth is based on land use and economic development and generally depicts overall growth in travel demand across the Fraser River. Redistribution includes more travel with decreased access costs (travel times) across the Fraser River and can be interpreted as induced traffic. The largest component is derived from trip diversion from the Alex Fraser Bridge as the Highway 99 corridor becomes a much more attractive corridor with capacity enhancements.

Figure 4: Breakdown of Traffic Forecast Components

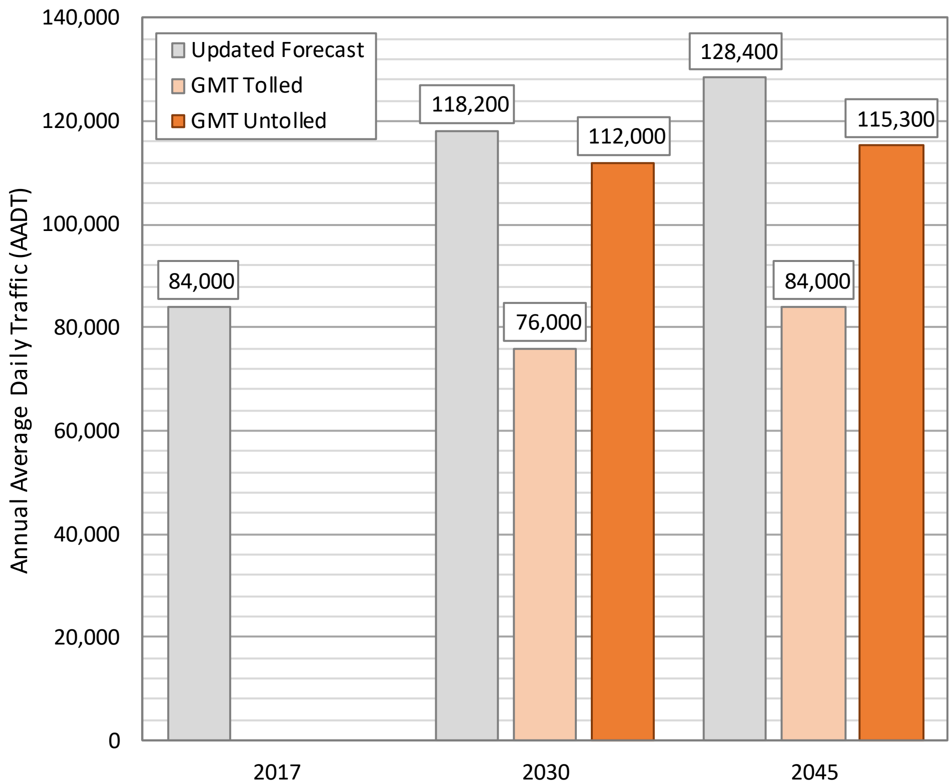


The 10-Lane Reference Concept clearly provides more capacity to cross the Fraser River. In terms of lane utilization, during the morning peak hour, the northbound general purpose (GP) lanes are about 74% utilized and the HOV/bus lane is about 55% utilized. Similarly, during the afternoon peak hour, the southbound GP lanes are about 84% utilized and the HOV/bus lane is about 71% utilized showing that there is spare capacity beyond 2045 with these enhancements.

Comparison to Previous Traffic Forecasts

The GMTR team produced traffic forecasts for a tolled and un-tolled 10-Lane Reference Concept scenario using the RTM Phase 0. **Figure 5** provides a comparison of the RTM3-based traffic forecasts to the previous GMTR forecasts. As shown, the updated model with extensive validation in the Highway 99 and 91 corridors is producing long-term traffic forecasts that are about 10% higher and there are several reasons why. Generally, the RTM3 is less sensitive to higher network costs in the distribution component of the model pushing more traffic across the Fraser River. Additionally, with better representation of network delay and slower network speeds, the RTM3 is more sensitive to changes in capacity in the assignment component of the model. This results in significant diversion related volume experienced in the traffic forecasts, as illustrated in **Figure 4** above.

Figure 5: 10-Lane GMTR Reference Concept Traffic Forecast Comparison



User Benefits

User benefits in the form of travel time and vehicle operating cost savings were calculated based on a 2023 opening date and 25 years of operation using the RTM3. All results were streamed back to 2018 using a 6% discount rate and are presented in 2018 dollars. The 10-Lane Reference Concept produces user benefits of $1.73 billion while the 6-Lane Do Minimum captures 42% of these benefits at $0.72 billion. The high proportion of the benefits captured by the 6-Lane Do Minimum is due to the large capacity increase in the off-peak directions during the peak periods (i.e. southbound in the morning peak and northbound in the afternoon peak) which sees significant congestion effects on the single lane provided during counterflow operation. The 6-Lane Do Minimum provides significant travel time benefits in the off-peak direction in the peak periods, providing operational speeds similar to the midday, off-peak period.

The peak direction also sees additional benefits as a new 6-lane crossing would be built to modern design standards and the inside lane would be physically separated from oncoming traffic. Today, the counterflow lane operates without a physical barrier which some drivers may shy from resulting in a fairly low lane utilization rate.

There are additional travel time, reliability and capacity benefits of providing additional capacity in the peak direction on the crossing, but approximately half of the benefits provided by the reference concept are attributable to the highway mainline and access improvements at interchanges along the corridor on either side of the crossing. These benefits are not captured in a do minimum option.

There are limited additional benefits provided by the 10-Lane Reference Concept in the short-term as the majority of the congestion has been relieved by the 6-Lane Do Minimum. The 10-Lane Reference Concept does provide benefits in the longer term with improvements to peak direction travel times and provides additional relief to the Alex Fraser bridge as well due to traffic diversion from Highway 91.

8-Lane Do Minimum and 8-Lane Reference Concept scenarios were modelled as well to determine how benefits are derived in the study area. These two scenarios are defined as follows:

- ***8-Lane Do Minimum –*** Same as the 6-Lane Do Minimum but with auxiliary lanes between the Steveston and Highway 17A interchanges
- ***8-Lane Reference Concept –*** Same as the 10-Lane Reference Concept but with the HOV/bus lanes removed between the Steveston and Highway 17A interchanges

In addition to travel time and vehicle operating cost savings, any improvements to GMT will result in reliability benefits. The current crossing sees significant variability in travel times due to accidents, vehicle stall, etc. In order to estimate reliability benefits, travel time information was gathered for the region and the average uncertainty in travel times was calculated. Then, with any improvement in capacity, an estimate in travel time reliability reduction was estimated. The 10-Lane Reference Concept results in an additional $509 million in NPV of reliability benefits. The 6-Lane Do Minimum achieves approximately 36% of these reliability benefits as it provides a capacity improvement in the off-peak direction. The 8-Lane Do Minimum achieves 46% and the 8-Lane Reference Concept achieves 98% of the reliability benefits, similar to the travel time and vehicle operating cost savings.

The following table (**Table 1**) provides a summary of the travel time and reliability benefits as a proportion (%) of the 10-Lane Reference Concept for the other options that were analyzed.

Table 1: Summary of Traffic Forecasts and User Benefits for GMTR Options

GMTR Option	Lane Configuration	Future Traffic Volume (2045 AADT)	2045 PM Peak Travel Times (mm:ss)		Travel Time and Operating Cost Benefits (NPV $ 2018)	Reliability Benefits (NPV $ 2018)
			NB	SB		
4-Lane Do Nothing	2/2 GP (Off Peak) 3/1 GP (Peak Counter Flow)	74%	31:30	35:00	0%	0%
6-Lane Do Minimum	3/3 GP	87%	16:10	33:50	42%	36%
8-Lane Do Minimum	4/4 GP	91%	15:10	32:30	50%	46%
8-Lane Reference Concept	4/4 GP	99%	13:25	17:30	95%	98%
10-Lane Reference Concept	4/4 GP + 1/1 HOV/Bus	100%	13:20	17:00	100%	100%
Summary Metric		128,400	-	-	$1,734 million	$509 million

The 6- and 8-Lane Do Minimum scenarios serve 87% and 91% of the 10-Lane Reference Concept traffic volumes. The 8-Lane Do Minimum achieves approximately half of the user benefits (travel time, vehicle operating cost savings and reliability) of the 10-Lane Reference Concept while the 8-Lane Reference Concept achieves close to 100% of the benefits of the 10-Lane Reference Concept. In terms of timing, the short-term need would be to replace the crossing (Do Minimum) and then provide the corridor improvements (Reference Concept) for the longer term. This would provide improvements that are “right sized” for the corridor context and aligned with the forecasts of traffic. Further, the corridor improvements can be staged over time and added as congestion trigger points are reached.

Regional Context

The GMTR project fits into a larger regional context and should reflect the larger goals and targets identified in the long-term plans for the region. The current Regional Transportation Strategy (RTS) developed by TransLink in 2013 sets out a long-term vision through the 2045 horizon year. A list of priority initiatives in support of this vision were identified in the 10-Year Vision, developed by the Mayor's Council in 2014 which is anticipated to be delivered in a series of phases as funding becomes available. Some key targets in the RTS involved designing the transportation system to support 33% shorter driving distances and a 50% active mode share target by the 2045 horizon year.

Although replacing the existing GMT with a higher capacity option is in contrast with the vehicle kilometres travelled (VKT) and sustainable mode share targets set out, there are other elements of the RTS that apply. The removal of most congestion in the project corridor with the GMTR reference case is supportive of many goals stated in the RTS, such as:

- Making travel more reliable;
- Increasing transportation options;
- Making it easier and less stressful to get to work and school;
- Giving us more time for doing the things we love;
- Ensuring businesses continue to prosper with better access to more workers and more markets;
- Making living, working and doing business in this region more affordable;
- Giving people better access to more jobs and more opportunities; and
- Making our roads safer.

A 6- or 8-lane option is more compatible with the RTS than the 10-Lane Reference Concept. Both scaled down options still provide significant relief to congestion, but at the same time provide an incentive for high occupancy vehicle and transit travel. Further, any future forms of travel demand management or mobility pricing would help ensure that a 6- or 8-lane option performs at optimal traffic levels.

Next Steps

The analysis presented in this report has provided a high-level review of options for replacement of the GMT and the benefits that are derived. There are additional next steps that would help to refine the analysis and address outstanding questions as follows:

1) **Refinement of the Do Minimum concept**
    a) Value of additional corridor improvements in immediate vicinity of crossing for 6- and 8-Lane Do Minimum;
    b) Costing of the 6- and 8-Lane Do Minimum options;
    c) Additional benefits and environmental impacts such as change to vehicle-kilometres travelled which is a metric tracked at the regional level and is a proxy for emissions along with vehicle-hours travelled;
    d) More refined analysis of potential safety benefits; and
    e) Incremental benefit/cost or value for money analysis for the various options.
2) **Refinement of the Reference Concept**
    a) Costing/Affordability/Benefits;
    b) Trade offs of different crossing capacity vs policy management options (utilization over 24 hours, tolls, travel demand management, mobility pricing);
    c) Right-sizing interchange designs for updated crossing configuration;
    d) Transit integration including consultation with TransLink; and
    e) Regional policy impacts (mobility pricing, sustainable mode targets, coordination with the RTS), and ability to manage congestion with other policy levers.
3) **Staging of ultimate corridor buildout, with refinements**
    a) Richmond corridor/interchanges value-for-money and potential timelines;
    b) Delta corridor/interchanges value-for-money and timelines;
    c) Triggers for improvements (regional and municipal plans); and
    d) Comparator to other highway improvement projects (Brunette Interchange, Lower Lynn interchanges, 216th Interchange and Highway 1 widening).

1. INTRODUCTION

1.1. BACKGROUND CONTEXT

The George Massey Tunnel (GMT) provides a significant 'gateway' facility for Metro Vancouver along the Highway 99 corridor connecting the US border, BC Ferries, deep sea terminals at Roberts Bank and communities on both sides of the Fraser River. Traffic volumes across GMT have remained relatively stable over the past few decades around 80,000 vehicles per day with significant congestion during the morning and afternoon peak periods. The neighbouring 6-lane Alex Fraser Bridge (AFB) has absorbed additional traffic volume growth since it has had spare capacity but is now also congested. Both the GMT and AFB crossings provide a couplet system linking both Highway 91 and 99 through Delta and Richmond. For longer distance trips, the choice between GMT and AFB is very close in terms of travel times. With both facilities experiencing significant congestion levels during peak times today, there is likely a level of traffic suppression occurring where people choose to not cross the Fraser River. This is a similar effect that happened when the AFB opened in 1986 or when the Golden Ears Bridge opened in 2009 and there was a significant ramp up in traffic volumes in the first few years of operation.

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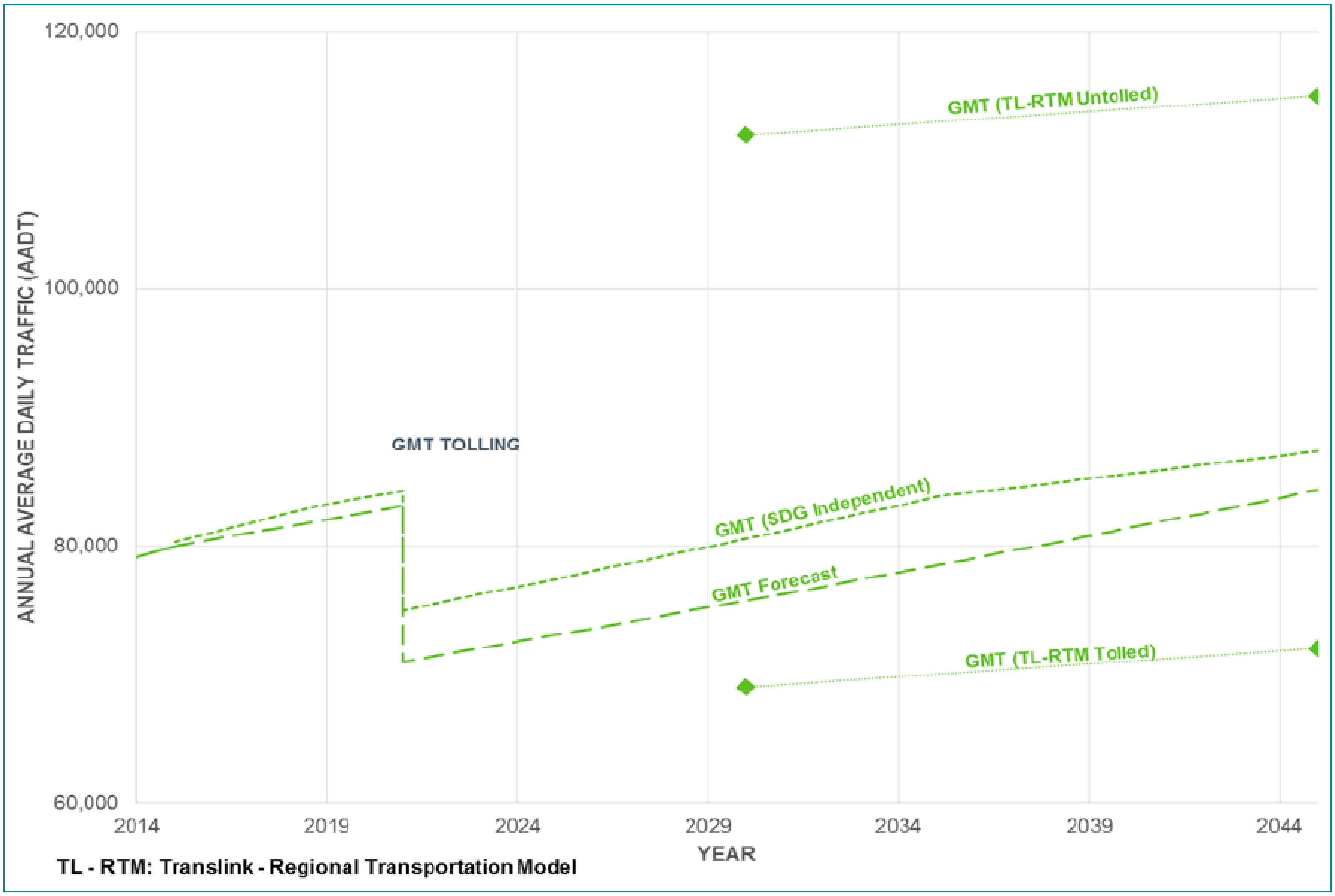
1.2. GMTR PROJECT TRAFFIC FORECASTS

As part of developing the GMTR business case, several methods to forecast traffic volumes were employed. **Figure 6** provides a summary of the range of previous traffic forecasts that were developed. The following describes how the GMTR Project estimated traffic impacts and future demand levels. In each case, the models were generally developed using sound judgement and traffic engineering/travel demand modelling principles accepted in industry at that time. As such, the traffic forecasts result in reasonable estimates within the accuracy of the models available at the time. Lack of base year validation within the study area corridor, however, was a deficiency in some of these previous attempts. In other words, there was limited information that provided a comparison of the modelled versus observed travel conditions (ie, traffic volumes, travel times, etc.) in the current year. This appears to be a deficiency in both the regional modelling tool at the time as well as the project traffic forecasting that was undertaken.

Figure 6: Range of Previous GMTR Traffic Forecasts



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RTM

Separately from the GSAM development, TransLink had developed the Regional Transportation Model (RTM) which modelled regional travel behaviour on a 24-hour basis and provided individual time slices for the AM and Midday time periods. This model was formulated using information from the 2011 TransLink Trip Diary and 2011 Census surveys.

The trip diary survey includes a random sample of households that are asked questions about their previous days travel including trip origin/destination, time of day, trip purpose, trip mode, etc. The level of network detail in the initial version of the RTM was significantly less than the GSAM which had seen numerous updates over the previous decade in the Gateway project corridors. The behavioural complexity and level of disaggregation of the RTM was significantly more detailed than the previous peak-period focused models. An early development snapshot (RTM Phase 0) was provided to the GMTR project for use in evaluating the project. This was a beta release of the regional model that was available at the time that had 641 traffic zones.

A PM time period was added to the RTM Phase 0 snapshot for the project as a separate slice of the 24 hour demand, but was not integrated into the overall model formulation, leaving it fundamentally driven off of the AM and Midday time periods. A validation report that provides a comparison of modelled versus observed travel conditions for the modified model was not provided making it difficult to evaluate the appropriateness of the model for use on tolled facilities or the project corridor in general. There were significant issues identified in this model being overly sensitive to tolling in addition to the large levels of demand adjustment present in the base model calibration. Demand adjust is applied to the model matrices as an adjustment factor to force the model to fit observed traffic counts.

Congestion Throughput Model

The RTM's lack of a validation report to observed conditions prompted the creation of a congestion estimation model based on calibrating measured delay to tunnel throughput measured by the Ministry's Advanced Traveller Information System (ATIS) through Bluetooth sensor capture along the Massey corridor. This model was calibrated to the directly measured volume and delay information for an entire year and provided a link from the modelled delay to total annual delay based on direct measurement.

The throughput model appears to be well calibrated to observed conditions and provides some insight into how weekday volume and delays relate to total annual values in the Massey corridor which is very useful when expanding the peak period models to annual values, particularly for user benefits. The congestion values produced by this model are highly dependent on the traffic arrival patterns and per-lane throughput assumptions made when evaluating the project options in the future and are difficult to quantify as the model is directly estimated from observed conditions and not a separate theoretical model based on traffic engineering fundamentals. In other words, this model fits well to observed conditions today but there is no theoretical basis from traffic engineering principles to support the levels of congestion forecast in the future. Some benchmarking of future congestion levels would be helpful to validate the congestion throughput model.

Econometric Demand Model

An independent econometric model was commissioned as a comparator to the forecasts developed previously by the project team and estimates the change in travel demand based on indicative regional measurements such as GDP, population, employment and other regional indicators. Retention of demand after applying tolling was estimated from the limited experience on the Port Mann Bridge to that point in time. The elasticity in travel demand to these indicators can vary widely and is highly context dependent as it implicitly represents the availability of alternatives in the urban setting and are most appropriate to benchmark the long-term growth potential of travel demand into the future. A review of this model shows that the assumptions and approach were sound and the outcomes reliable given the availability of data at the time.

1.3. ITR – TRAFFIC FORECAST: PURPOSE & OBJECTIVES

The purpose of this study is to demonstrate the validation of RTM3 within the Highway 99 corridor context and application for travel demand forecasting. The RTM3 is the latest available travel demand forecasting model that is suitable for application within the Highway 99 corridor. It has been recently updated and calibrated using latest available travel survey and traffic count information. Updated traffic forecasts for the GMTR were produced for various options for the 2030 and 2045 horizons. Consumer surplus calculations were then carried out to estimate user benefits in terms of travel time savings, vehicle operating cost savings and reliability benefits. The objective of this study is to demonstrate the effectiveness of each option to address congestion issues at the current GMT crossing. Key model outputs include traffic volume forecasts, components of traffic volume forecasts, travel time savings and vehicle operating cost savings and reliability benefits.

1.4. REPORT OUTLINE

This traffic technical report is presented in five sections including this introduction. **Section 2** provides a primer on travel demand modelling, application in the Metro Vancouver region and specification of the current regional model. **Section 3** provides detailed information on the validation of RTM3 in the Highway 99 corridor context including traffic volumes, travel times and trip distribution patterns. **Section 4** provides a summary of the traffic forecasts for various GMTR laning options for the 2030 and 2045 horizons. **Section 5** provides the estimates of user benefits using the consumer surplus methodology and an updated methodology to produce an estimate of reliability benefits.

2. TRANSPORTATION DEMAND MODELLING BACKGROUNDER

This section provides background information on travel demand modelling, how the current RTM3 is specified, and recent application of the model.

2.1. TRAVEL DEMAND MODELS

A Travel Demand Model (TDM) is a tool consisting of several interlinked components. It is used by transportation professionals, mainly planners and engineers, to accomplish various tasks such as estimating the number of vehicles or people that will use a major transportation facility in the future (e.g. freeway, bridge or rapid transit line). A TDM can also be used to assess the regional impacts of proposed transportation, land-use and policy initiatives such as a future rapid transit project, urban densification or the tolling of a road facility. Some of these impacts can include shorter commute times, a shift in travel mode from personal vehicles to transit, or a change in green-house gas emissions. The Metro Vancouver region has relied on a TDM for over 25 years to evaluate everything from multi-million dollar transportation projects to transit routes in support of its sustainable and economic vision for the future. Some of the region's signature transportation facilities such as the Canada Line and Golden Ears Bridge were evaluated using a TDM.

The region's first TDM was developed in the mid-80s. It was used at the time to forecast the expected ridership on the Expo Line which became operational in 1986. Since then, the TDM has undergone periodic updates to reflect shifts in the region's socio-economic attributes, transportation network and travel behaviour. In addition, advancements in computing power and the increasing availability of travel data over the last 20 years has allowed for more sophisticated modelling processes to become standard practice within the TDM framework.

There are several specialized software platforms available for regional transportation demand modelling. The software used for Metro Vancouver's model is called EMME; short for Equilibre Multimodal/Multimodal Equilibrium. Developed by INRO, a company specializing in transportation planning software development and based in Montreal, Canada, the EMME software platform is used worldwide by many municipalities and regions to plan and develop their transportation networks.

TDMs are developed and calibrated to reflect current travel patterns and network conditions. Afterwards, they are used to forecast future travel conditions usually based on land use growth estimates and network assumptions. The horizon for these forecasts is typically about 20 to 30 years. There are several inputs required to develop a TDM's components. These include land use/demographic inputs (e.g. population and employment figures), a representation of the region's transportation network and a travel survey. A travel survey provides information on the current travel patterns (origin / destination (OD), mode, purpose, time of day, etc.) of a representative, random sample of the population. This region's TDM follows the industry standard four-step travel demand modelling approach. The four-step model is a sequential framework that was first developed and implemented in the 1950s for the Detroit and Chicago Metropolitan Areas. In this approach, a region is split into smaller geographical components, referred to as traffic analysis zones (TAZs). The four-step model is further illustrated in **Figure 7**.

Figure 7: Four-Step Travel Demand Model Process

Step 1: Trip Generation

- The process of estimating the number of trips (such as work trips or school trips) originating from and destined to various TAZs.
- Productions defined as trips from "i" zone and attractions to "j" zone.

Step 2: Trip Distribution

- The process of modelling 'where trips go' - In other words, this step involves distributing trips from an origin TAZ to various TAZ destinations in the region.
- Number of trips (T) from i zone to j zone.

Step 3: Mode Choice

- The process of splitting the total number of modelled trips between every TAZ pair into various travel modes – For example if the total number of modelled trips between two TAZs is 100, the mode choice step can split these into 70 trips by vehicle and 30 by transit.
- Trips from i zone to j zone by mode.

Step 4: Trip Assignment

- The process of determining the route choice taken by the trip maker – For example, if there is more than one route connecting two TAZs, the trip assignment process splits the trips between the routes based on various factors such as total travel time and cost of each route.
- Trips from i zone to j zone by route.

Earlier versions of the regional TDM focused on the representation of travel occurring in specific travel periods during the day such as the AM or Midday peak hours, while more recent versions have been formulated to estimate the 24-hour travel demands which are then assigned to specific peak periods. In other words, previous models were developed for specific time periods such as the AM peak, while the latest model conducts the first three stages of the demand model on a 24-hour basis and then is time-sliced for the peak periods before the trips are assigned to the network.

2.2. MODEL APPLICATION IN THE REGION

The application of the travel demand model includes a range of projects. Some of these applications include - economic and engineering design studies related to urban growth; demand management analysis; and transportation project facility improvements. The model can be used for long range strategic planning studies or more detailed studies for individual development impacts. For example, it can be used to assess the travel impacts resulting from significant urban densification at regional town centres. It can also be used to compare the benefits and costs of building a Bus

Rapid Transit (BRT) line versus a Light Rail Transit (LRT) line running on a specific corridor in the region or a highway expansion or interchange development project.

All of these applications can be summarized in response to three basic questions at different levels of detail:

- What impacts on travel conditions can be expected from land development or demographic changes?
- What changes to travel conditions can be expected from specific improvements to the transportation system including network improvements or service enhancements?
- What impacts on travel demand levels result from changes to travel costs including parking fees, transit fares or bridge tolls?

It is important to note that despite the complex range of operations performed in the regional TDM framework, it remains a simplification of reality. A TDM is most accurate when used as a comparative tool and should be used primarily in that role. Many of the data inputs, as well as the frameworks used to estimate travel represent average / typical conditions or behaviour. Therefore, it is not possible to replicate the real world in all its complexity and variability. While the model can produce reasonably accurate estimates of travel over a transportation system in general and reasonable comparisons with observed counts on many individual road and transit links, significant variations between observed and estimated values remain in several cases that cannot be logically explained. After all, the TDM is a human behaviour model and decisions made are not always rational nor easily expressed mathematically. What is most important is to validate (discussed further in **Section 3**) and assess the TDM outputs and benchmark against actual behaviour using real world examples. That way, model outputs can be properly interpreted which provides more confidence in the TDM forecasts.

TDMs are regional in scale and should be used for analysis within that context. For studies at a smaller scale, such as the design of signal timing at intersections or analysis of traffic queues at a particular location, other transportation planning tools tailored for those specific needs are available. In fact, the regional TDM is one part of a hierarchy of complementary tools available for transportation planners and engineers.

2.3. PREVIOUS REGIONAL MODELS

The application of a TDM to evaluate major infrastructure investments has a long history in the region. All of the major rapid transit projects were evaluated during the planning process using the TDM available at the time. This includes the original Expo line which precipitated the creation of the first Regional TDM and all later rapid transit projects such as the Millennium Line, the Canada Line and the Evergreen extension. The TDM was used to evaluate different technologies, station locations and alignments when developing the business cases and supporting the design process. Both of the major rapid transit projects identified in TransLink's 10-year capital plan, the Millennium Line Broadway Extension and the Surrey-Newton-Guildford Light Rail project were evaluated using earlier versions of the regional TDM.

The MoTI Gateway program invested significant effort in the development of an enhanced TDM (GSAM) to evaluate the major roadway projects considered as part of the investment program. These included the PMB / Highway 1 expansion, SFPR, GEB and Pitt River Bridge replacement. An updated version of this model was applied in the early stages of the GMTR project for initial traffic forecasts before moving on to an early development version of the RTM. Recent business cases for the Pattullo Bridge replacement and a gondola to SFU were completed using TransLink's more recent RTM to develop traffic volume forecasts and inputs to the multiple account evaluation process used to select a preferred replacement option.

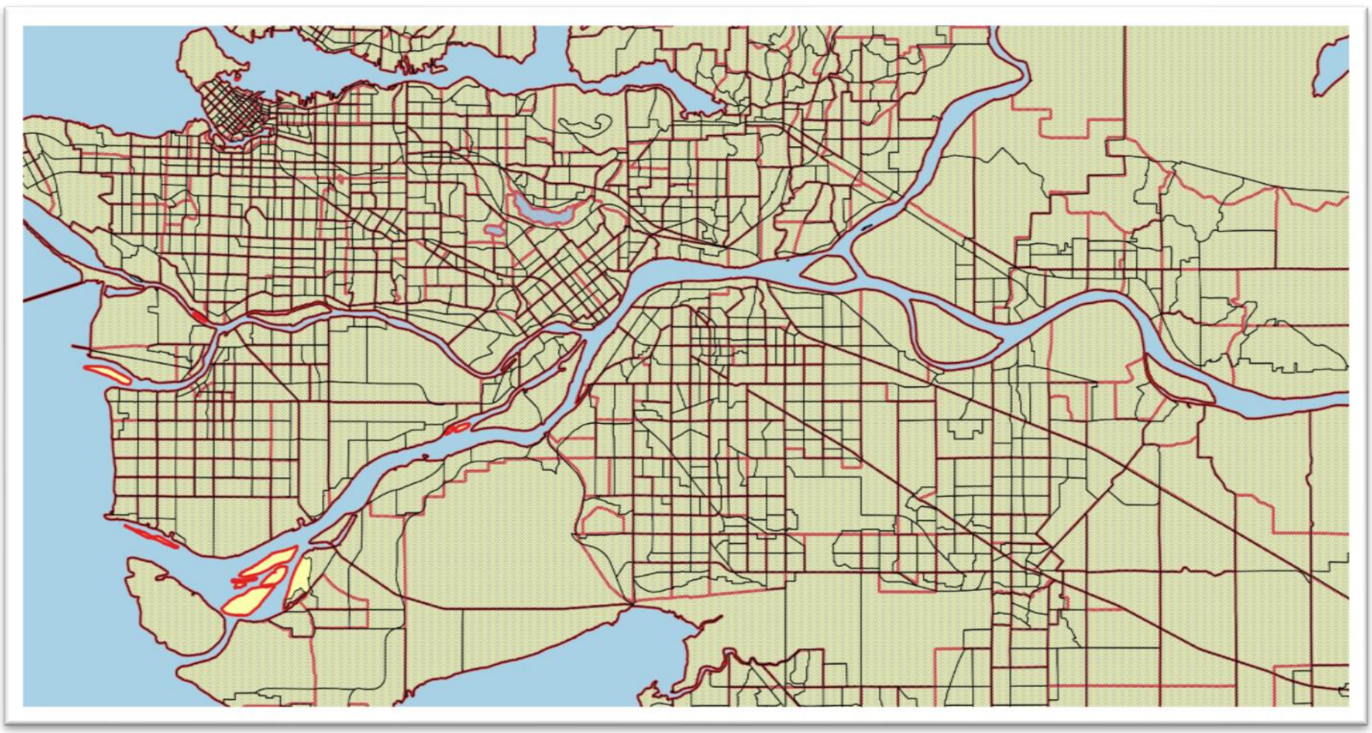
Other longer term regional planning projects such as the Mobility Pricing Independent Review and the update to TransLink's Regional Transportation Strategy (RTS) will leverage the RTM3 to evaluate pricing and infrastructure policy impacts through the 2045 time horizon which provides the basis for long term planning in the region. This context will inform which projects are consistent with the objectives of increasing regional sustainable mode share, reducing vehicle kilometres travelled (VKT) and greenhouse gas emissions (GHG), and supporting sustainable regional development.

2.4. SPECIFICATIONS OF CURRENT MODEL (RTM3)

Since the previous business case for the GMTR was developed, an updated and improved version of the regional transportation model has been developed and adopted for infrastructure planning. This includes updates to land use inputs (population, households and employment), road and transit networks, and the formulation of the model. These refinements provide this tool with a higher level of detail and predictive capability (compared to the previous GSAM and RTM beta release) for travel demand forecasting of major infrastructure projects. Recent application of the model to predict the traffic impact of toll removal on Port Mann and Golden Ears bridges, as well as ridership on the Evergreen Line, has shown that it is a reliable tool for travel demand forecasting. The following provides more specifics on the recent enhancements to the RTM3.

- ***Updated Traffic Zone System –*** The traffic zone system was disaggregated from a previous 641 zone system to a 1,700 zone system as shown in **Figure 8** below. This higher level of detail provides more accurate representation of land use patterns and network costs, particularly in more developed areas.

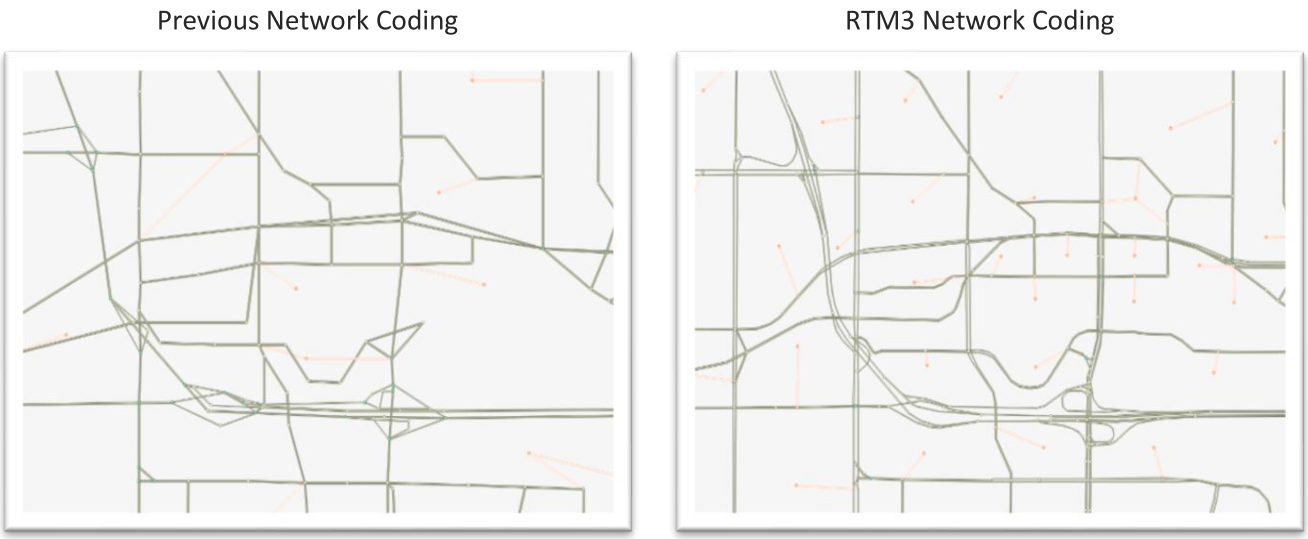
Figure 8: Comparison of 641 Traffic Zone System (Red) to Updated 1,700 Zone System (Black)



- ***Updated Road and Transit Networks –*** The road network was previous coded manually which was a time-consuming process that was inconsistent and prone to human error. A new systematic approach to coding the network was employed to develop a network from a properly geocoded transportation network. Better representation of the network in terms of roadway geometry, connectivity and travel distances resulted in more accurate representation of network costs and travel demand patterns.

Figure 9 provides an illustration of the previous network coding and the updated RTM3 network coding showing the higher level of network representation and accuracy.

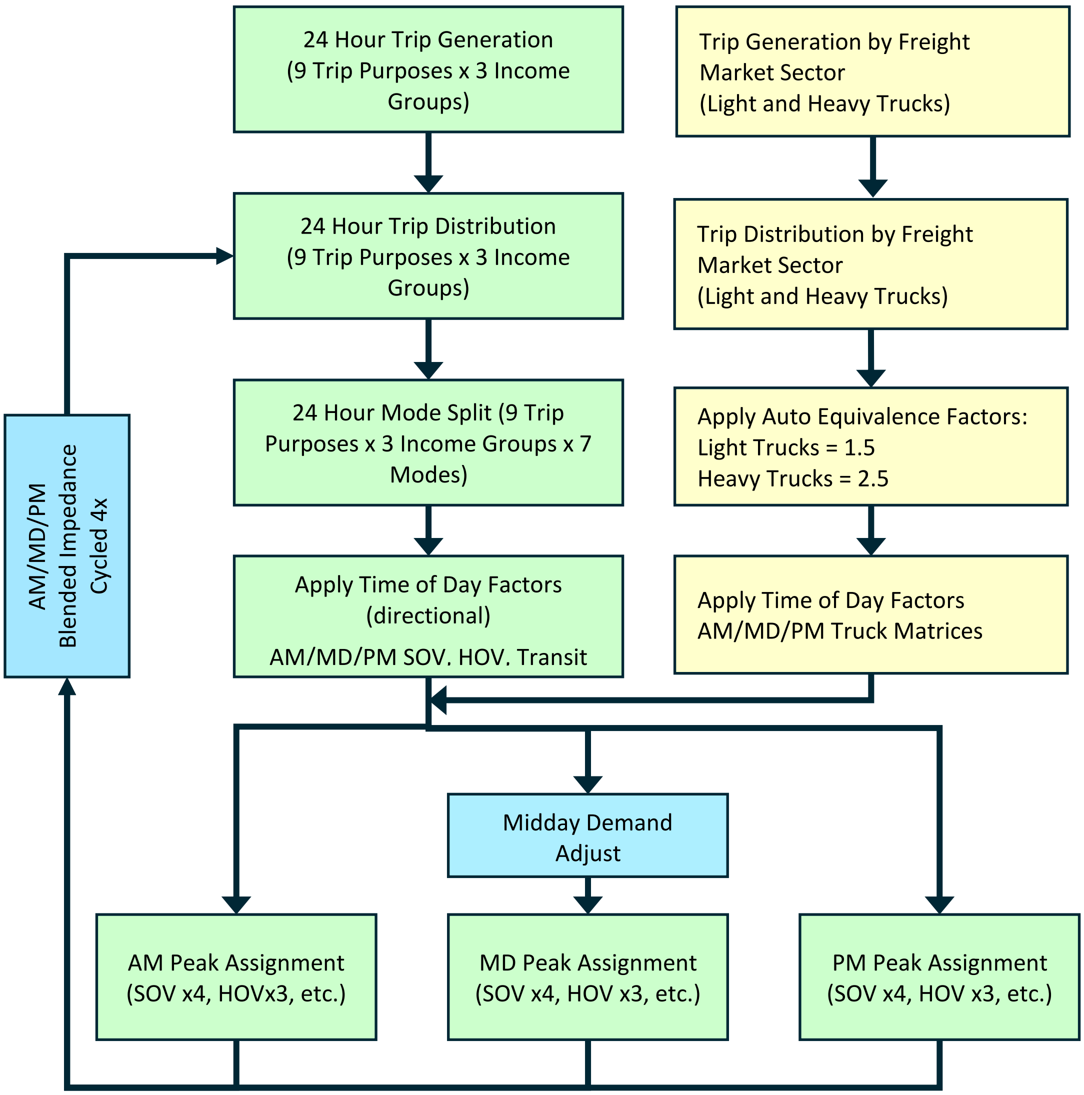
Figure 9: Comparison of Previous Network Coding to RTM3 Coding



- ***Updated Model Formulation and Other Elements –*** The following additional enhancements were made to the RTM3:
  - Addition of PM time period to model the busiest time period in the region;
  - Midday demand adjust applied within model cycling so that adjustments to travel demand are reflected in network costs and other components of the model;
  - Distribution and mode split developed at production-attraction level rather than origin-destination to better represent directionality of travel during peak times;
  - Updated directional time of day factors for time slicing to better represent travel volumes;
  - Volume delay function (VDF) updates and changed formulation to better represent network travel times and congestion effects;
  - Transit assignment is congested and capacitated to better represent capacity of the transit system; and
  - Application of heavy vehicle passenger car equivalent (PCE) factors to better represent the impact of larger and slower moving vehicles on the network.

Figure 10 provides the general structure of the RTM3 four step travel demand model and generally how the model cycles through the different steps. It also shows the truck sub model that is applied outside the four-step commuter model, but then integrated just before the trip assignment stage. After the assignment stage, network costs are fed back into the trip distribution stage so that updated distribution patterns and mode choices can be made. The model generally cycles through trip distribution and assignment until a state of equilibrium has been reached. The equilibrium component works in such a way that each traveller seeks to minimize their travel costs on a congested network for their trip from origin to destination. By definition, a model has reached equilibrium when users can no longer find a faster path from origin to destination by choosing a different route.

Figure 10: General Structure of the RTM3 Four Step Travel Demand Model



3. BASE MODEL VALIDATION

Before forecasting future conditions, the base year model required extensive validation to ensure that it is replicating observed conditions. The base year model is simply a scenario that represents today's conditions. Generally, the regional transportation model is calibrated and validated to fall peak conditions when students are attending classes, employees travel to work and commute patterns are fairly consistent. Off the shelf, RTM3 is calibrated and validated to regional traffic volumes, mode shares and travel patterns, and does not necessarily provide a sufficient level of detail and validation within a specific corridor such as Highway 99. Greater confidence in traffic forecasts is provided by ensuring that traffic volumes, trip distribution patterns and travel times are well represented for a specific facility. Various data sources were compiled to provide a set of validation metrics including automated traffic counts, ramp volumes (for trip distribution) and Google Maps API travel times. Some updates to network coding and model specification were required to fine tune the RTM3 within the Highway 99 and 91 study area. With these improvements, a sufficient level of model validation was achieved and provided a solid basis for developing the updated traffic forecasts.

3.1. TRAFFIC VOLUME VALIDATION

Traffic volumes are one of the key metrics produced by the regional transportation model and are instrumental in terms of model validation. The EMME-based traffic volumes are an estimate of demand and not necessarily a true reflection of throughput; the amount of traffic served across the Fraser River. Traffic counts provide a measure of throughput generally on a 15-minute or hourly basis. Any queuing is then a measure of total demand that may be served outside the true peak hour. Observed queuing on Highway 99 is then an indication that traffic demand is greater than throughput or capacity. Available traffic count information from the GMTR data room as well as latest information from the Ministry of Transportation and Infrastructure permanent counters were compiled.

Figure 11 provides a summary of the northbound and southbound traffic volumes, both modelled and observed, for the current George Massey Tunnel. As shown, the model is generally predicting higher than observed traffic volumes across the Fraser River. As mentioned, the model provides a measure of demand and, overall, the model is replicating the actual measured peak and off-peak directions within 10-15%. **Figure 12** and **Figure 13** provide network volume plots showing the difference between observed volumes (in blue outline) and modelled volumes (in solid red) for the morning and afternoon peak hours respectively. The model validates very well to overall traffic volumes, with the exception of Highway 91 eastbound along the East-West Connector in Richmond where the model is low during the morning peak eastbound and low during afternoon peak westbound. The remaining links fit very close to the observed volumes providing confidence that the model is replicating observed conditions.

Figure 11: Peak Period GMT Traffic Volume Validation (AM)

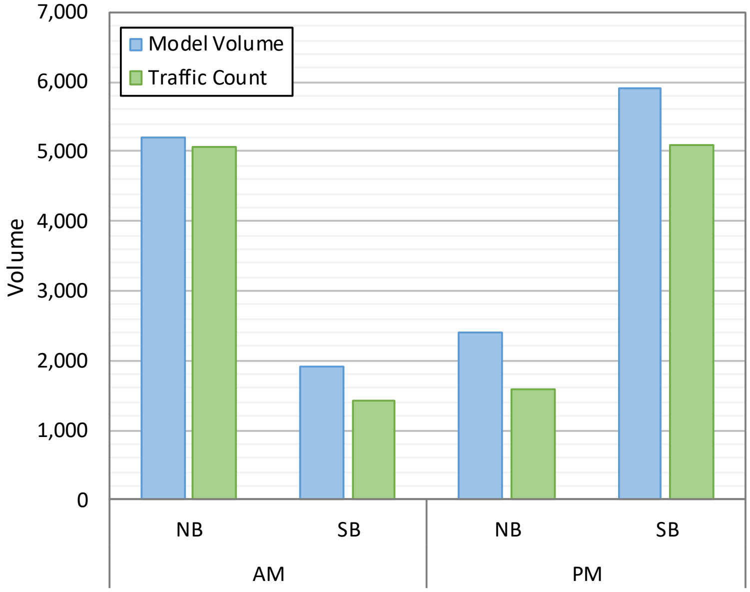


Figure 12: 2017 AM Traffic Volume Validation Plot (7:30-8:30am)

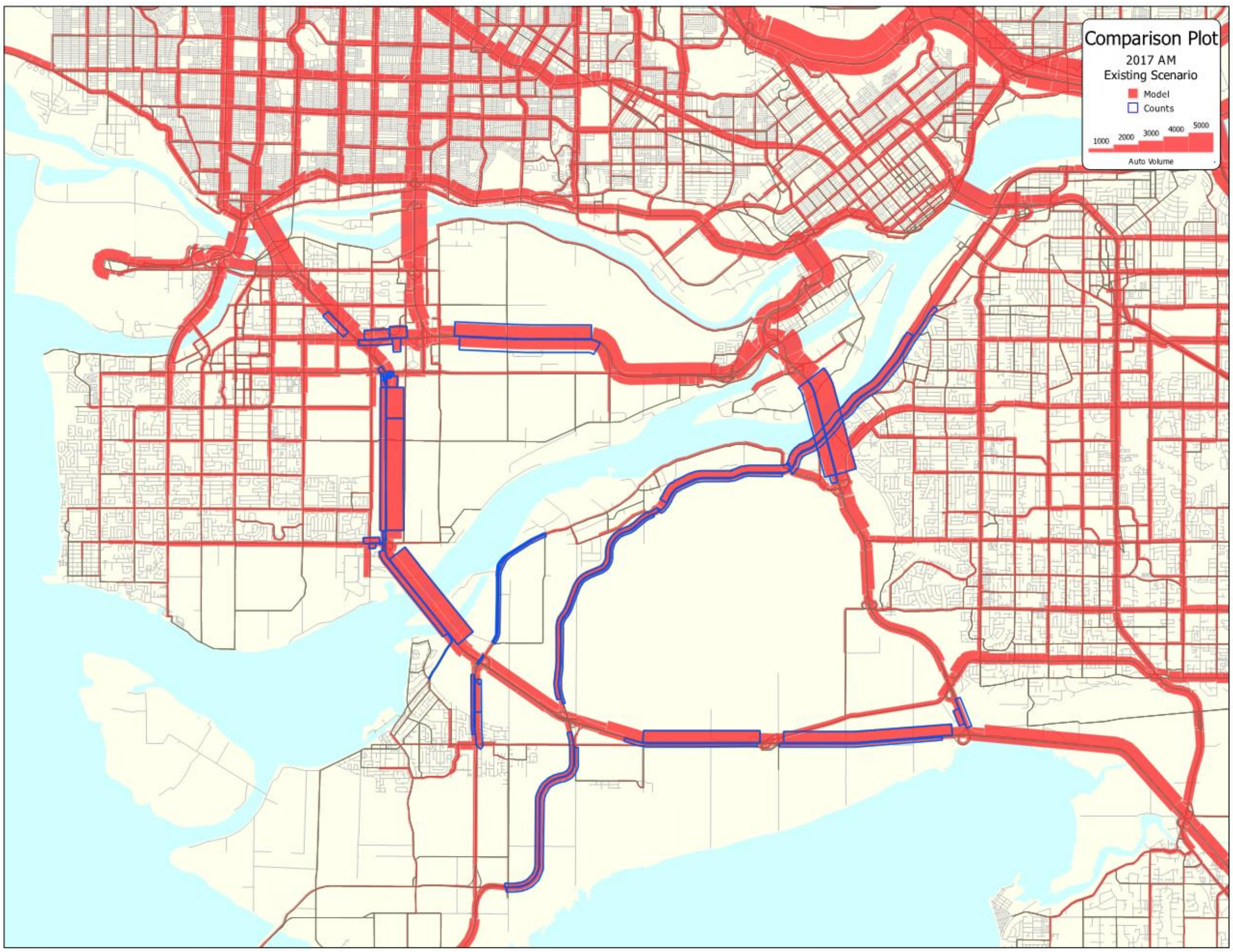
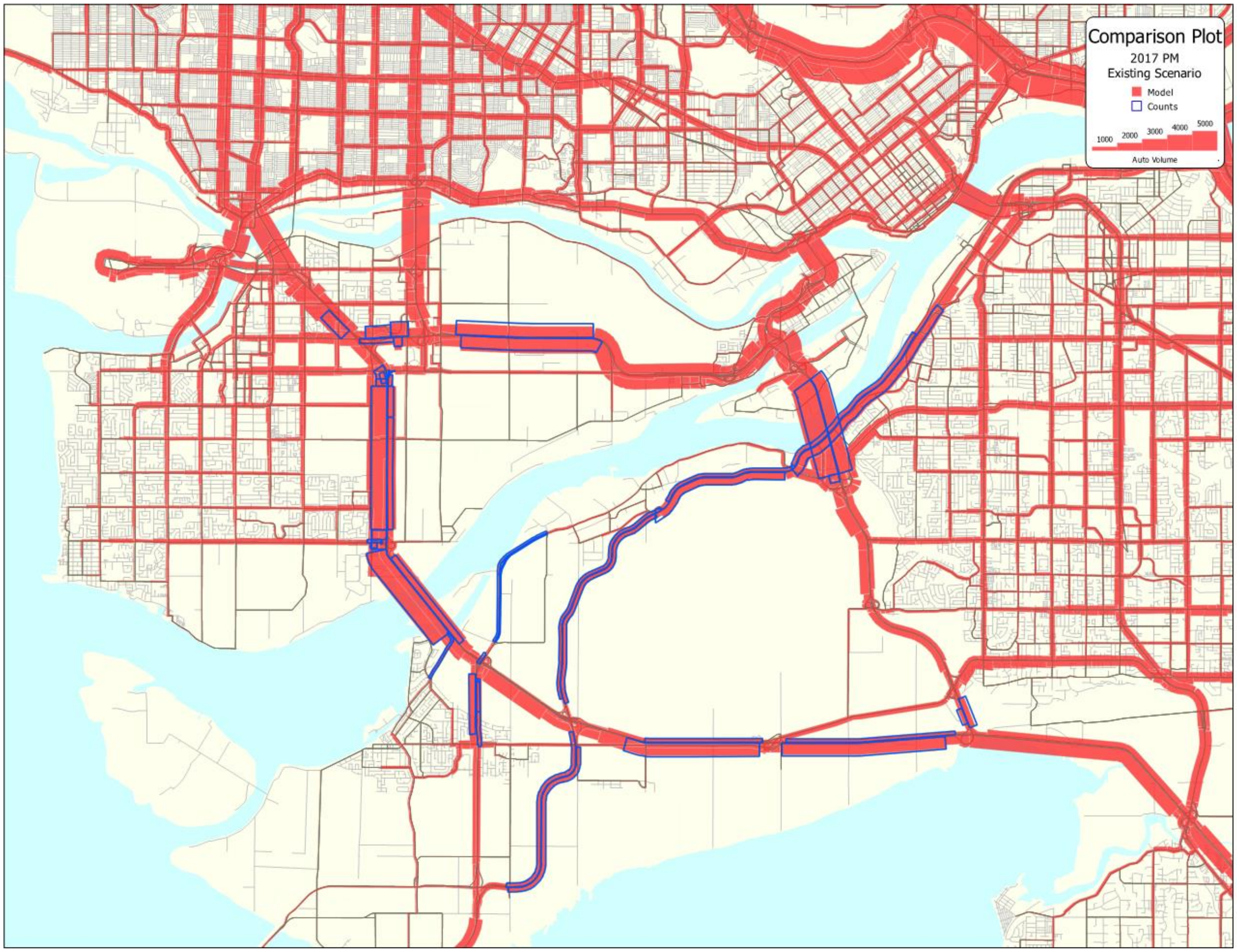


Figure 13: 2017 PM Traffic Volume Validation Plot (4:30-5:30pm)



3.2. TRAVEL TIME VALIDATION

The next primary model validation metric is travel times along key corridors. Travel times during the morning peak, midday and afternoon peak were reviewed for the following study area corridors in both directions:

- Highway 99 from the US Border crossing to 71st Ave in Vancouver
- Highway 91 from Shell Road in Richmond to the Highway 99 offramp in Delta
- Highway 17 from 28th Ave in Delta to Highway 1 in Surrey
- Highway 17A from 28th Ave in Delta to 60th Ave in Delta
- Knight St from Westminster Highway in Richmond to 61st Ave in Vancouver
- King George Blvd from 72nd Ave in Surrey to Royal Ave in New Westminster

The model should accurately represent travel times which are a proxy for road network costs for the following reasons:

- Users make route and mode choice decisions based on estimated network travel times;
- Provides reliable base for comparison and future growth;
- Provides an estimate for congestion for network bottlenecks;
- Required to correctly calculate travel time savings for project options;
- Travel time savings are the primary source of user benefits for this project

Observed travel times were summarized from the Google Maps API which provides a best guess and optimistic and pessimistic travel time estimate. The model should generally fall within the optimistic and pessimistic range, and ideally fall within 10% of the average.

Figure 14 and **Figure 15** shows the overall performance of the model in aggregate for the corridors that were reviewed. Generally, the model fits very close to observed travel times with the exception of Highway 99 northbound in the AM peak and Highway 99 southbound in the PM peak where the model is operating too slow. A similar issue is observed on Highway 91. **Figure 16** to **Figure 18** show the observed versus modelled travel times for the Highway 99 corridor during the morning, midday and afternoon peak periods. **Figure 19** shows the observed versus modelled travel times for the Highway 91 corridor for the peak travel. As shown, the model is a bit slow in the northbound morning peak period. This is likely due to merge functions being used to restrict traffic flow at highway onramp locations. The southbound direction fits very close to the observed travel time. These plots show that the travel speeds are consistent throughout much of the network and there are only a few places where travel speeds are not a close match to observed. Additional, travel time validation plots are presented in **Appendix A**. Overall, though, the model is replicating observed travel times very well.

Figure 14: 2017 AM Travel Time Validation Along Key Corridors

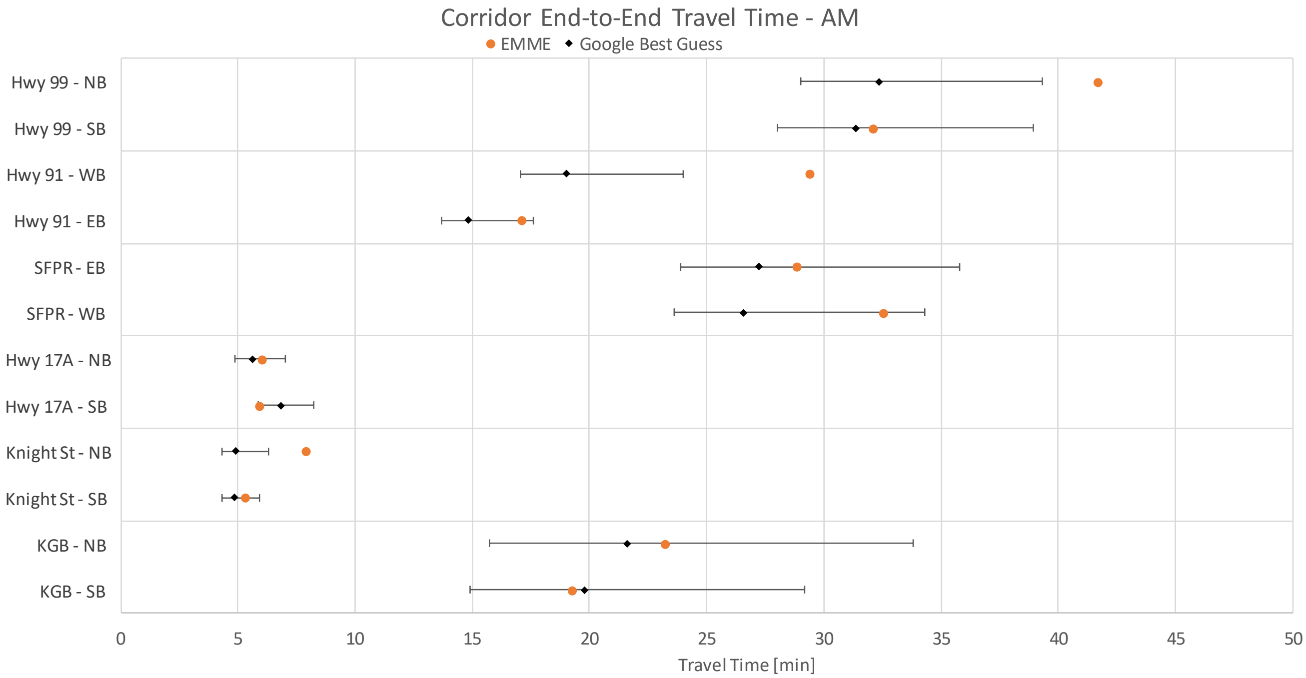


Figure 15: 2017 PM Travel Time Validation Along Key Corridors

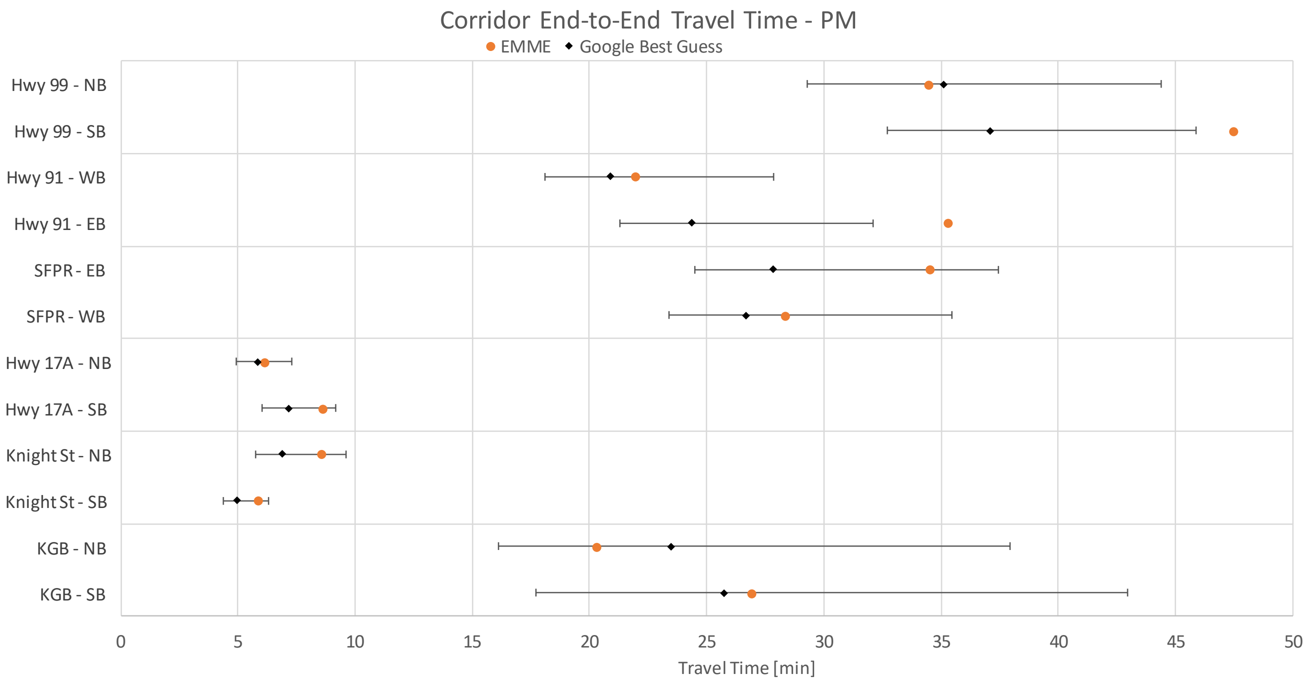
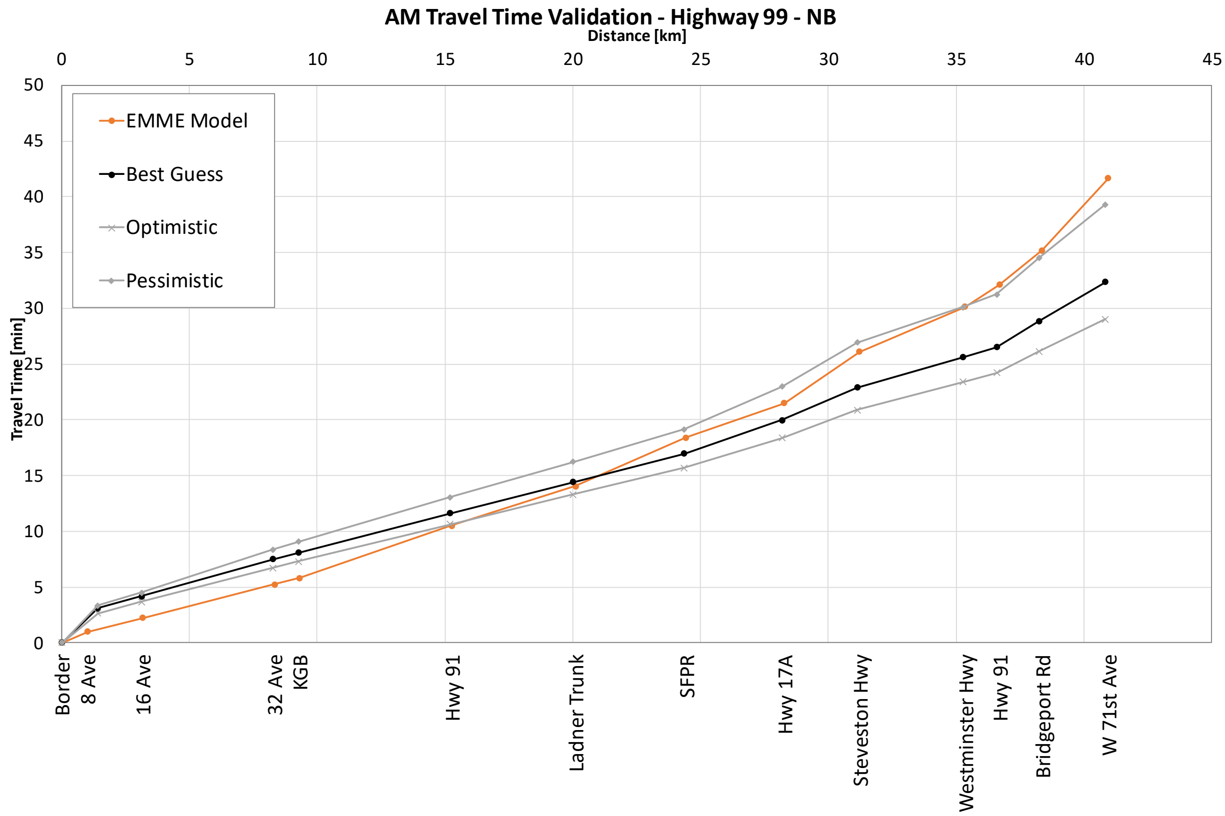


Figure 16: Travel Time Validation - Hwy 99 (AM)



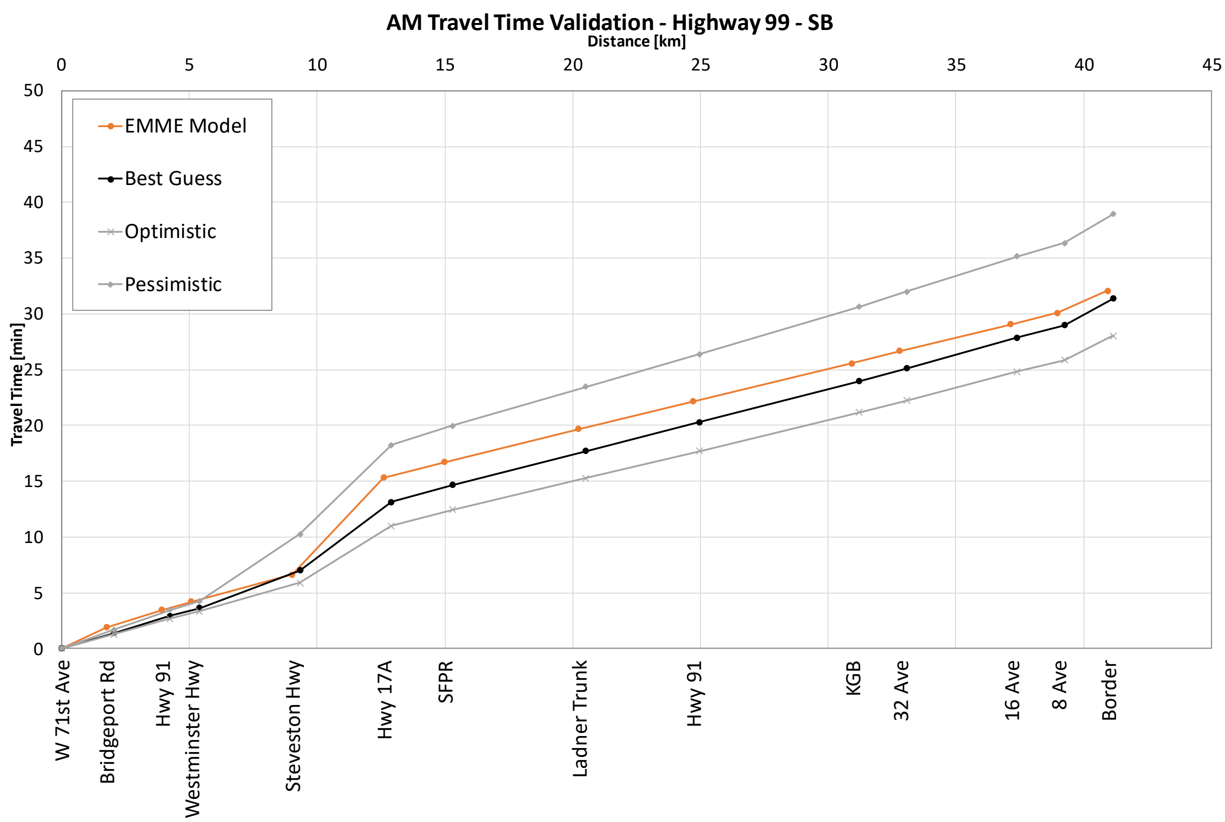
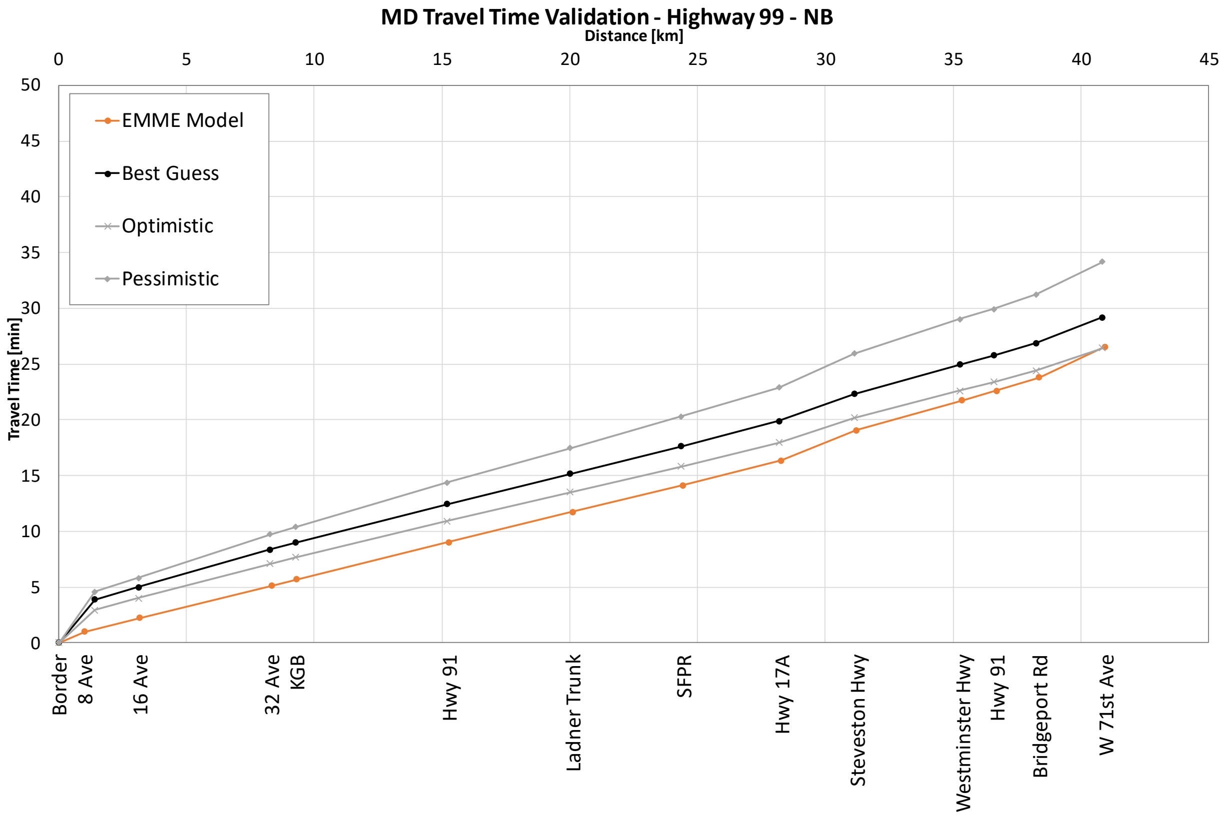


Figure 17: Travel Time Validation - Hwy 99 (MD)



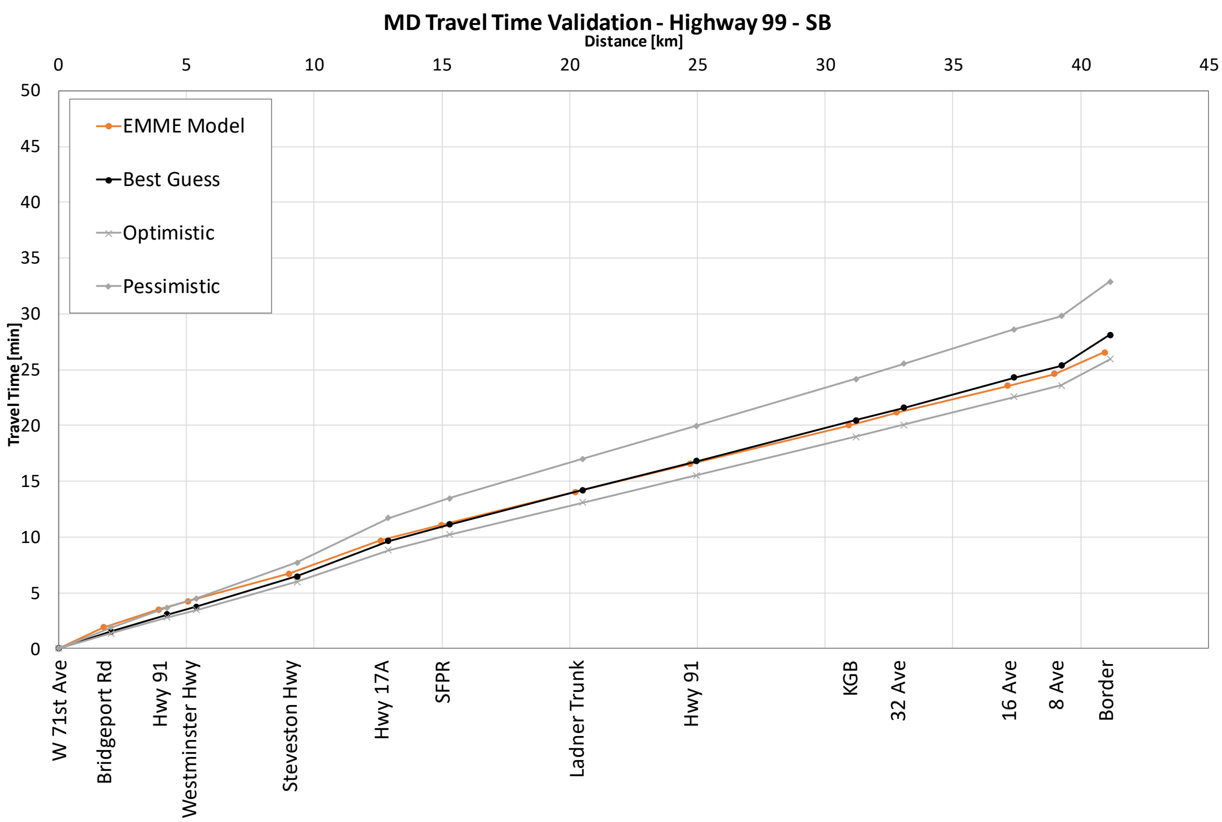
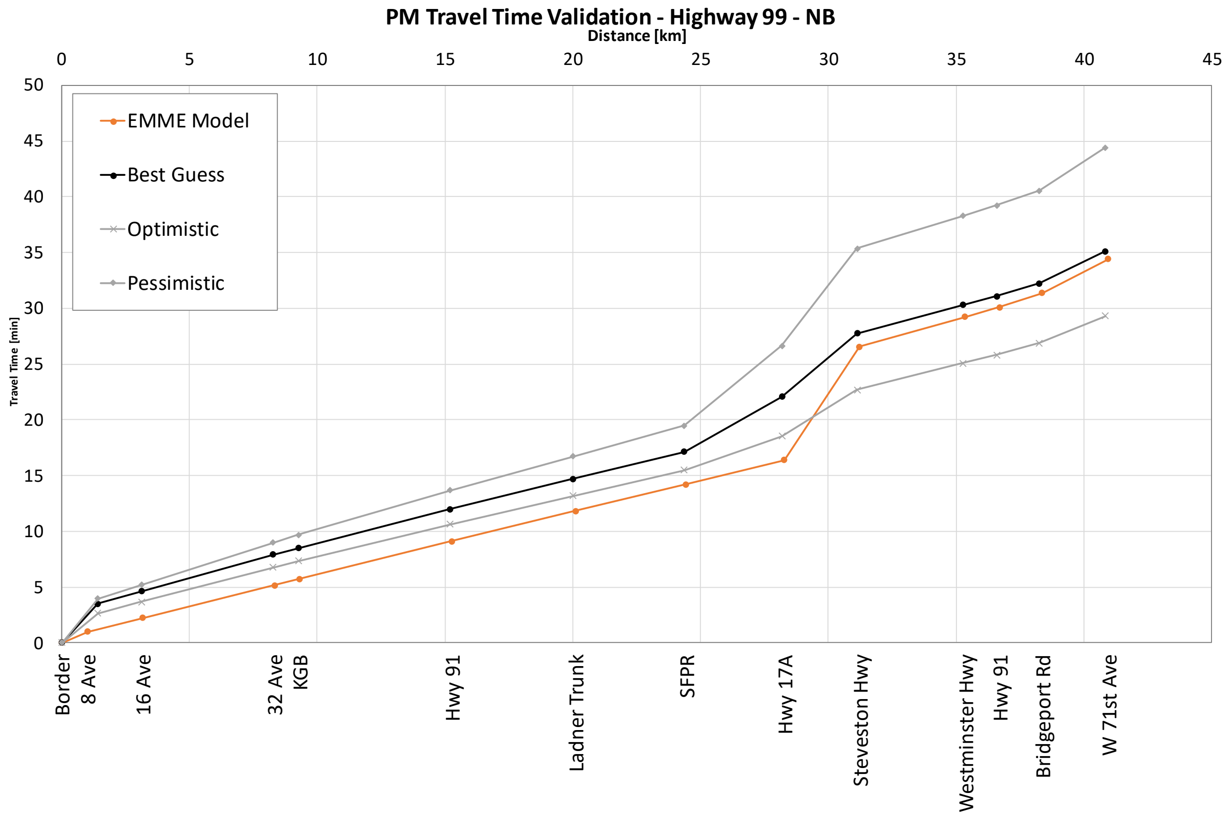


Figure 18: Travel Time Validation - Hwy 99 (PM)



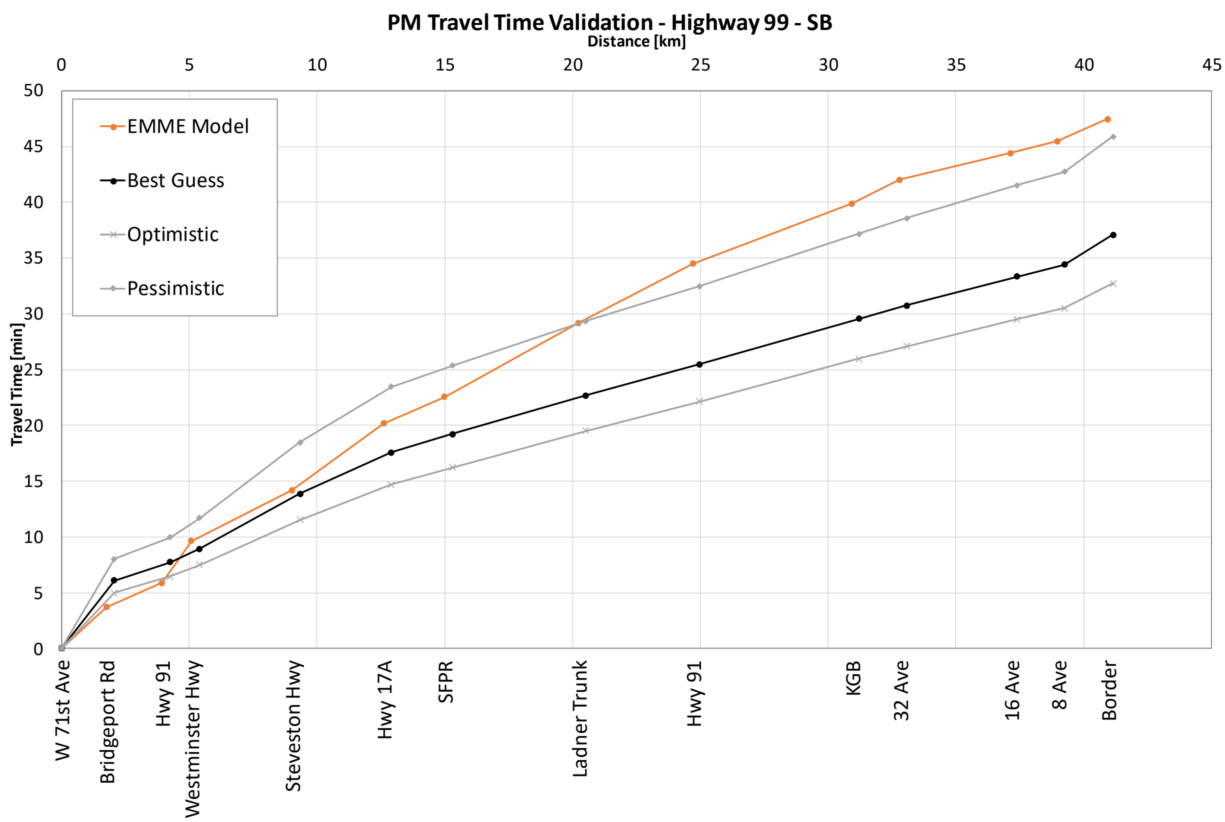
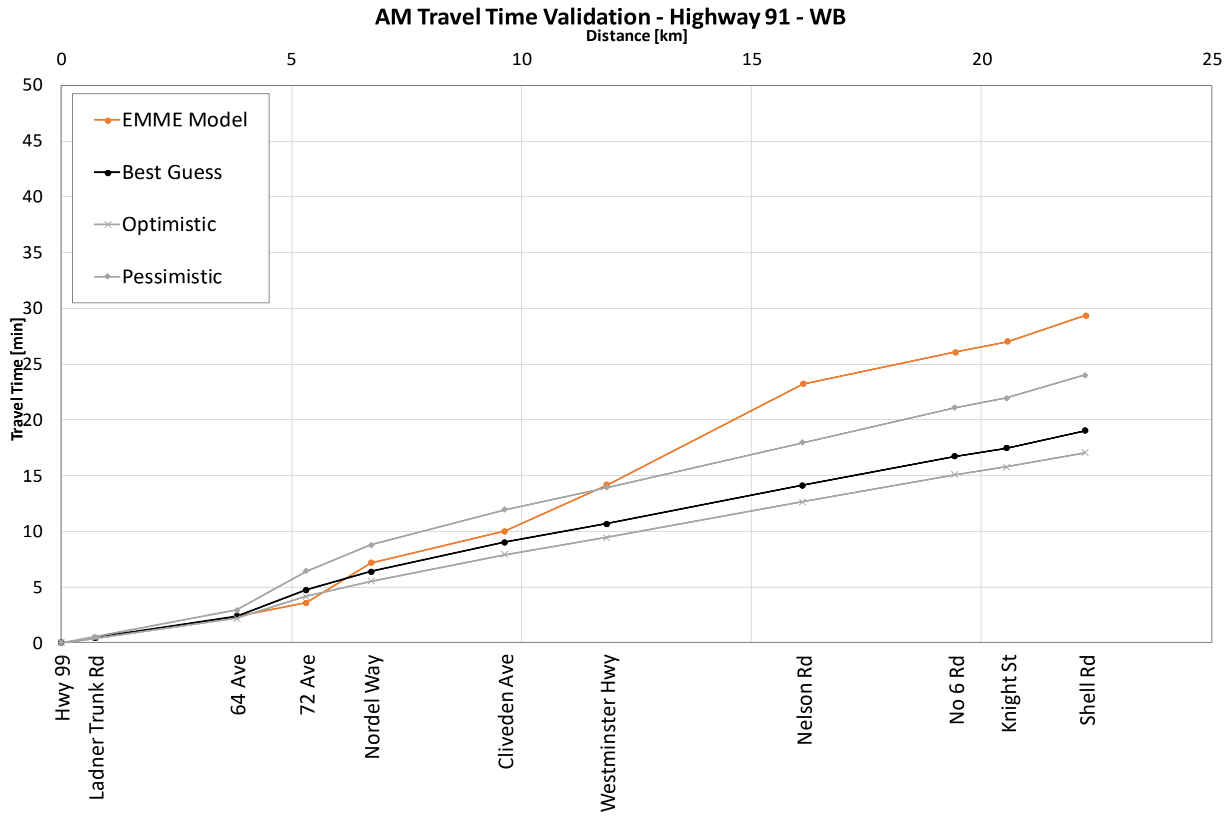
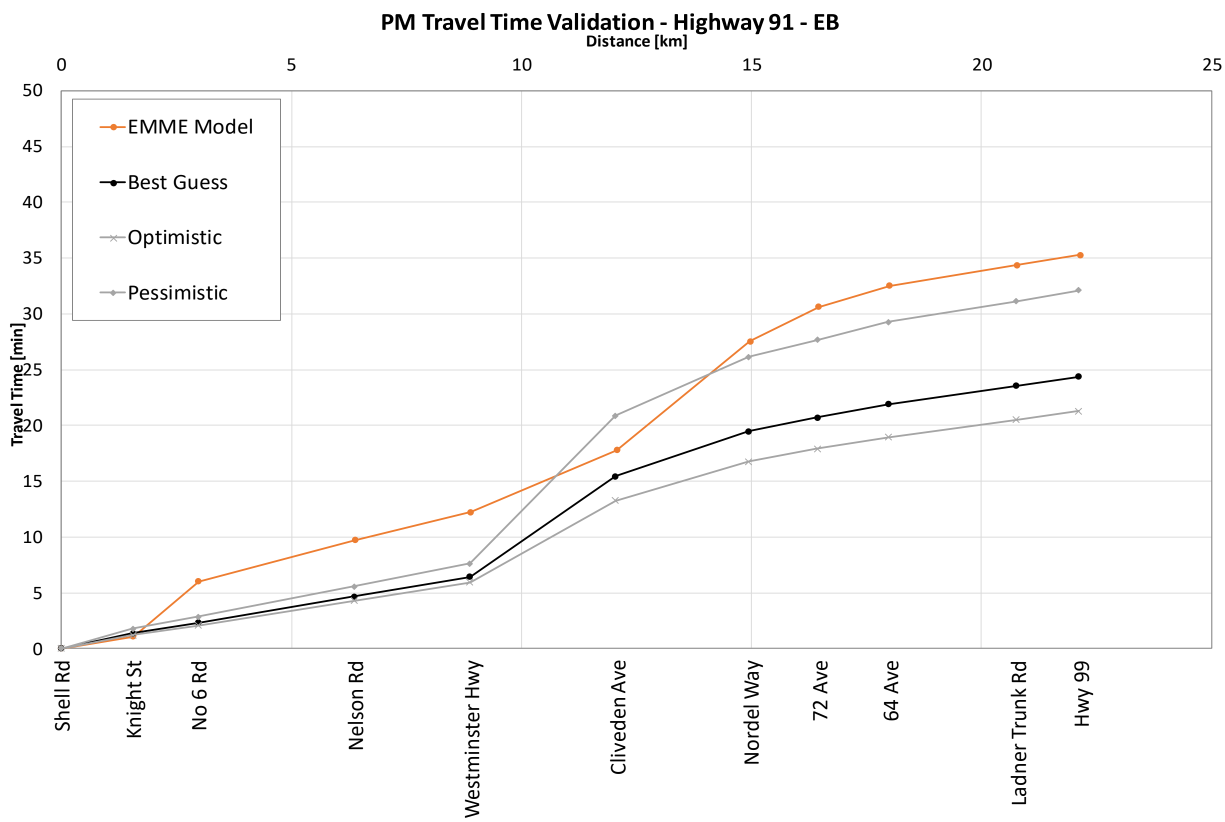


Figure 19: Travel Time Validation - Hwy 91 (Peak Hours)





3.3. CATCHMENT AREA ANALYSIS / TRIP DISTRIBUTION

The final component of the model that was checked included a review of general trip distribution patterns within the travel catchment of the study area. The catchment area is generally defined as the geographic scope from which trip origins and destinations are defined. **Figure 20** shows the general distribution of two-way traffic during the 2017 AM peak hour. This shows that of trips using GMT, approximately 62% are either going to or coming from Richmond which is consistent with observed patterns. The GMTR project utilized Bluetooth readers along Highway 99 and 91 to collect highway ramp on and off data as part of ATIS. This allowed the team to determine the portion of traffic that travelled different segments of the corridor.

There is considerable overlap between the users of GMT and AFB. This is confirmed with travel times that are fairly consistent for users of either Highway 99 or 91 between the interchanges in Delta and Richmond where the highways converge. **Figure 21** shows the density of trip origins on the south side of the Fraser River and trip destinations on the north side of the Fraser River during the 2017 AM peak hour for GMT users. These patterns generally show that NB GMT users are coming from Ladner and Tsawwassen in South Delta, Newton and South Surrey and White Rock as well as parts of Langley. Trips are then generally destined to East and Central Richmond, Steveston, South Vancouver and the University of British Columbia. As expected, many of these trips are concentrated in the southwestern quadrant of the Metro Vancouver region.

As a comparator, **Figure 22** shows the density of trip origins on the south side of the Fraser River and trip destinations on the north side of the Fraser River during the 2017 AM peak hour for AFB users. Trips are generally originating from North Delta, North Surrey, South Surrey and parts of Langley. Trip destinations are generally concentrated in Eastern Richmond, Sea Island, South and Central Burnaby and parts of New Westminster. Although there is considerable overlap between the catchment areas for GMT and AFB users, AFB users are more focussed in the central and more urbanized and dense parts of Metro Vancouver.

Figure 20: 2017 AM Peak Trip Distribution Patterns for Highway 99 and 91 (Two Way)

Figure 21: 2017 AM Peak Trip Distribution Patterns for Northbound George Massey Tunnel Users

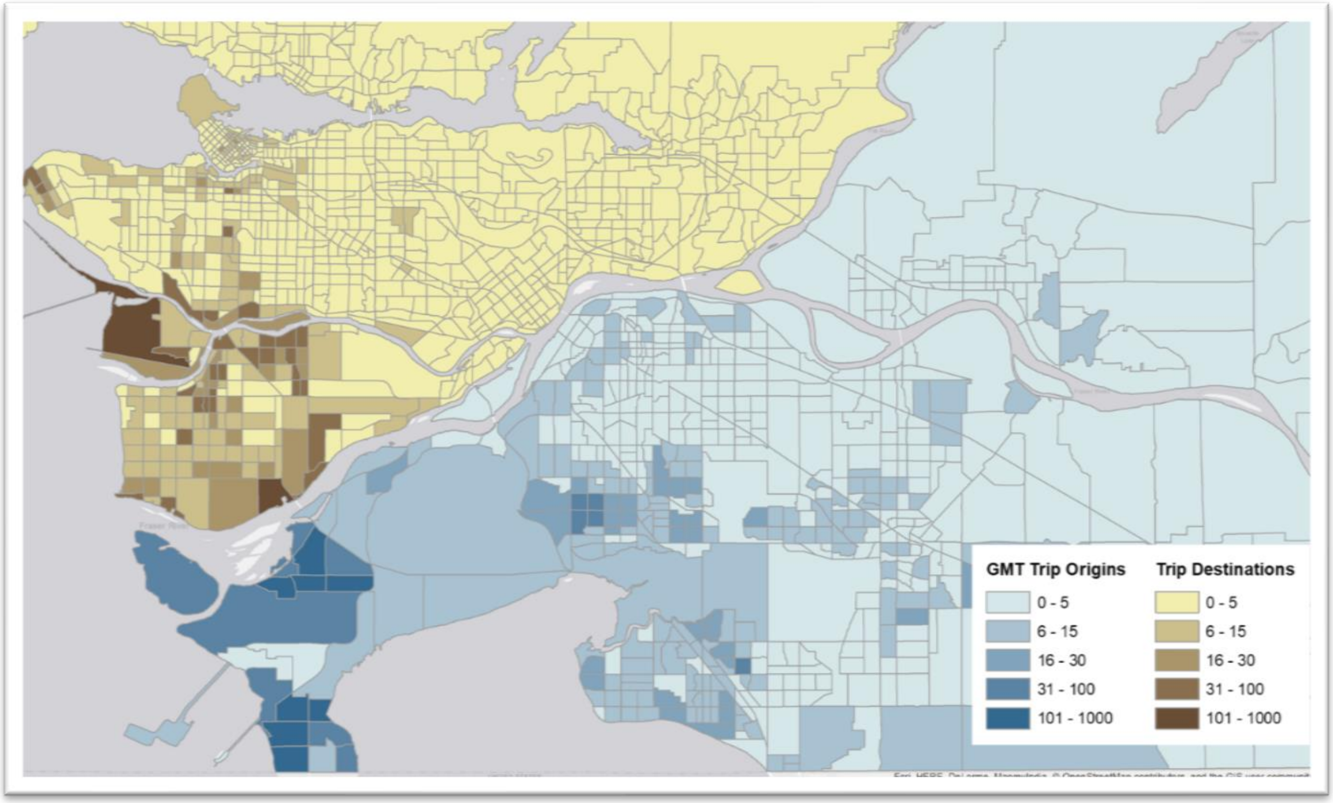
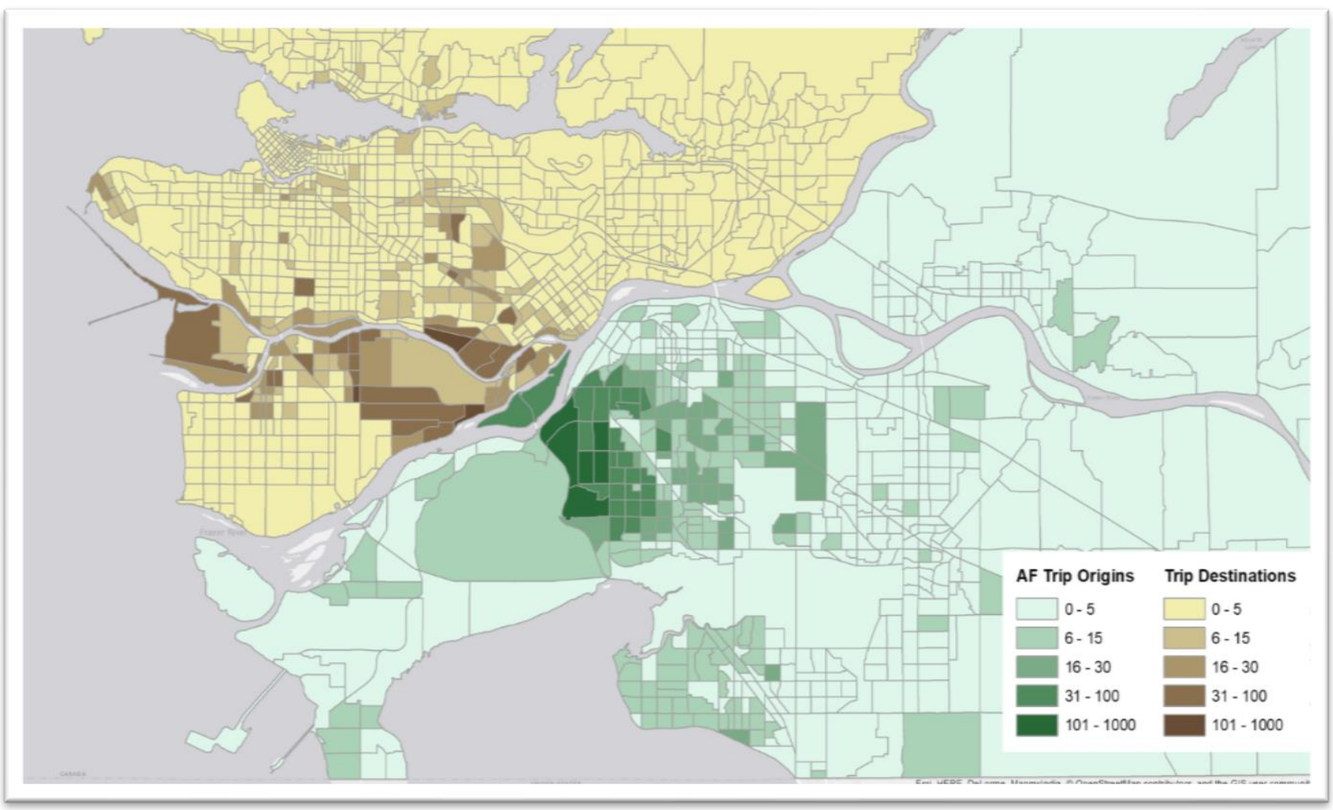


Figure 22: 2017 AM Peak Trip Distribution Patterns for Northbound Alex Fraser Bridge Users



4. UPDATED TRAFFIC FORECASTS

This section provides the key assumptions, methodology and outcomes for the traffic volume forecasts for the various options including an assessment of the components of traffic volume growth.

4.1. SCENARIOS ANALYZED AND KEY ASSUMPTIONS

The following provides a summary of the various assumptions, times periods, horizon years and network configurations that were modelled using RTM3:

- ***Land Use Horizons –*** The model was used to develop a 2017 base year and 2030 and 2045 future horizons. Land use forecasts for population, employment and households were based on Metro Vancouver's officially adopted Regional Growth Strategy (RGS) numbers. **Figure 24** to **Figure 26** provide the forecast population, employment and households respectively which are the primary drivers of growth in the RTM3. The Metro Vancouver region grows from 2016 to 2045 by 43% in terms of population, 30% in terms of employment and 49% in terms of households. For all variables, Surrey's growth rate is the highest.

- ***Time Periods –*** The RTM3 develops travel demand estimates on a 24-hour basis. Time slices from the model are then developed to provide estimates of travel demand for the morning peak hour (07:30-08:30), the midday period (12:00-13:00) and the afternoon peak hour (16:30-17:30). The true peak on GMT occurs earlier in the morning peak, however this is adjusted for using update expansion factors that account for the hourly profiling of traffic using the crossing.

- ***Network Configuration –*** The model roadway network was updated for the following configurations:

    - **Four-Lane Business as Usual (BAU) –** To represent a future business as usual which provides a basis for estimating travel time savings of any future improvement options.

    - **Six-Lane Do Minimum –** Provides a new six lane crossing of the Fraser River with no counter-flow operation. This includes improvements to the Steveston Highway interchange to accommodate higher traffic volumes accessing this municipal arterial.

    - **Ten-Lane Reference Concept –** This includes a new ten-lane crossing with extensive Highway 99 interchange and laning improvements as defined in GMTR Reference Concept.

Figure 23 illustrates the extent of the 6-Lane Do Minimum versus the 10-Lane Reference Concept along the Highway 99 corridor. For completeness of analysis, an 8-Lane Do Minimum scenario was also analyzed which is similar to the 6-Lane Do Minimum but with auxiliary lanes provided between the Highway 17A and Steveston Highway interchanges. An 8-Lane Reference Concept was also analyzed which is similar to the 10-Lane Reference Concept but with the HOV / transit lanes removed from the Fraser River crossing.

Other key model assumptions include the following:

- ***Other Relevant Infrastructure Improvements –*** Includes network improvements that have a high likelihood of occurrence (i.e., funding committed or already underway) and a material impact to traffic using either Highway 91 or 99 within the study area. These include the following:

- Alex Fraser Bridge Counterflow
- Pattullo Bridge Replacement
- 72nd Ave Interchange
- 216th St Interchange
- Surrey Light Rail Transit

- ***Special Traffic Generators –*** Includes expansion of Roberts Bank Terminal 2 which doubles container handling capacity at this deep-sea terminal.
- ***Pricing Variables –*** All economic variables are assumed to inflate at the same rate, such as incomes, value of time, fuel prices, parking, etc. No bridge tolls or mobility pricing options were included in this analysis.

Figure 23: Extent of Do Minimum (Green) and Reference Concept (Blue) Improvements along Highway 99

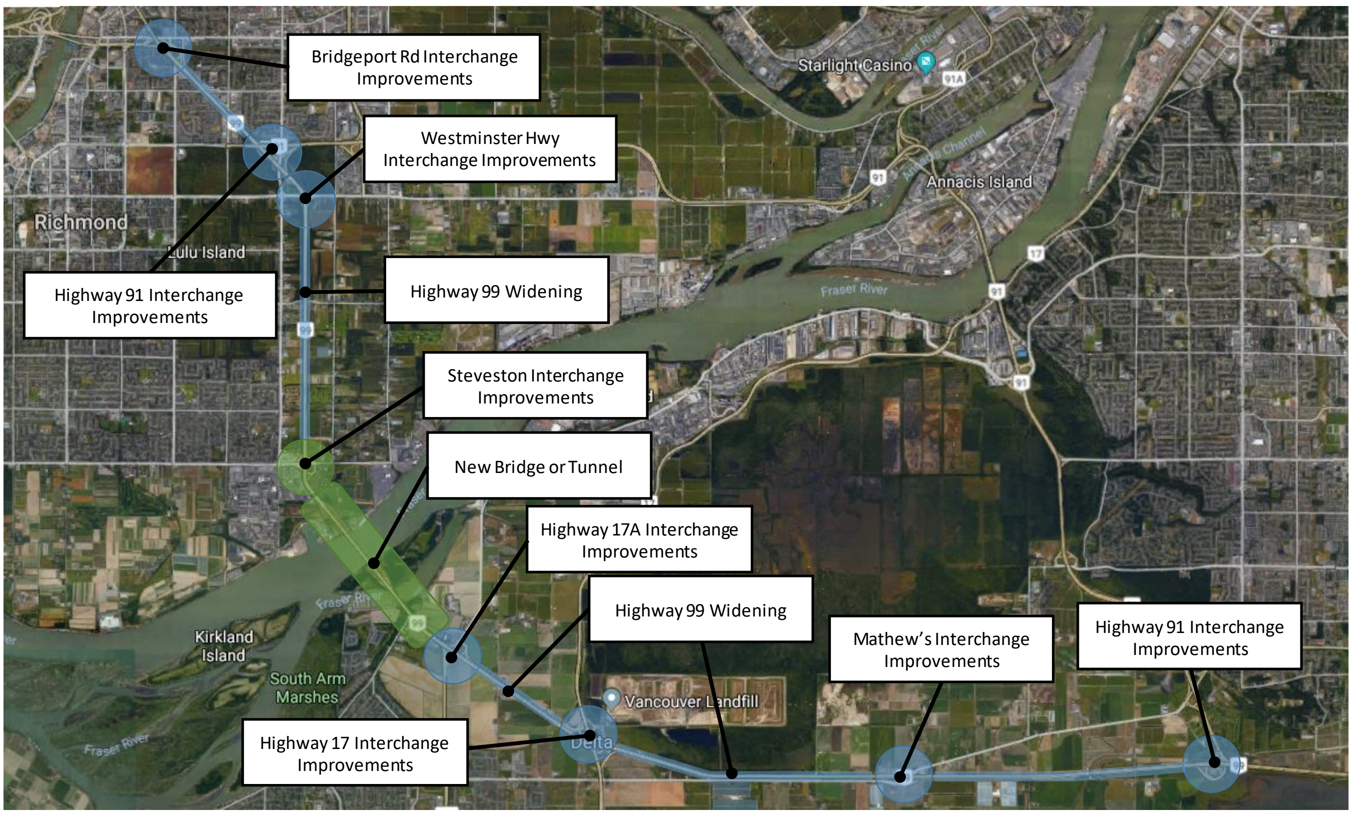


Figure 24: Metro Vancouver Population Projections

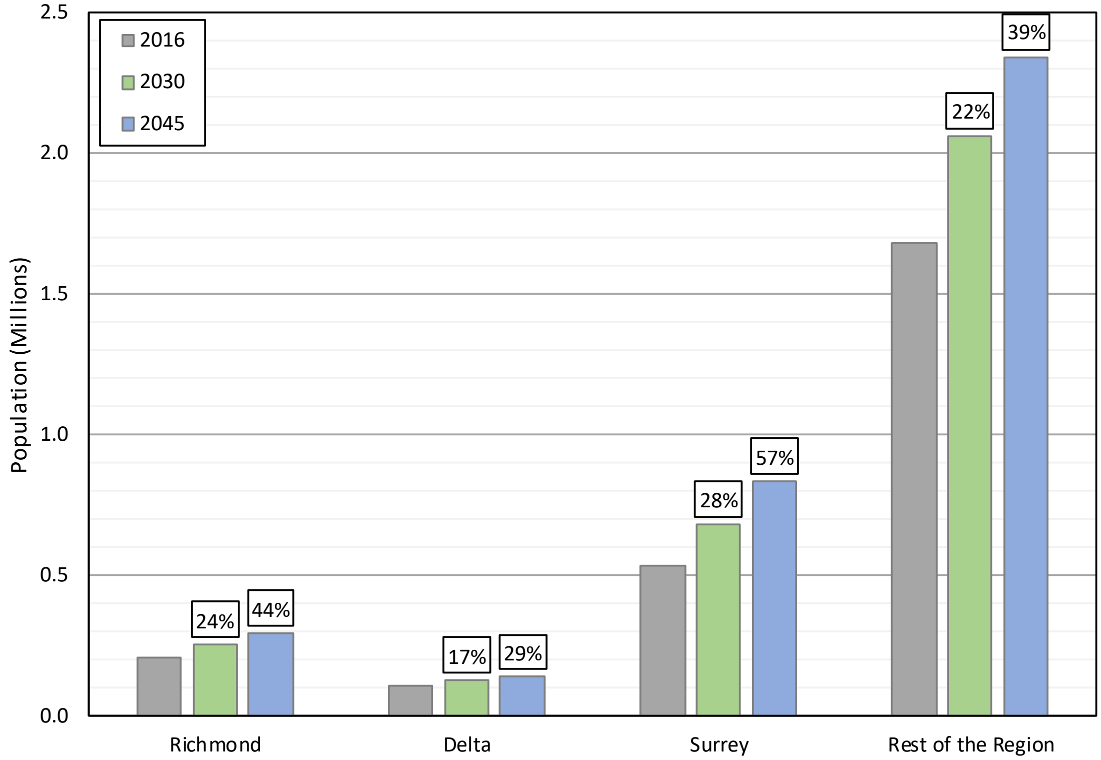


Figure 25: Metro Vancouver Employment Projections

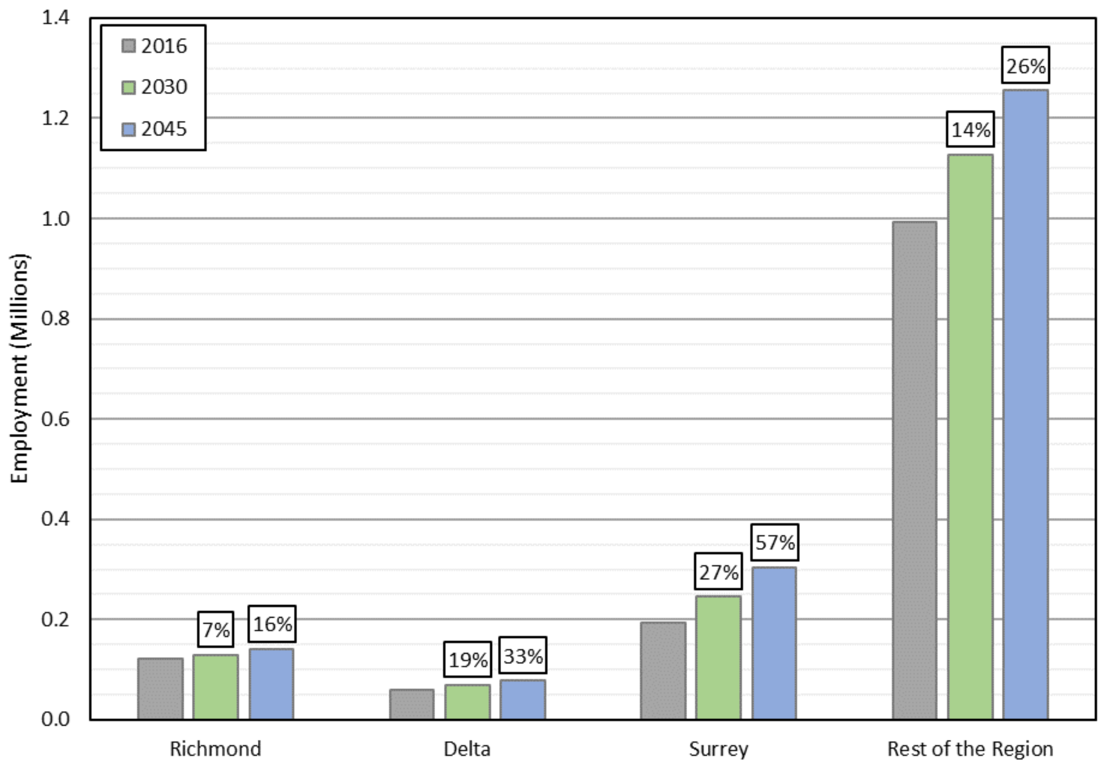
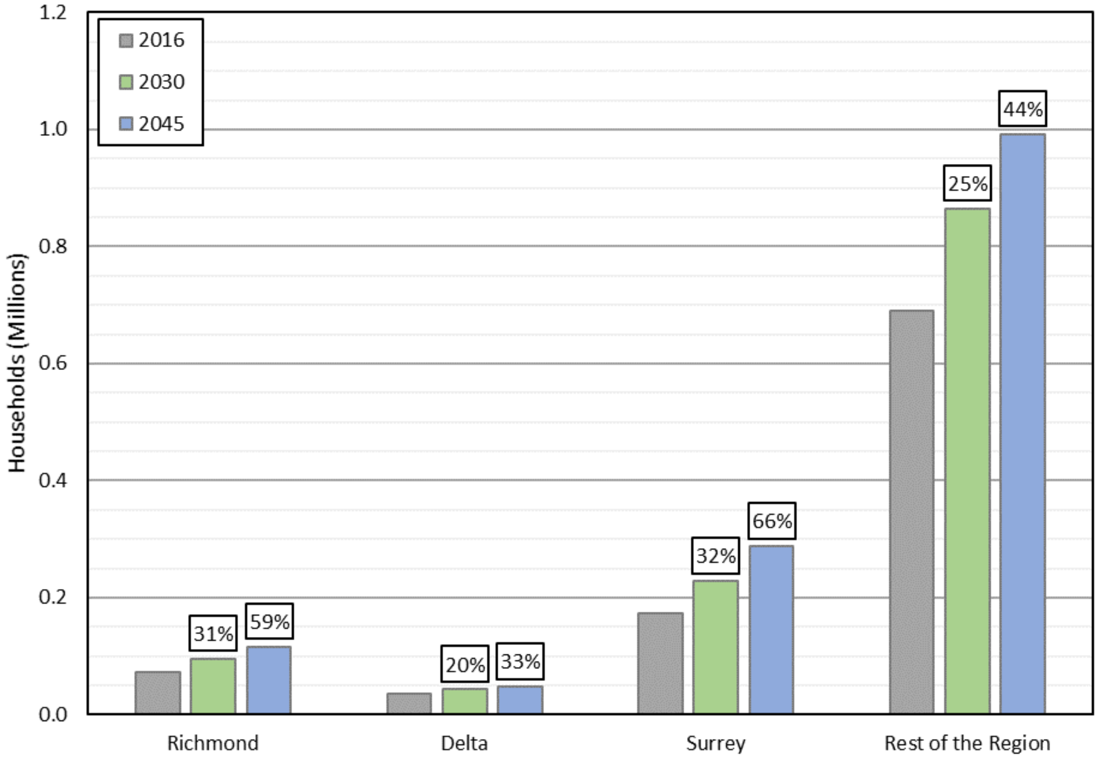


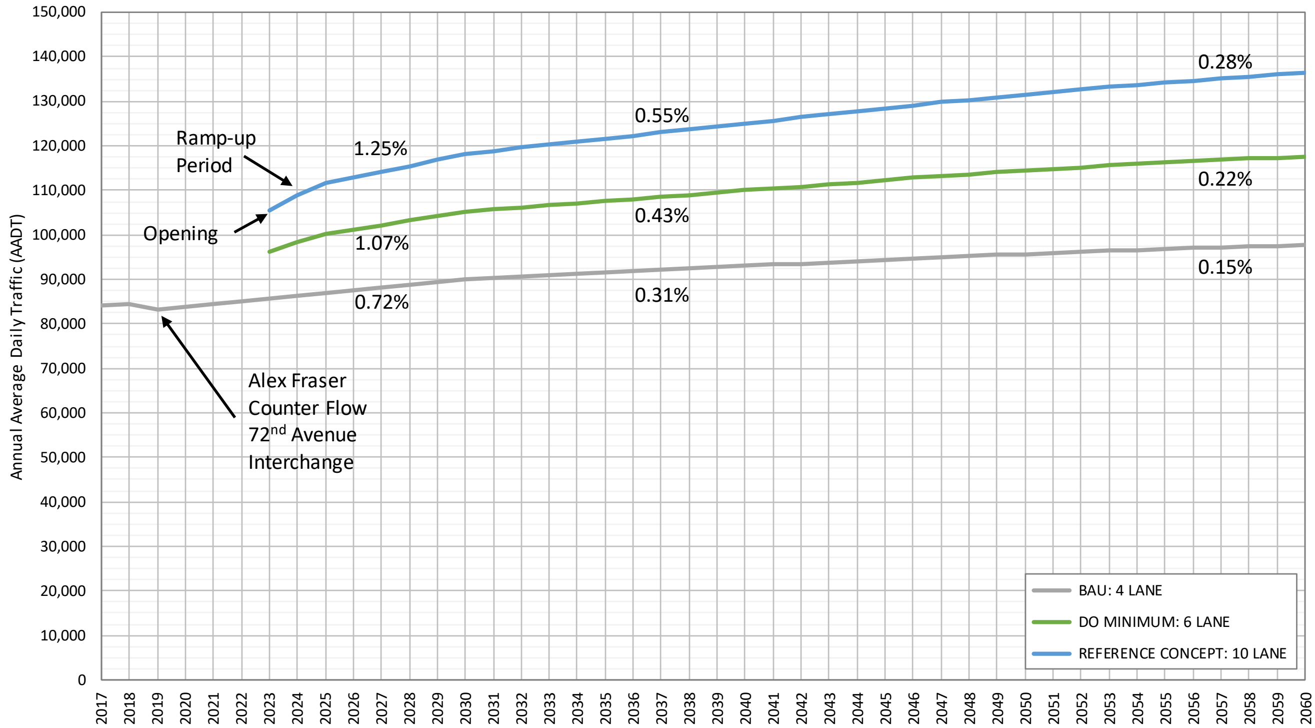
Figure 26: Metro Vancouver Household Projections



4.2. TRAFFIC FORECAST RESULTS

The RTM3 was used to develop updated traffic forecasts based on the land use and demographic growth and network assumptions. **Figure 27** below shows the traffic forecasts for the 4-Lane BAU, 6-Lane Do Minimum and 10-Lane Reference Concept expressed as average annual daily traffic (weekday and weekend). The annual growth rates for the short, medium and long-term show that traffic initially grows fairly quickly, and then levels out over the long term. Capacity constraints in the BAU suppresses growth in traffic volumes, while any improvements provide travel time savings making the corridor more reliable and attractive. The 10-Lane Reference Concept grows to approximately 130,000 AADT in 2045.

Figure 27: George Massey Tunnel Replacement Traffic Forecasts



Note: Percentages show average annual growth rates.

Figure 28 and **Figure 29** show the 2045 AM peak hour network plots for the 4-Lane BAU and 10-Lane Reference Concept scenarios respectively. These plots show the significant diversion trips from Highway 91 to Highway 99 as the GMT is replaced with the 10-Lane Reference Concept. Most of the traffic increase on the new crossing is diverted from the AFB. There is a marginal increase in traffic volumes across the Oak St and Knight St bridges. Both of these crossings are congested today and could not handle much more additional traffic during the peak hour.

Figure 28: 2045 AM Peak Hour Traffic Forecasts for the Business as Usual Scenario

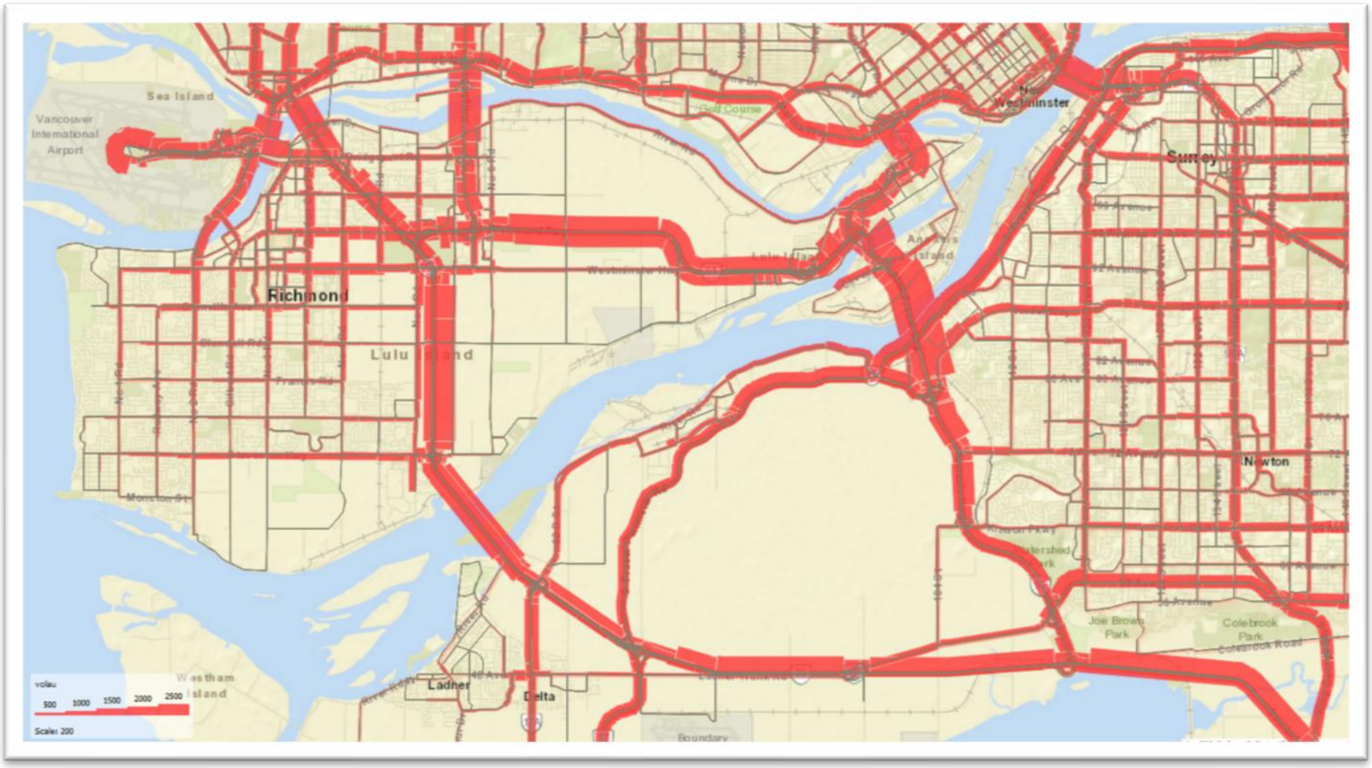
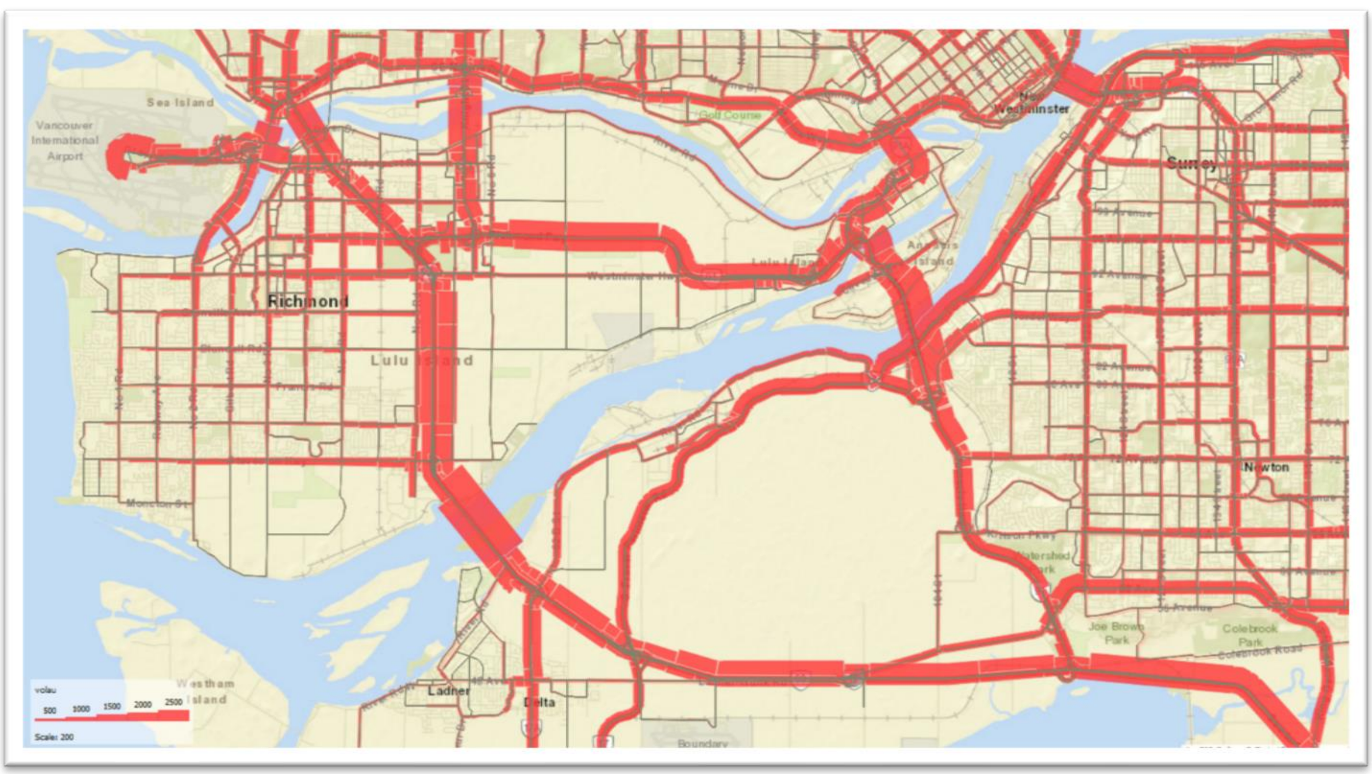
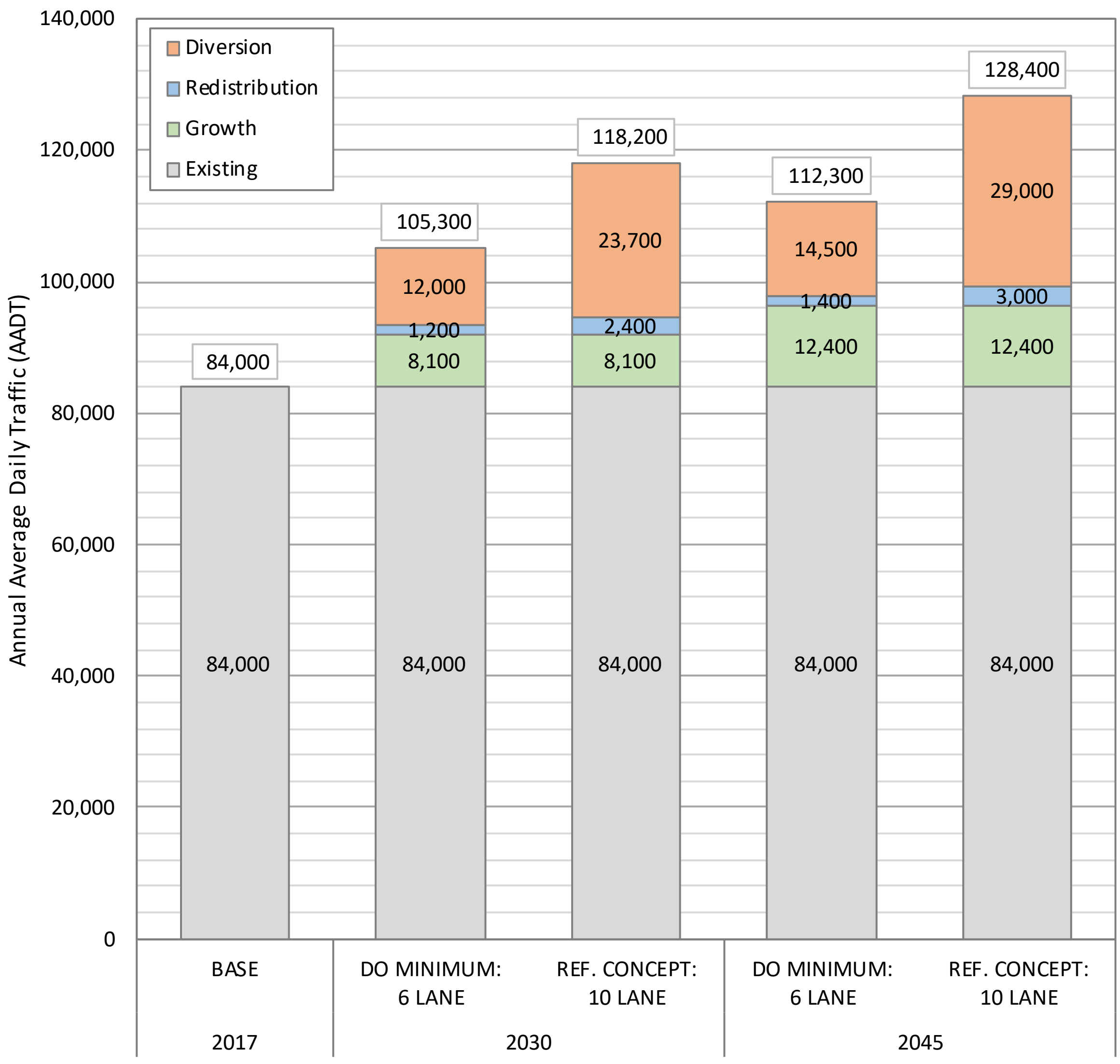


Figure 29: 2045 AM Peak Hour Traffic Forecasts for the 10-Lane GMTR Reference Concept



In order to clearly understand the traffic forecasts, a breakdown of each key component is provided in **Figure 30** for the 6-Lane Do Minimum and 10-Lane Reference Concept . Existing traffic is based on actual traffic count information today and forms the foundation for the traffic forecast. Growth is based on land use and economic development and generally depicts overall growth in travel demand across the Fraser River. Redistribution includes more travel with decreased access costs (travel times) across the Fraser River and can be interpreted as induced traffic. The largest component is derived from trip diversion from the AFB as the Highway 99 corridor becomes a much more attractive corridor with capacity enhancements. Traffic diversion from the AFB represents 65% of the increased traffic from the base case for the 10-lane reference concept in 2045.

Figure 30: 2045 AM Peak Hour Traffic Forecasts for the 10-Lane GMTR Reference Concept



For comparison, the 8-Lane Do Minimum carries 91% of the 10-Lane Reference Concept traffic volumes and the 8-Lane Reference Concept carries 99% showing that these scenarios serve most of the forecast traffic volumes.

4.3. COMPARISON TO PREVIOUS TRAFFIC FORECASTS

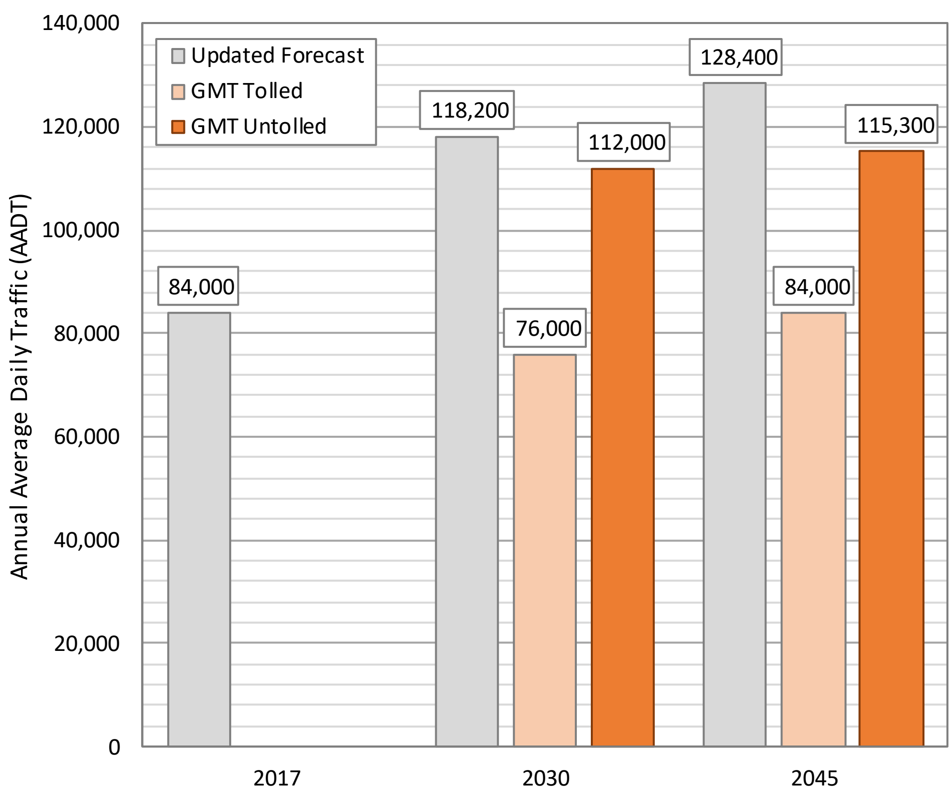
The GMTR team produced traffic forecasts for a tolled and un-tolled 10-Lane Reference Concept scenario using the RTM Phase 0. **Figure 31** provides a comparison of the RTM3-based traffic forecasts compared to the previous GMTR forecasts. As shown, the updated model with extensive validation in the Highway 99 and 91 corridors is producing long-term traffic forecasts that are about 10% higher and there are several reasons for this. These are described as follows:

- The travel speeds are in RTM3 are slower (and closer to observed) causing the model to be less sensitive to changes in network costs. The RTM3 was re-estimated using these slower speeds causing the RTM3 to be less sensitive in the distribution component to high network cost trips such as those crossing the Fraser River. This results in more trip making across the Fraser River in the long term.

- The Highway 99 and 91 corridors across the Fraser River both represent high network cost trips due to longer trip lengths and high levels of congestion. These high network costs represent a stronger advantage for any improvements on the Highway 99 corridor since both facilities are very congested. Being highly congested means that any reductions in network costs for an alternative would attract more traffic and is reflected in the assignment component of the model.

- The previous RTM (Phase 0) used demand adjust factors to account for the peak directionality of travel across the Fraser River. These demand adjust factors were applied outside of the cycling of the model such that their effect was not represented in the distribution or mode split components of the model. These factors have a suppressive effect on the long-term traffic forecasts for GMTR.

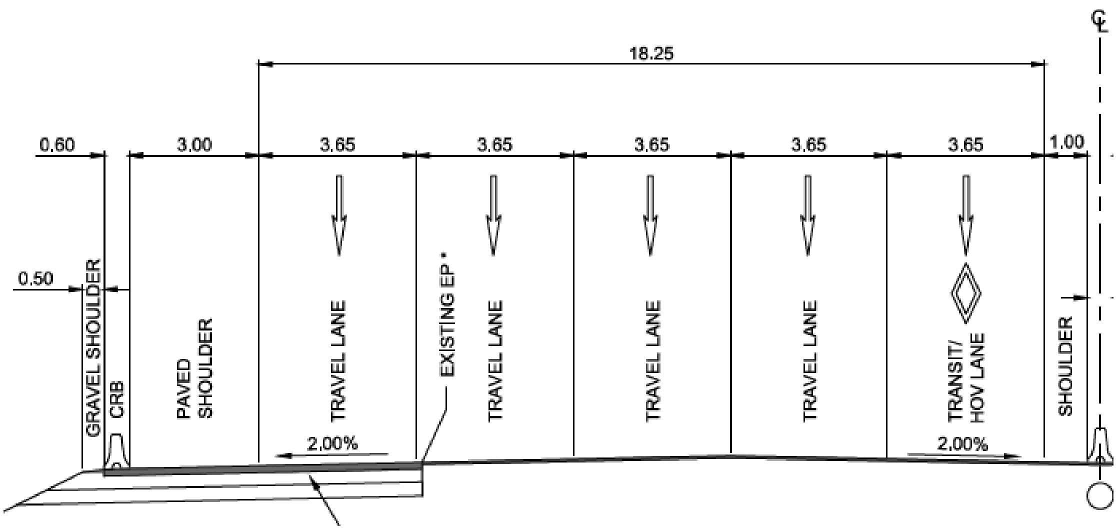
Figure 31: 10-Lane GMTR Reference Concept Traffic Forecast Comparison



4.4. FORECAST LANE UTILIZATION

The 10-Lane Reference Concept is defined directionally as four GP lanes and one HOV/transit lane along the Highway 99 corridor within the vicinity of the Fraser River crossing. **Figure 32** shows a cross section of the corridor showing the lane widths and shoulders for one direction of travel.

Figure 32: Cross Section of Laning for the 10-Lane Reference Concept



The traffic forecast information was factored to estimate the directional volumes during the peak hours in order to determine the utilization of lanes. Lane utilization rates were observed on the AFB during peak times as follows:

- Inside Lane: 2,200
- Middle Lane: 1,950
- Outside Lane: 1,500
- Average for 4 Lanes: 1,900

Under ideal conditions, most freeway segments can carry 2,200 vehicles per hour per lane (vphpl) as observed for the inside lane on the AFB. This is similar to the Highway Capacity Manual[1] calculation for traffic flow at onset of significant delay (Level of Service E). A facility is able to carry more but would operate at LOS F which is significantly congested and would result in longer travel times. In terms of lane utilization, the following is provided for the 2045 horizon for the peak periods and directions of travel:

- AM NB - GP: 74%; HOV: 55%
- PM SB - GP: 84%; HOV: 71%

The 10-Lane Reference Concept clearly provides more capacity to cross the Fraser River. In terms of lane utilization for the 10-Lane Reference Concept, during the AM peak hour, the NB GP lanes are about 74% utilized and the HOV / bus lane is about 55% utilized. Similarly, during the PM peak hour, the SB GP lanes are about 84% utilized and the HOV / bus lane is about 71% utilized showing that there is spare capacity in the peak direction beyond 2045 with these enhancements.

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[1] *Transportation Research Board, "Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis", 2016.*

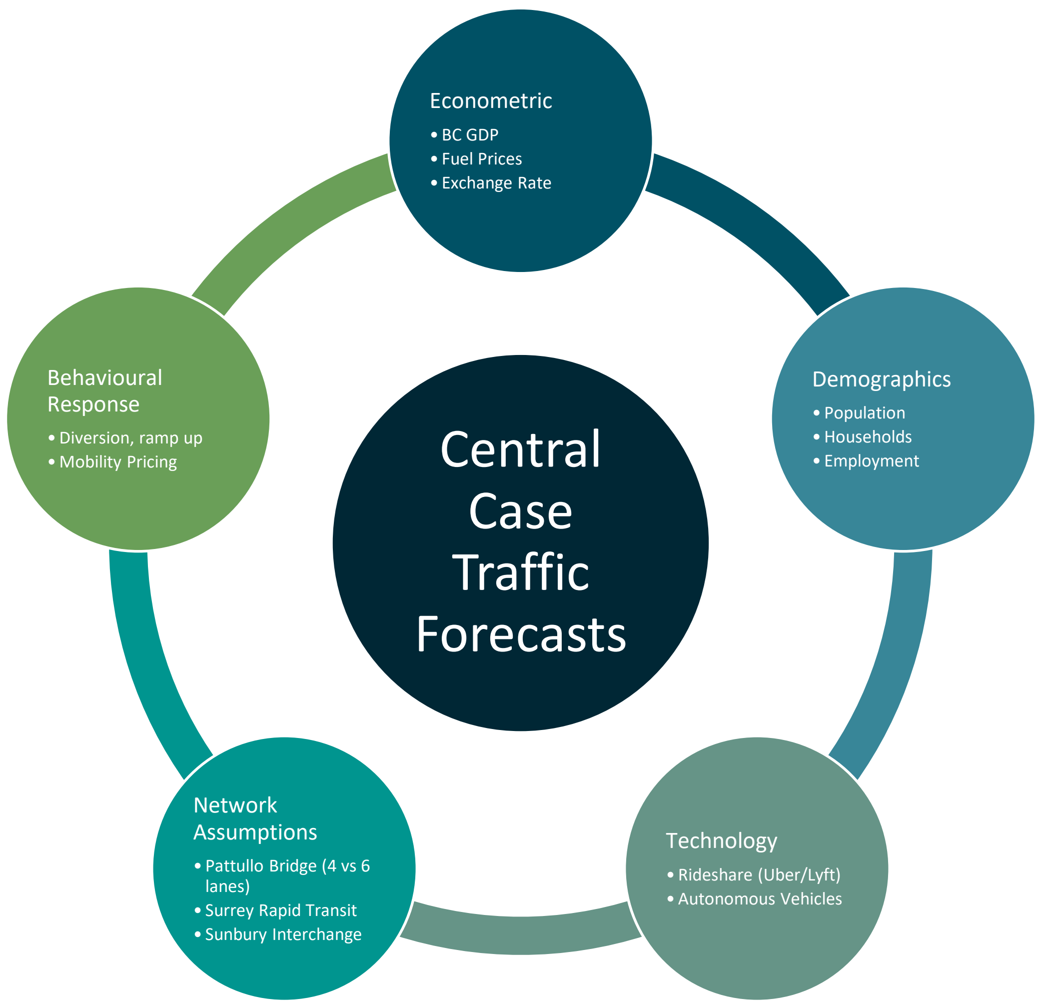
4.5. FORECAST UNCERTAINTY

The central case traffic forecasts presented in the previous section are based on several assumptions and estimates of future economic and travel behaviour conditions. Variations in these assumptions and forecasts are expected and they will result in changes to the traffic forecast. Such variations may concern any one of several factors, for example different employment growth, different fuel price forecasts or different economic outcomes.

The central case provides a vision of the future that is based on today's knowledge, calibrated model parameters and a set of reasonable future assumptions and estimates regarding the direction and magnitude of change in the years to come. If we could predict the future with absolute certainty, it would be possible to define the demand levels for the Highway 99 corridor associated with particular economic conditions at specific points in time. But, clearly, this is not the case. Whilst we can make 'best estimates' of future demand levels, even with the most sophisticated forecasting techniques, the future cannot be predicted with absolute certainty.

Given that uncertainty exists, it is beneficial to identify principal uncertainties that would have a significant impact to the central case traffic forecasts. For a more formal business case that would lead towards more investment-grade traffic forecasts, a risk analysis should be undertaken to quantify this uncertainty. Decisions can be greatly informed by this type of analysis and quantification, as the range in which vehicle demand levels are most likely to fall can be identified. Thus, the risk associated with the forecast traffic level can be judged and quantified. Rather than carry out a comprehensive risk analysis, the following (**Figure 33**) identifies the principle uncertainties that would have an impact to traffic levels.

Figure 33: Principle Uncertainties Affecting Central Case Traffic Forecasts



The traffic forecasts that have been developed are the most likely given current conditions and projections of key explanatory variables for the future. Given these assumptions, however, there is likely more downside risk than upside risk meaning that the probability of the forecast being exceeded is lower than the probability of future traffic being less that the forecast. Economic conditions are generally good these days with BC GDP growing at approximately 3% annually. There is no certainty that this trend will continue at this rate over the next several decades. Fuel prices have risen substantially over the past couple of years, but there is no indication that they would drop significantly over the forecast horizon. Tolls were removed on the Port Mann and Golden Ears bridges recently, but the region just completed a comprehensive review of Mobility Pricing options which could negatively affect traffic volumes on GMT. If ridesharing services take off in Metro Vancouver, there is a high likelihood of vehicle occupancies increasing which would result in fewer vehicles on the region's roadways. Finally, other network elements such as a six lane Pattullo Bridge could draw traffic away from the Highway 99 corridor. It is difficult to envision significant upside factors for future traffic on GMT with the exception of trucking which would grow significantly with the development of Terminal 2 at Roberts Bank and associated logistics facilities in the South of Fraser area.

4.6. REGIONAL CONTEXT

The GMTR project fits into a larger regional context and should reflect the larger goals and targets identified in the long-term plans for the region. The current RTS developed by TransLink in 2013 sets out a long-term vision through the 2045 horizon year. A list of priority initiatives in support of this vision were identified in the 10-Year Vision, developed by the Mayor's Council in 2014 which is anticipated to be delivered in a series of phases as funding becomes available. Some key targets in the RTS involved designing the transportation system to support 33% shorter driving distances and a 50% active mode share target by the 2045 horizon year.

Although replacing the existing GMT with a higher capacity option is in contrast with the VKT and sustainable mode share targets set out, there are other elements of the RTS that apply. The removal of some congestion in the project corridor with the GMTR reference case is supportive of many goals stated in the RTS, such as:

- Making travel more reliable;
- Increasing transportation options;
- Making it easier and less stressful to get to work and school;
- Giving us more time for doing the things we love;
- Ensuring businesses continue to prosper with better access to more workers and more markets;
- Making living, working and doing business in this region more affordable;
- Giving people better access to more jobs and more opportunities; and
- Making our roads safer.

A 6- or 8-lane option is more compatible with the RTS than the 10-Lane Reference Concept. Both scaled down options still provide significant relief to congestion, but at the same time provide an incentive for high occupancy vehicle and transit travel. Further, any future forms of travel demand management or mobility pricing would help ensure that a 6- or 8-lane option performs at optimal traffic levels.

5. USER BENEFITS

This section describes the methodology and key assumptions for calculating user benefits for the various options for the GMTR. Conventional benefits that have been calculated include travel time savings, vehicle operating cost savings and reliability benefits.

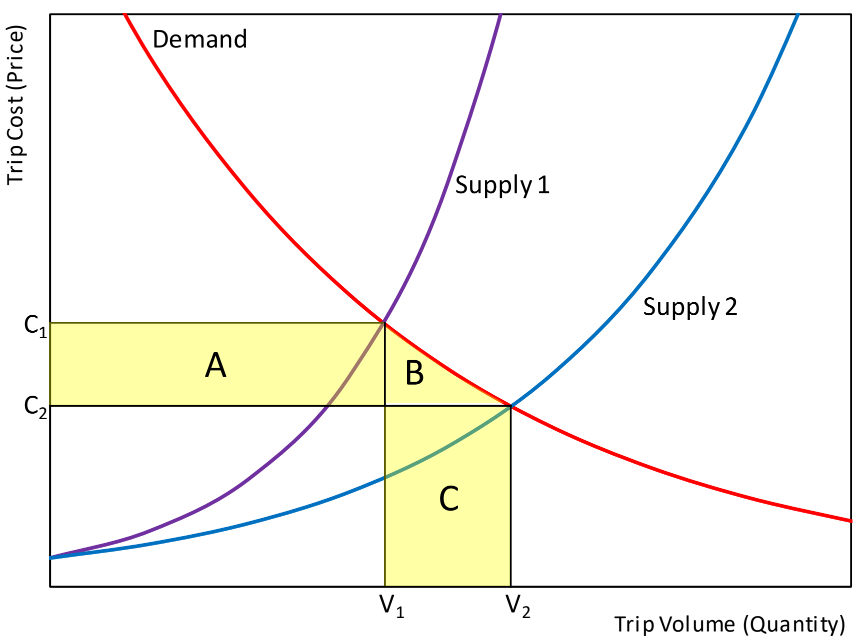
5.1. CONSUMER SURPLUS METHOD

The conventional matrix-based calculation of user benefits is based on the concept of consumer surplus which assumes that the trip maker behaves in a rational manner. In other words, a person is willing to pay a certain cost to make a trip as long as they are deriving some utility or benefit from making the trip that is greater than or equal to the cost.

In **Figure 34**, under the Supply 1 (e.g. 4-Lane BAU) curve there is a total of V1 trips travelling at a cost C1. At the intersect between Supply 1 and Demand 1, the network is assumed to be in a state of equilibrium. In other words, all users have chosen their shortest generalized cost path across a congested network. Under the Supply 2 (e.g. 10-Lane Reference Concept) curve, the total trips increase from V1 to V2 as a result of the travel costs decreasing (from C1 to C2). This is based on the increased capacity of the corridor which results in decreased travel costs. For existing trips V1, the benefits are represented by the rectangular area A which is equal to V1*(C1-C2). New users (V2-V1) accrue a benefit that is equivalent to the triangular area B, or (V2-V1)*(C1-C2)/2.

At C1, the costs exceeded the new user’s willingness to pay to undertake a particular trip. As costs drop to C2 the cost becomes lower than their willingness to pay. The difference between the new cost and the user’s willingness to pay is the ‘surplus’ and can range anywhere between 0 and C1-C2. As such each new user is assumed to accrue benefits equivalent to the midpoint or (C1-C2)/2 which in industry is referred to as the ‘rule of a half’.

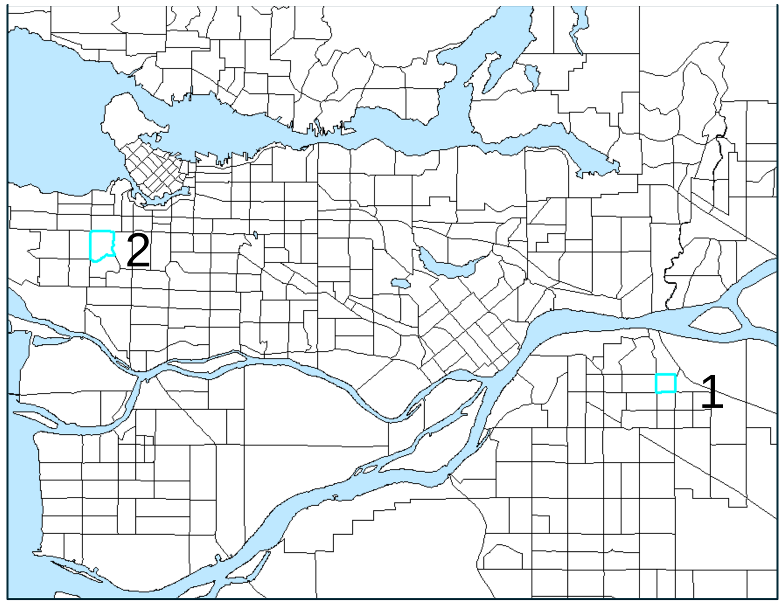
Figure 34: Definition of Consumer Surplus



The following example is used to demonstrate the application of consumer surplus in the context of the RTM matrix-based calculation. Assume that under base year conditions there are 50 auto trips travelling between two traffic zones (see **Figure 35**) under base year conditions. Based on a model run, a new roadway link reduces travel time between the two zones by 5 minutes and increases trip making by 20. The user benefits are calculated as follows:

- Existing Users' Benefits: 50 x 5 = 250 person-minutes
- New Users' Benefits: 20 x 5 / 2 = 50 person-minutes
- Total Benefits: 300 person-minutes

Figure 35: Sample of Origin Zone (1) and Destination Zone (2)



The benefits are then monetized using the assumed value of time for each of the user classes and expressed in current year dollars. This process is repeated for each zone pair in the RTM3 (1,700 x 1,700 = 2.9 million origin-destination pairs) and for each transportation account (auto and transit journey time savings and auto operating costs).

The following formula provides the general implementation in RTM3:

$$Surplus\ (min) = \frac{1}{2} \cdot (Demand_{Base} + Demand_{Test}) \cdot \left((Time_{Base} + OpCost_{Base} \cdot VoT) - (Time_{Test} + OpCost_{Test} \cdot VoT)\right)$$

The following provides the breakdown of user benefits by the model user and vehicle classes (9 vehicle + 3 transit = 12 total):

- Single Occupancy Vehicles (SOV1, SOV2, SOV3, SOV4)
- High Occupancy Vehicles (HOV1, HOV2, HOV3)
- Trucks: Light Gross Weight Vehicles (LGV) and Heavy Gross Weight Vehicles (HGV)
- Transit (WCE, Rail, Bus)

5.2. INPUT ASSUMPTIONS

The following provides a summary of the key input assumptions for undertaking the consumer surplus calculations in RTM3. One of the fundamental principles in consumer surplus is how people value their time which is used to monetize travel time savings. Generally, the value of time is derived from the 2016 Census using the median household income. The following values of time are developed using BC MoTI Business Case Guidelines:

- Auto (SOV and HOV per person): $18.49/hour
- LGV: $38.11/hour
- HGV: $47.10/hour
- Transit: $18.49

The RTM3 provides estimates of travel time savings for the morning, midday and afternoon peak periods. In order to carry out an analysis of net present value (NPV) of benefits, expansion/annualization factors are used. The following describes the key factors in developing the expansion/annualization factors:

- Default expansion factors from RTM3 are for generating AADT and will overestimate project benefits as they are distributed differently than demand. Projects generally provide benefits during peak periods, and not as much during off peak times.

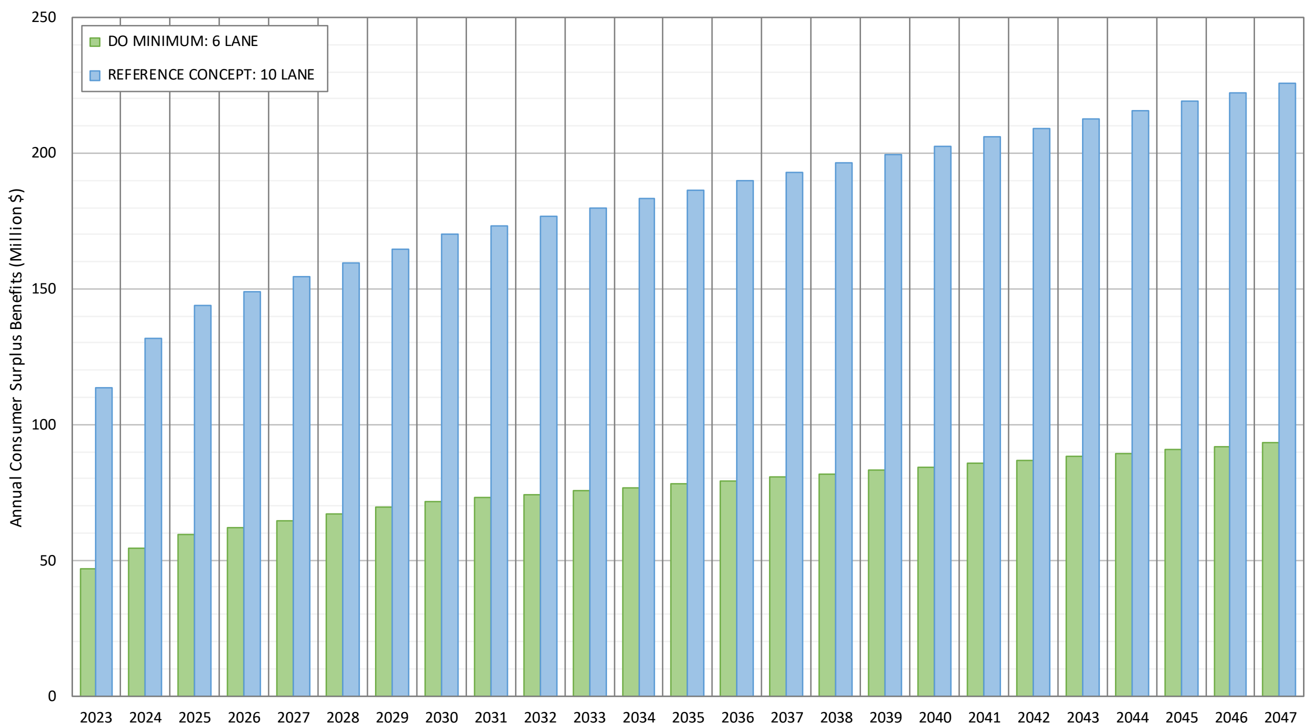
- The RTM3 provides estimates of travel demands and travel times at a 24-hour level which were used to develop the estimates of user benefits without use of peak to daily expansion factors.

- An expansion factor of 270 was used for the Daily to Annual factor.

5.3. TRAVEL TIME AND VEHICLE OPERATING COST BENEFITS

Because of the generalized cost formulation (travel time + out of pocket costs) of the RTM3, the consumer surplus calculations will automatically produce a total estimate of both travel time and vehicle operating cost savings on an annual basis. Annual benefits were streamed back to 2018 using a 6% discount rate and are expressed in 2018 dollars. User benefits were developed for the life cycle of the project which is assumed to be opening day in 2023 to 2047. **Figure 36** below illustrates the annual streaming of benefits from opening day for a 25-year operating period for both the 10-Lane Reference Concept and the 6-Lane Do Minimum. The total NPV of benefits is $1,734 million for the 10-Lane Reference Concept and $723 million for the 6-Lane Do Minimum which is 42% of the total benefits of the full build out of the corridor. This shows that there are significant benefits of just improving the crossing.

Figure 36: Annual Streaming of User Benefits



8-Lane Do Minimum and 8-Lane Reference Concept were also modelled to determine how benefits are derived in the study area as the scale of the project is dialed up or down. These two scenarios are defined as follows:

- ***8-Lane Do Minimum –*** Same as the 6-Lane Do Minimum but with auxiliary lanes between the Steveston and Highway 17A interchanges.

- ***8-Lane Reference Concept –*** Same as the 10-Lane Reference Concept but with the HOV/bus lanes removed between the Steveston and Highway 17A interchanges.

The 8-Lane Do Minimum scenario generates 50% of the 10-lane Reference Concept benefits and the 8-Lane Reference Concept generates 95% of the user benefits. This shows that the wider network expansion is required to realize the full benefits of the project. Widening the crossing to 8 lanes generates about half of the total benefits with the remaining coming from the remaining corridor expansion.

In order to validate these results, a summary of travel time comparisons for the Highway 99 and 91 corridors was analyzed. This helps to interpret the user benefits in a meaningful way that can be relatable to the average corridor user. Travel time comparisons for the following routes have been developed:

- Hwy 99 - From Hwy 91 Ramps (Surrey) to Hwy 91 Ramps (Richmond)

- Hwy 91 - From Hwy 99 Ramps (Surrey) to Shell Road (Richmond)

Figure 37 to **Figure 39** provide a summary of travel times for the AM, midday and PM peak periods respectively. The following key findings are observed:

- For off-peak travel during the peaks (i.e. SB during AM peak and NB during PM peak), most of the travel time savings are captured by the 6-Lane Do Minimum (85 to 100% compared to the 10-Lane Reference Concept);

- For peak direction travel during the peaks (i.e. NB during AM peak and SB during PM peak), minimal travel time savings are captured by the 6-Lane Do Minimum (< 10% compared to the 10-Lane Reference Concept);

- Outside the AM and PM peak periods, the travel time savings are much less and similar for all scenarios;

- The 6-Lane Do Minimum is just as good as the 10-Lane Reference Concept for all times/direction except peak period peak direction (i.e. AM NB & PM SB)

Figure 37: 2045 AM Travel Times for Highway 99 and 91 Corridors

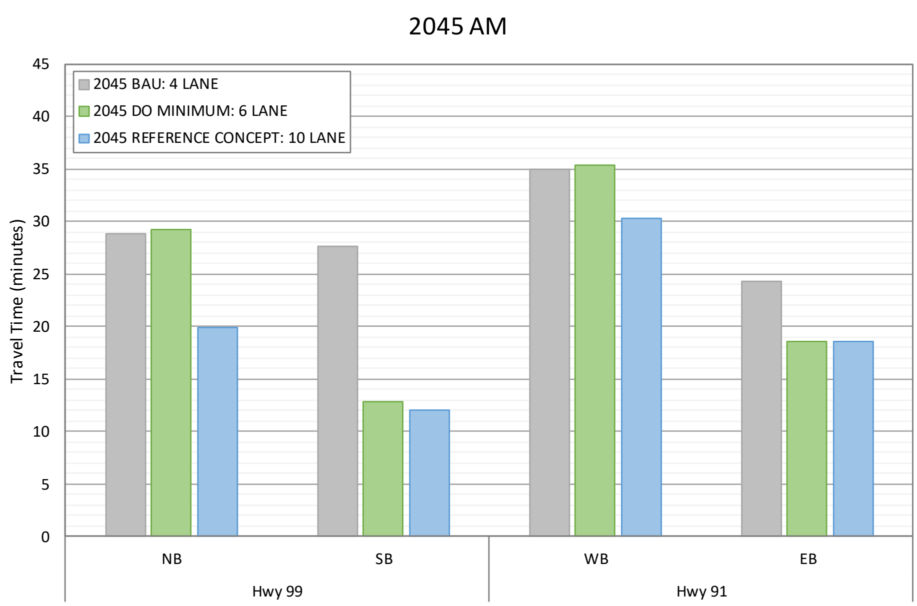


Figure 38: 2045 MD Travel Times for Highway 99 and 91 Corridors

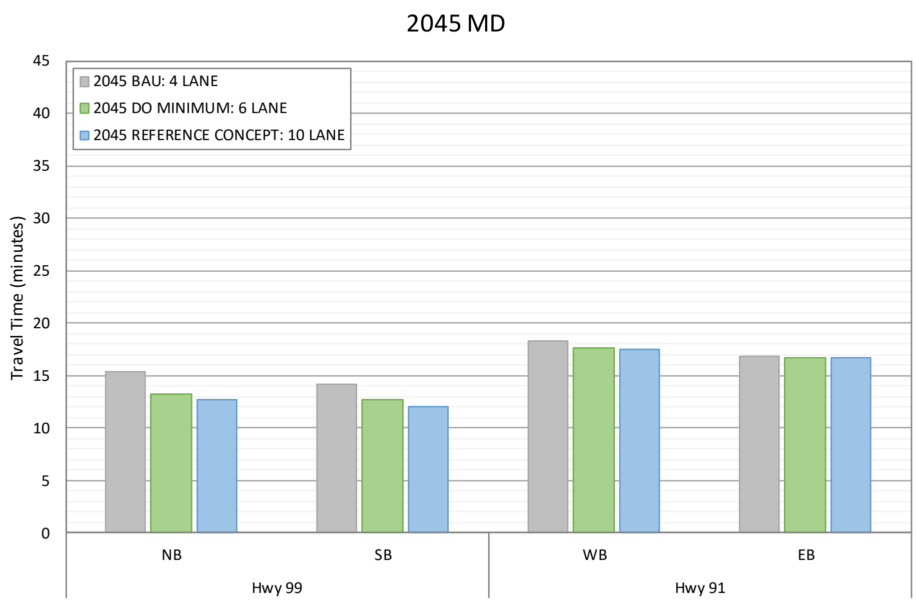
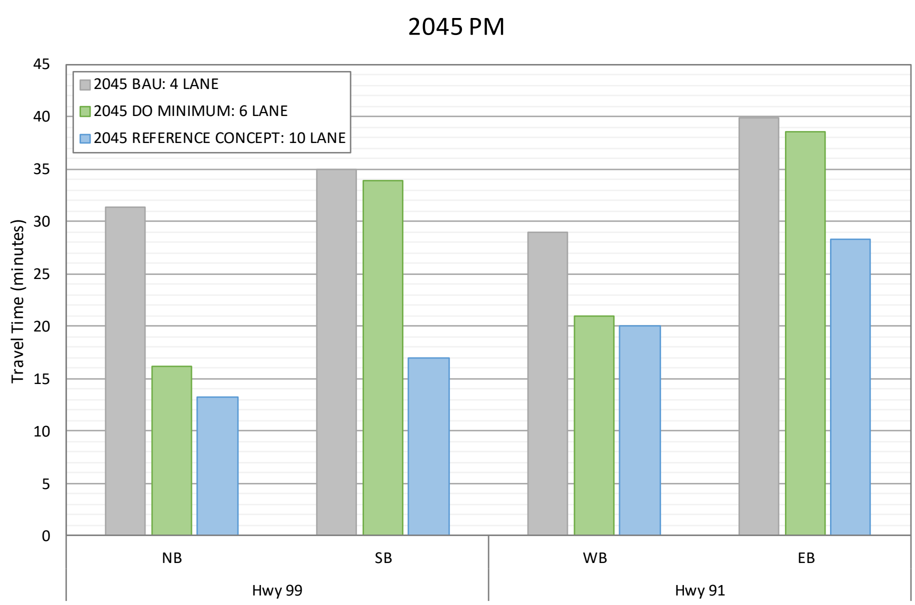


Figure 39: 2045 PM Travel Times for Highway 99 and 91 Corridors



Comparison of User Benefits to Corridor Congestion Model (CCM)

A comparison to the CCM, which was a completely independent method, was made to benchmark the user benefit estimates coming out of RTM3. For both approaches, the project is assumed to open in 2023 and is in operation for 25 years. The key differences are highlighted in **Table 2** below. Note that the CCM is expressed in $ 2017 while the RTM3 is expressed in $ 2018. The CCM is implicitly an all-day model which is expanded to annual estimates. It does not include network effects outside of the Highway 99 corridor and assumes a tolled crossing which results in a reduction in traffic volumes. This shows that the estimate of user benefits is fairly consistent comparing the two independent approaches.

Table 2: Comparison of User Benefits from CCM and RTM3 (in millions)

Account	CCM	RTM3
Travel Time Savings	$1,475	$1,734
Fuel Cost Savings	$154	
Cost of Traffic Lost to Tolling	($93)	-
Total	$1,536	$1,734

Estimate of Benefits by Sub Region

The replacement of the GMT will result in user benefits that span across broad areas of the Metro Vancouver region, not just the Highway 99 corridor. **Table 3** provides a summary of user benefits (aggregated travel time savings in $ 2018) for the 10-Lane Reference Concept and the 6-Lane Do Minimum breaking up the Metro Vancouver region into 15 sub-regions. Note that travel time savings are highlighted in green and travel time increases are highlighted in red. The following provides a discussion of the key findings:

- Trips between Richmond and South Delta sees largest amount of user benefit;
- North Surrey to Richmond sees increased benefits as capacity is freed up on the Alex Fraser Bridge as users divert to the GMTR;
- Vancouver-Richmond trips see some dis-benefits due to increased congestion on the Oak and Knight St bridges;
- South Surrey sees increased congestion as users divert from Highway 91 to 99 and cause congestion on South Surrey municipal roadways; and
- Some disbenefits for trips between South Delta and Surrey as diverted trips cause congestion on municipal roadways.

Table 3: Estimate of User Benefits by Sub Region for 10-Lane Reference Concept and 6-Lane Do Minimum

Reference Concept: 10 Lane 2045 Annual Consumer Surplus (2018 $)	West Vancouver	North Vancouver	Vancouver CBD	Vancouver	Burnaby / New West	Tri-Cities	Richmond	Ladner / Tsawwassen	North Surrey	South Surrey	Maple Ridge / Pitt Meadows	Langelys	FVRD - North	FVRD - South	External + Park & Ride
West Vancouver	-2,000	19,000	86,000	79,000	36,000	44,000	-25,000	217,000	173,000	43,000	27,000	53,000	6,000	25,000	105,000
North Vancouver	38,000	25,000	155,000	147,000	115,000	152,000	16,000	523,000	550,000	113,000	80,000	149,000	14,000	69,000	194,000
Vancouver CBD	11,000	75,000	32,000	111,000	580,000	277,000	62,000	1,941,000	1,437,000	1,546,000	95,000	232,000	19,000	74,000	624,000
Vancouver	2,000	89,000	20,000	1,016,000	2,611,000	928,000	-67,000	6,505,000	7,333,000	3,875,000	350,000	1,045,000	60,000	296,000	2,698,000
Burnaby / New Westminster	62,000	182,000	405,000	2,447,000	2,175,000	743,000	2,350,000	1,336,000	5,444,000	964,000	351,000	704,000	53,000	299,000	592,000
Tri-Cities	47,000	147,000	208,000	803,000	596,000	212,000	1,021,000	9,000	1,918,000	242,000	421,000	399,000	55,000	170,000	182,000
Richmond	-32,000	-118,000	276,000	-99,000	1,681,000	924,000	3,053,000	18,790,000	17,922,000	7,632,000	939,000	3,233,000	185,000	863,000	2,527,000
Ladner / Tsawwassen	258,000	595,000	1,251,000	7,595,000	1,938,000	203,000	21,293,000	538,000	1,370,000	366,000	10,000	54,000	2,000	22,000	717,000
North Surrey	119,000	364,000	558,000	4,249,000	4,052,000	1,025,000	11,803,000	293,000	2,919,000	131,000	-65,000	168,000	-	148,000	5,815,000
South Surrey	12,000	33,000	514,000	1,752,000	383,000	76,000	4,023,000	58,000	-435,000	-677,000	-15,000	-217,000	-13,000	-80,000	416,000
Maple Ridge / Pitt Meadows	15,000	46,000	36,000	184,000	176,000	155,000	642,000	-36,000	37,000	35,000	85,000	65,000	26,000	59,000	140,000
Langelys	30,000	88,000	89,000	664,000	380,000	110,000	2,066,000	-32,000	160,000	2,000	-45,000	308,000	-17,000	32,000	331,000
FVRD - North	2,000	7,000	6,000	27,000	23,000	16,000	84,000	-2,000	-	-2,000	12,000	-	15,000	31,000	75,000
FVRD - South	13,000	34,000	25,000	180,000	132,000	42,000	589,000	-25,000	33,000	-22,000	-12,000	30,000	-71,000	-141,000	338,000
External + Park & Ride	194,000	221,000	798,000	3,185,000	593,000	94,000	3,298,000	337,000	3,530,000	392,000	90,000	267,000	67,000	207,000	5,590,000

Do Minimum: 6 Lane 2045 Annual Consumer Surplus (2018 $)	West Vancouver	North Vancouver	Vancouver CBD	Vancouver	Burnaby / New West	Tri-Cities	Richmond	Ladner / Tsawwassen	North Surrey	South Surrey	Maple Ridge / Pitt Meadows	Langelys	FVRD - North	FVRD - South	External + Park & Ride
West Vancouver	-1,000	6,000	9,000	43,000	21,000	9,000	8,000	124,000	34,000	7,000	3,000	8,000	-	4,000	61,000
North Vancouver	14,000	8,000	36,000	112,000	71,000	21,000	44,000	271,000	102,000	18,000	10,000	22,000	1,000	11,000	99,000
Vancouver CBD	-99,000	-117,000	19,000	208,000	56,000	8,000	128,000	1,018,000	154,000	404,000	1,000	21,000	1,000	6,000	349,000
Vancouver	-99,000	-152,000	-4,000	373,000	382,000	72,000	305,000	3,453,000	1,371,000	1,083,000	38,000	148,000	7,000	33,000	1,202,000
Burnaby / New Westminster	48,000	181,000	146,000	1,533,000	930,000	107,000	1,571,000	600,000	999,000	130,000	51,000	104,000	6,000	44,000	231,000
Tri-Cities	22,000	58,000	22,000	301,000	207,000	21,000	484,000	51,000	251,000	22,000	50,000	21,000	4,000	23,000	87,000
Richmond	-68,000	-253,000	-34,000	-1,318,000	210,000	207,000	932,000	10,925,000	6,033,000	2,637,000	345,000	1,120,000	51,000	273,000	1,298,000
Ladner / Tsawwassen	135,000	320,000	517,000	4,127,000	929,000	100,000	11,677,000	99,000	-273,000	-207,000	-13,000	-84,000	-3,000	-15,000	335,000
North Surrey	56,000	165,000	135,000	1,703,000	1,965,000	614,000	5,734,000	289,000	809,000	-94,000	20,000	66,000	-	54,000	3,510,000
South Surrey	6,000	19,000	82,000	681,000	227,000	60,000	1,885,000	-42,000	-50,000	-249,000	12,000	8,000	-	-13,000	273,000
Maple Ridge / Pitt Meadows	6,000	21,000	5,000	66,000	69,000	94,000	296,000	-5,000	-79,000	-13,000	1,000	-46,000	-1,000	1,000	76,000
Langelys	13,000	41,000	10,000	239,000	148,000	72,000	1,046,000	-15,000	-1,000	-113,000	22,000	77,000	-	17,000	197,000
FVRD - North	-	2,000	-	5,000	6,000	6,000	27,000	2,000	-3,000	-3,000	4,000	-3,000	3,000	-5,000	41,000
FVRD - South	6,000	16,000	2,000	54,000	50,000	49,000	275,000	-	65,000	-40,000	21,000	16,000	6,000	-38,000	208,000
External + Park & Ride	125,000	139,000	477,000	2,066,000	333,000	46,000	2,262,000	163,000	927,000	113,000	24,000	64,000	10,000	7,000	3,166,000

5.4. RELIABILITY BENEFITS

Travel time reliability is not a standard output from the RTM3 and requires additional calculations outside of the standard model results. The recent Metro Vancouver Mobility Pricing Study (May 2018) developed a methodology for estimating trip level travel time reliability within the RTM3 framework[1]. The model was estimated by collecting weekday travel time data observations for four months (February, March, October, November) during 2016 and 2017. Observations were only included for the 0700-1900 time period due to low levels of travel time variation in the overnight period. 14 locations were selected for monitoring with travel times between each of the locations being measured on an ongoing basis. The resulting 14 x 14 travel time matrix was then compared to modelled origin/destination travel times for estimation.

A log-log model was developed producing the standard deviation in travel time minutes based on a number of trip level and time of day specific factors. **Table 4** below contains a list of the input and output parameters used in the regression model formulation:

Table 4: Travel Time Reliability Model Parameters

Parameter	Value
Intercept	-3.374
Log (Travel Time Index)	3.119
Peak Period = True	0.178
Log (Travel distance in km)	0.837
Crosses Regional Bridge = True	0.162
Log (Travel Time Index: Peak Only)	0.438

Once travel time reliability had been calculated for each trip in the RTM3, the consumer surplus approach was used to value the improvements in travel time reliability in the same manner as benefits were calculated for the travel time savings account. For consistency with the approach used in the Mobility Pricing study, improvements in reliability were valued at 80% of the actual representing the perception of the value of variability in travel time suggested by a literature review.

The 10-Lane Reference Concept produces $509 million in reliability benefits while the 6-Lane Do Minimum provides $186 million which is 36% of the full buildout of the corridor. The reliability benefits are added in addition to the travel time and vehicle operating cost savings. This shows that the 6-Lane Do Minimum generates fairly significant reliability benefits with the replacement of just the crossing. For comparison, the 8-Lane Do Minimum generates 46% of the total reliability benefit from the 10-Lane Reference Concept and the 8-Lane Reference Concept generates 98% of the total reliability benefits. This further emphasizes that replacing the crossing generates about half of the total project benefits and the remaining half comes from expanding the Highway 99 corridor from the Highway 91 interchange in Delta to the Highway 91 interchange in Richmond.

[1] Metro Vancouver Mobility Pricing Study, Appendix B-2: 4.4 Reliability model estimation and output https://www.itstimemv.ca/uploads/1/0/6/9/106921821/mpic_full_report_-_final.pdf

5.5. SUMMARY OF USER BENEFITS

Because of the high levels of congestion and travel time variability, any improvements to the existing George Massey Tunnel and Highway 99 corridor will result in user benefits. This section provides a summary of those benefits for the options reviewed.

The high proportion of the benefits captured by the 6-Lane Do Minimum is due to the large capacity increase in the off-peak directions during the peak periods which sees significant congestion effects on the single lane provided during counterflow operation. The peak direction also sees additional benefits as a new 6-lane crossing would be built to modern design standards and the inside lane would be physically separated from oncoming traffic. Today, the counterflow lane operates without a physical barrier which some drivers may shy from resulting in a fairly low lane utilization rate. The 6-Lane Do Minimum provides significant travel time benefits in the off-peak direction in the peak periods, providing operational speeds similar to the midday, off-peak period.

There are additional travel time, reliability and capacity benefits of providing additional capacity in the peak direction on the crossing, but approximately half of the benefits provided by the reference concept are attributable to the highway mainline and access improvements at interchanges along the corridor on either side of the crossing. These benefits are not captured in a Do Minimum option. There are limited additional benefits provided by the 10-Lane Reference Concept in the short-term as the majority of the non-peak direction congestion has been relieved by the 6-Lane Do Minimum. Compared to the 6-Lane Do Minimum, the 10-Lane Reference Concept does provide benefits in the longer term with improvements to peak direction travel times and provides additional relief to the AFB and Highway 91. However, these benefits are similar to those seen in the 8-Lane Reference Concept.

In addition to travel time and vehicle operating cost savings, any improvements to GMT will result in reliability benefits. The current crossing sees significant variability in travel times due to accidents, vehicle stall, etc. The 10-Lane Reference Concept results in an additional $509 million in NPV of user benefits. The 6-Lane Do Minimum achieves approximately 36% of these reliability benefits as it provides a capacity improvement in the off-peak direction. The 8-Lane Do Minimum achieves 46% and the 8-Lane Reference Concept achieves 98% of the full build option, similar to the travel time and vehicle operating cost savings.

The following table (**Table 5**) provides a summary of the travel time and reliability benefits as a proportion (%) of the 10-Lane Reference Concept for the options that were analyzed.

Table 5: Summary of Traffic Forecasts and User Benefits for GMTR Options

GMTR Option	Lane Configuration	Future Traffic Volume (2045 AADT)	2045 PM Peak Travel Times (mm:ss)		Travel Time and Operating Cost Benefits (NPV $ 2018)	Reliability Benefits (NPV $ 2018)
			NB	SB		
4-Lane Do Nothing	2/2 GP (Off Peak) 3/1 GP (Peak Counter Flow)	74%	31:30	35:00	0%	0%
6-Lane Do Minimum	3/3 GP	87%	16:10	33:50	42%	36%
8-Lane Do Minimum	4/4 GP	91%	15:10	32:30	50%	46%
8-Lane Reference Concept	4/4 GP	99%	13:25	17:30	95%	98%
10-Lane Reference Concept	4/4 GP + 1/1 HOV/Bus	100%	13:20	17:00	100%	100%
Summary Metric		128,400	-	-	$1,734 million	$509 million

The 6- and 8-Lane Do Minimum options serve 87% and 91% of the 10-Lane Reference Concept traffic volumes. The 8-Lane Do Minimum achieves approximately half of the benefits (travel time and reliability) of the 10-Lane Reference Concept while the 8-Lane Reference Concept achieves close to 100% of the benefits. In terms of timing, the short-term need would be to replace the crossing (Do Minimum) and then provide the corridor improvements (Reference Concept) for the longer term. This would provide improvements that are "right sized" for the corridor context and aligned with the forecasts of traffic. Further, the corridor improvements can be staged over time and added as congestion trigger points are reached.

5.6. NEXT STEPS

The analysis presented in this report has provided a high-level review of options for replacement of the GMT and the benefits that are derived. There are additional next steps that would help to refine the analysis and address outstanding questions as follows:

4) Refinement of the Do Minimum concept

- f) Value of additional corridor improvements in immediate vicinity of crossing for 6- and 8-Lane Do Minimum;
- g) Costing of the 6- and 8-Lane Do Minimum options;
- h) Additional benefits and environmental impacts such as change to vehicle-kilometres travelled which is a metric tracked at the regional level and is a proxy for emissions along with vehicle-hours travelled;
- i) More refined analysis of potential safety benefits; and
- j) Incremental benefit/cost or value for money analysis for the various options.

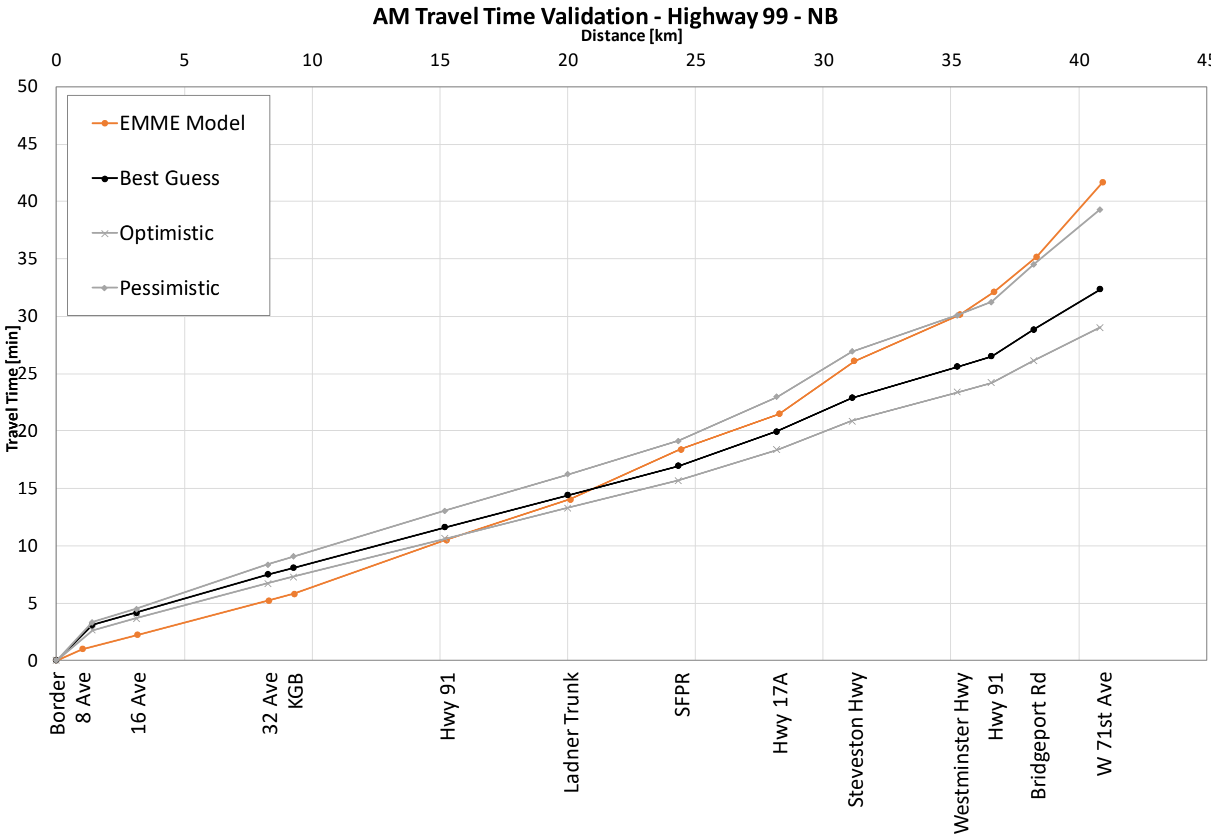
5) Refinement of the Reference Concept

- f) Costing/Affordability/Benefits;
- g) Trade offs of different crossing capacity vs policy management options (utilization over 24 hours, tolls, travel demand management, mobility pricing);
- h) Right-sizing interchange designs for updated crossing configuration;
- i) Transit integration including consultation with TransLink; and
- j) Regional policy impacts (mobility pricing, sustainable mode targets, coordination with the RTS), and ability to manage congestion with other policy levers.

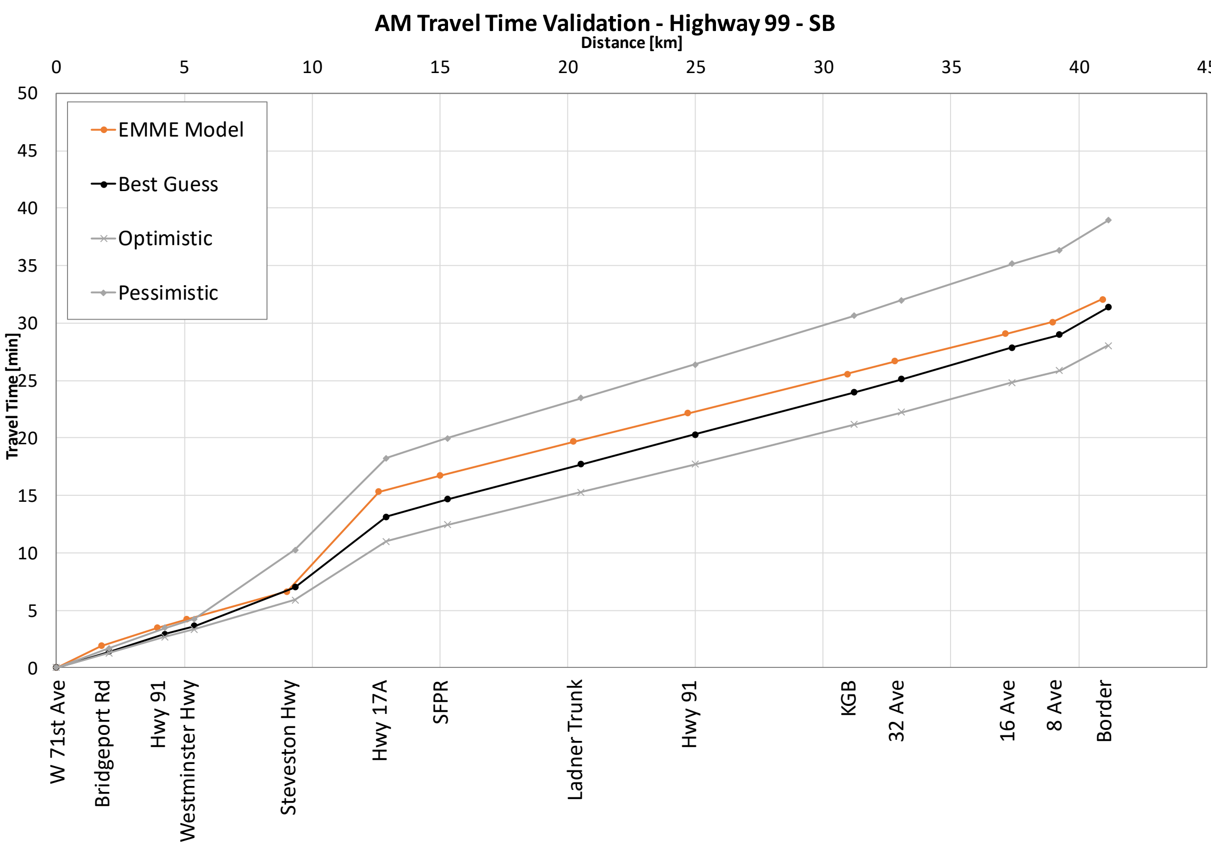
6) Staging of ultimate corridor buildout, with refinements

- e) Richmond corridor/interchanges value-for-money and potential timelines;
- f) Delta corridor/interchanges value-for-money and timelines;
- g) Triggers for improvements (regional and municipal plans); and
- h) Comparator to other highway improvement projects (Brunette Interchange, Lower Lynn interchanges, 216th Interchange and Highway 1 widening).

APPENDIX A: TRAVEL TIME VALIDATION PLOTS



AM Travel Time Validation - Highway 99 - NB
Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
Border
8 Ave
16 Ave
32 Ave
KGB
Hwy 91
Ladner Trunk
SFPR
Hwy 17A
Steveston Hwy
Westminster Hwy
Hwy 91
Bridgeport Rd
W 71st Ave



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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Bridgeport Rd
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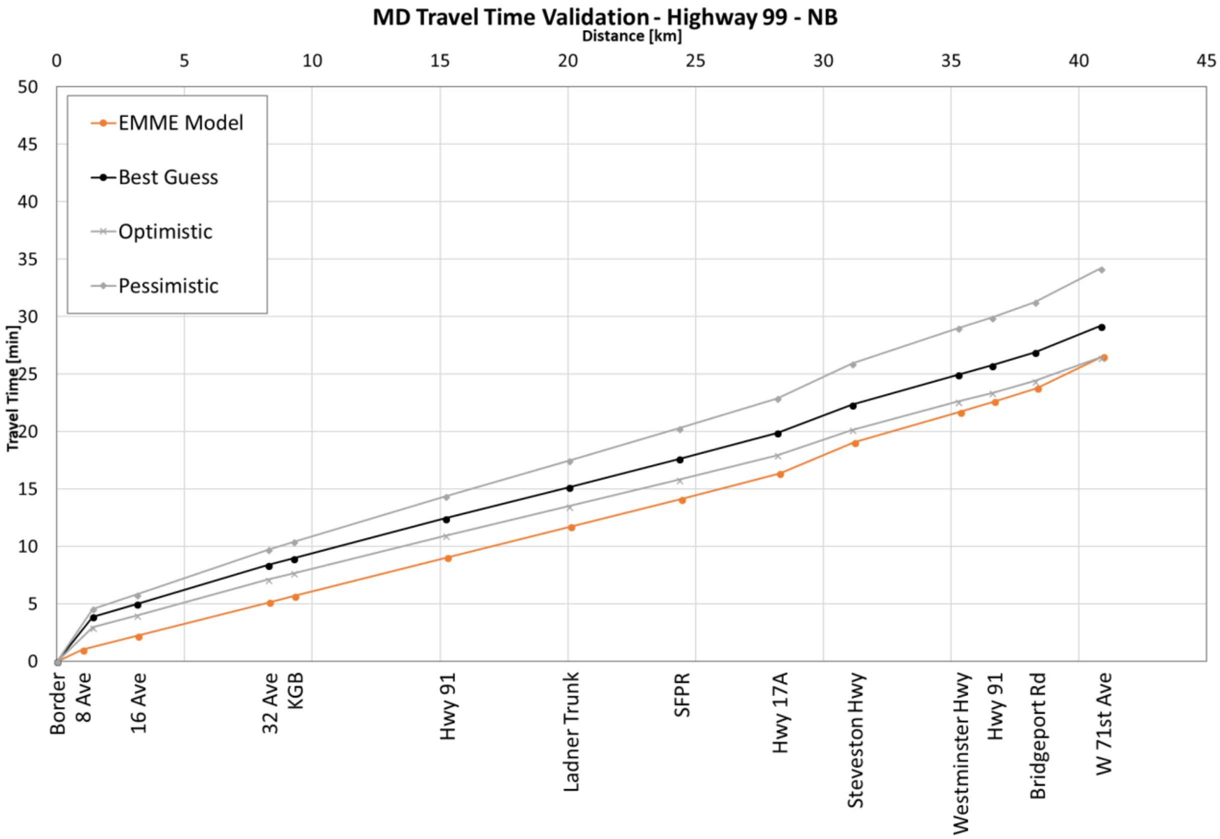
Ladner Trunk
Hwy 91
KGB
32 Ave
16 Ave
8 Ave
Border



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
Border
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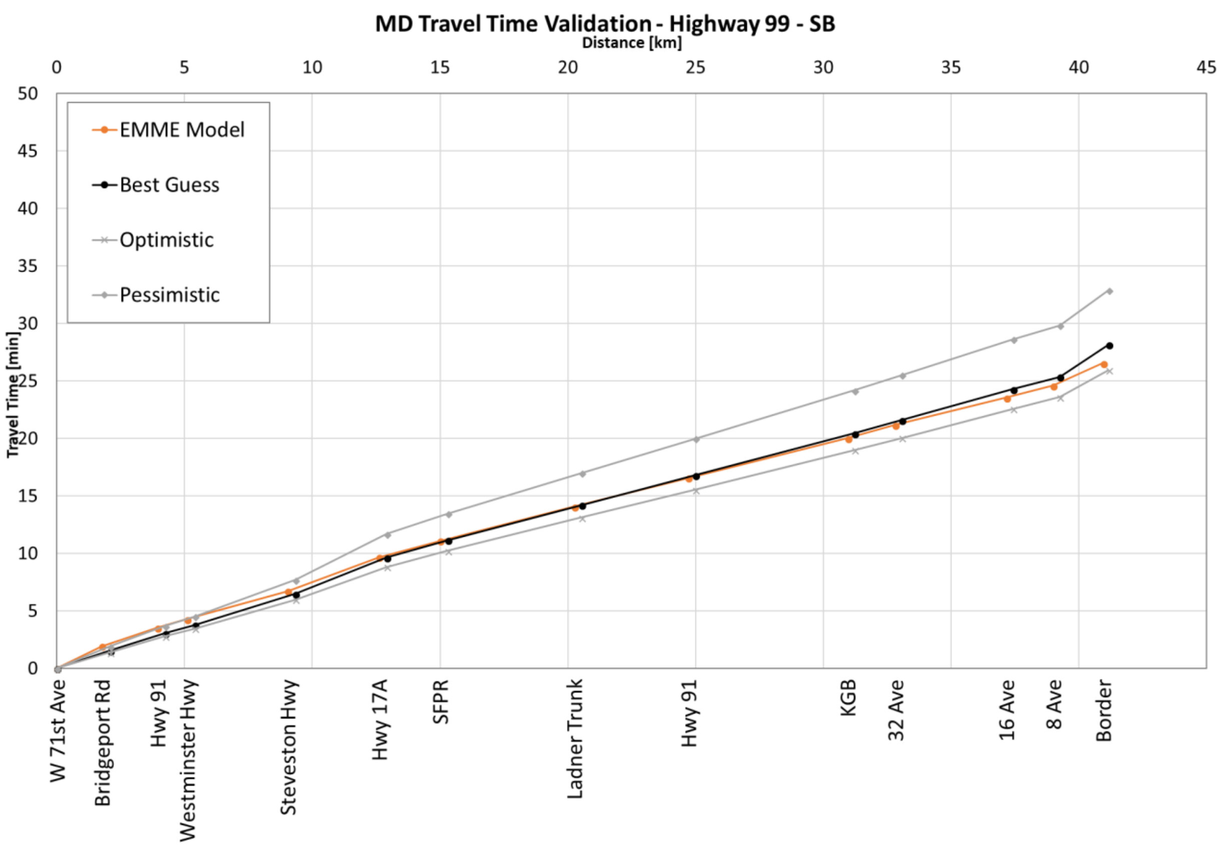
16 Ave
32 Ave
KGB
Hwy 91
Ladner Trunk
SFPR
Hwy 17A
Steveston Hwy
Westminster Hwy
Hwy 91
Bridgeport Rd
W 71st Ave



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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Bridgeport Rd
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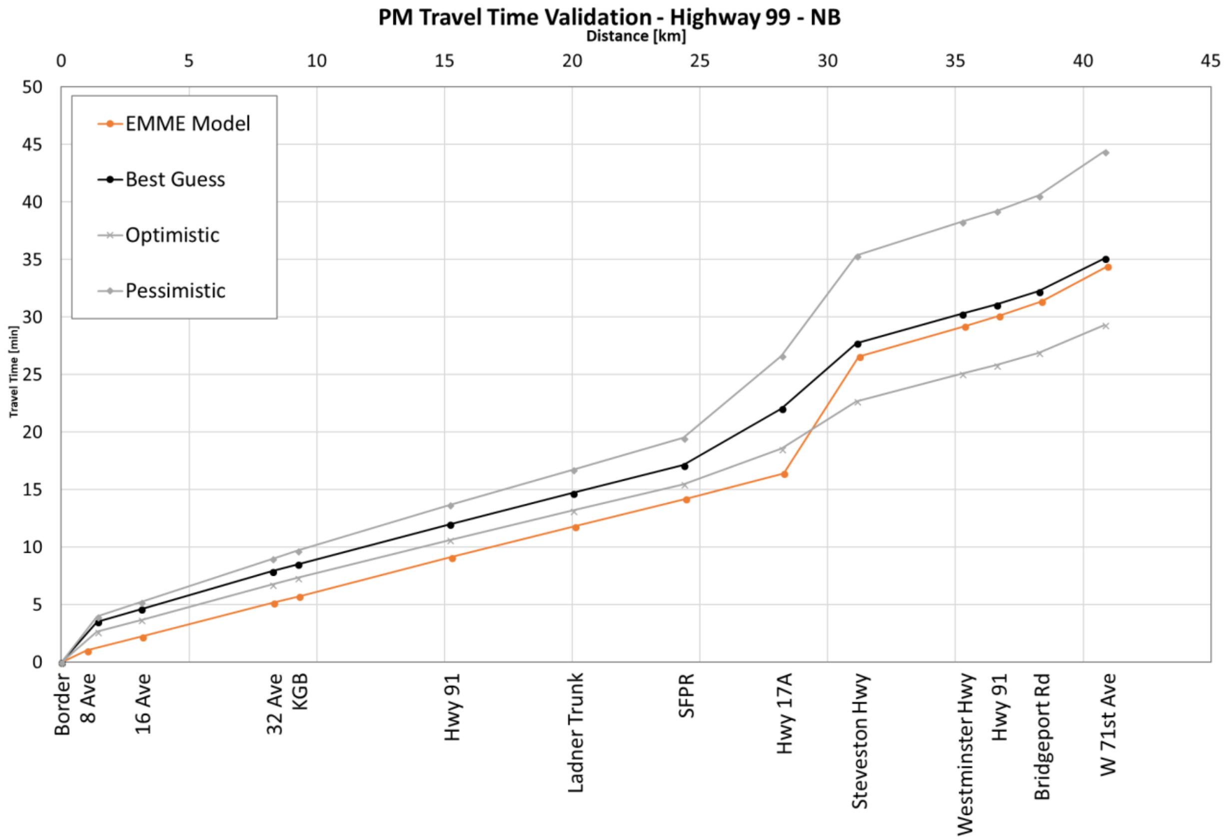
Westminster Hwy
Steveston Hwy
Hwy 17A
SFPR
Ladner Trunk
Hwy 91
KGB
32 Ave
16 Ave
8 Ave
Border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Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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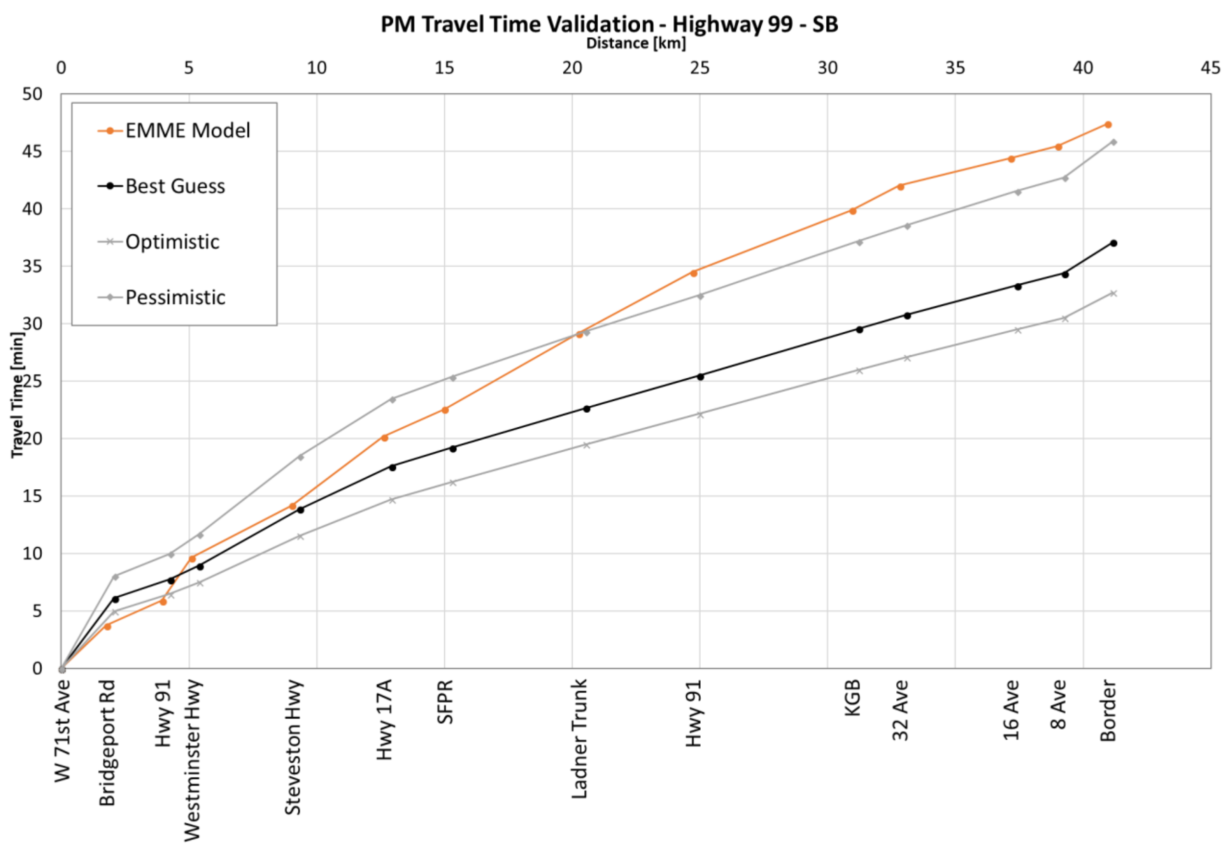
Hwy 91
Bridgeport Rd
W 71st Ave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Distance [km]
Travel Time [min]
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Best Guess
Optimistic
Pessimistic
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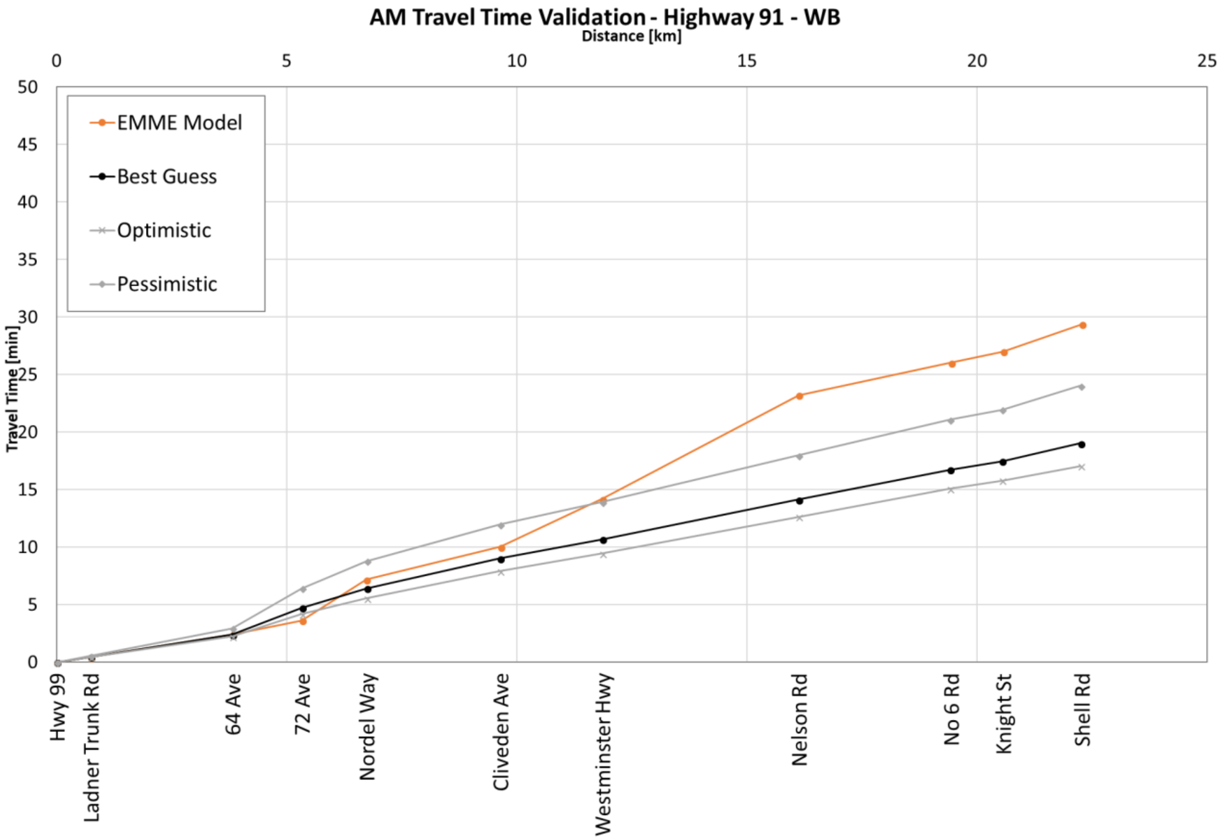
SFPR
Ladner Trunk
Hwy 91
KGB
32 Ave
16 Ave
8 Ave
Border



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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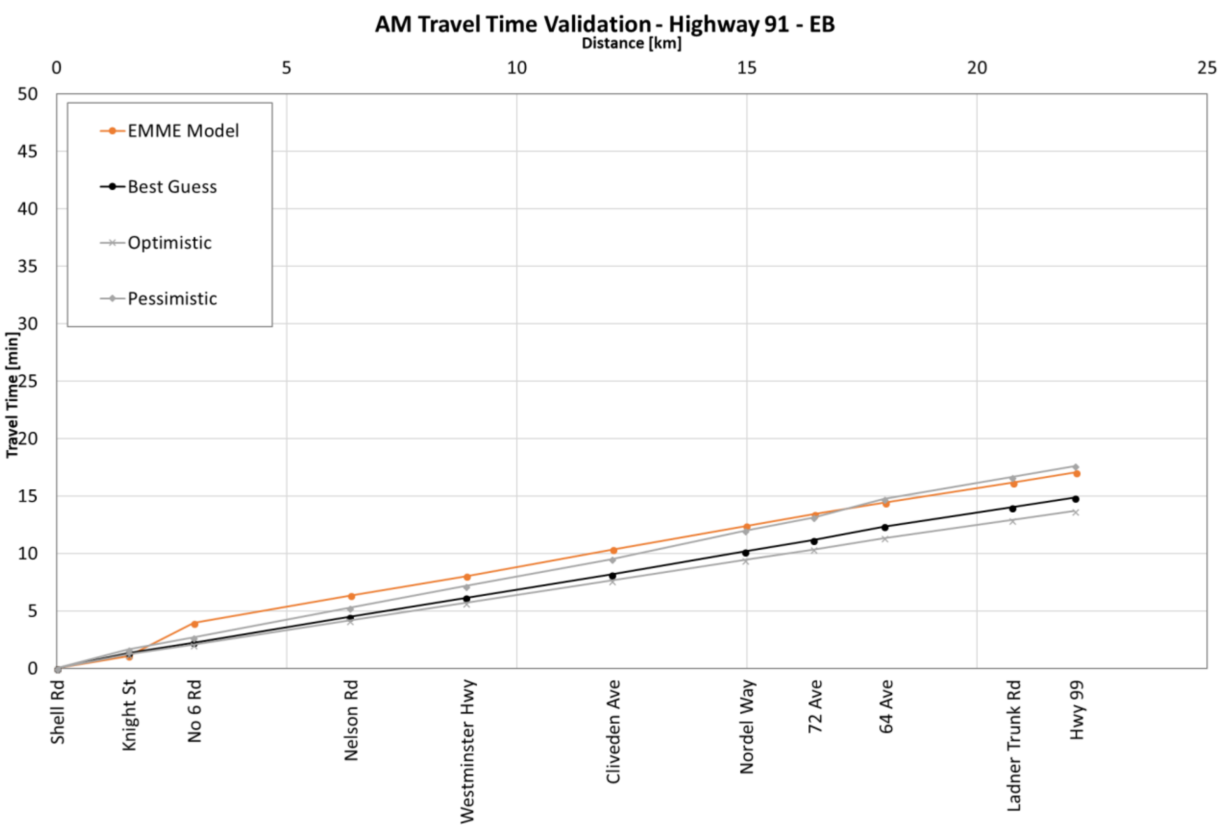
72 Ave
Nordel Way
Cliveden Ave
Westminster Hwy
Nelson Rd
No 6 Rd
Knight St
Shell Rd



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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Nelson Rd
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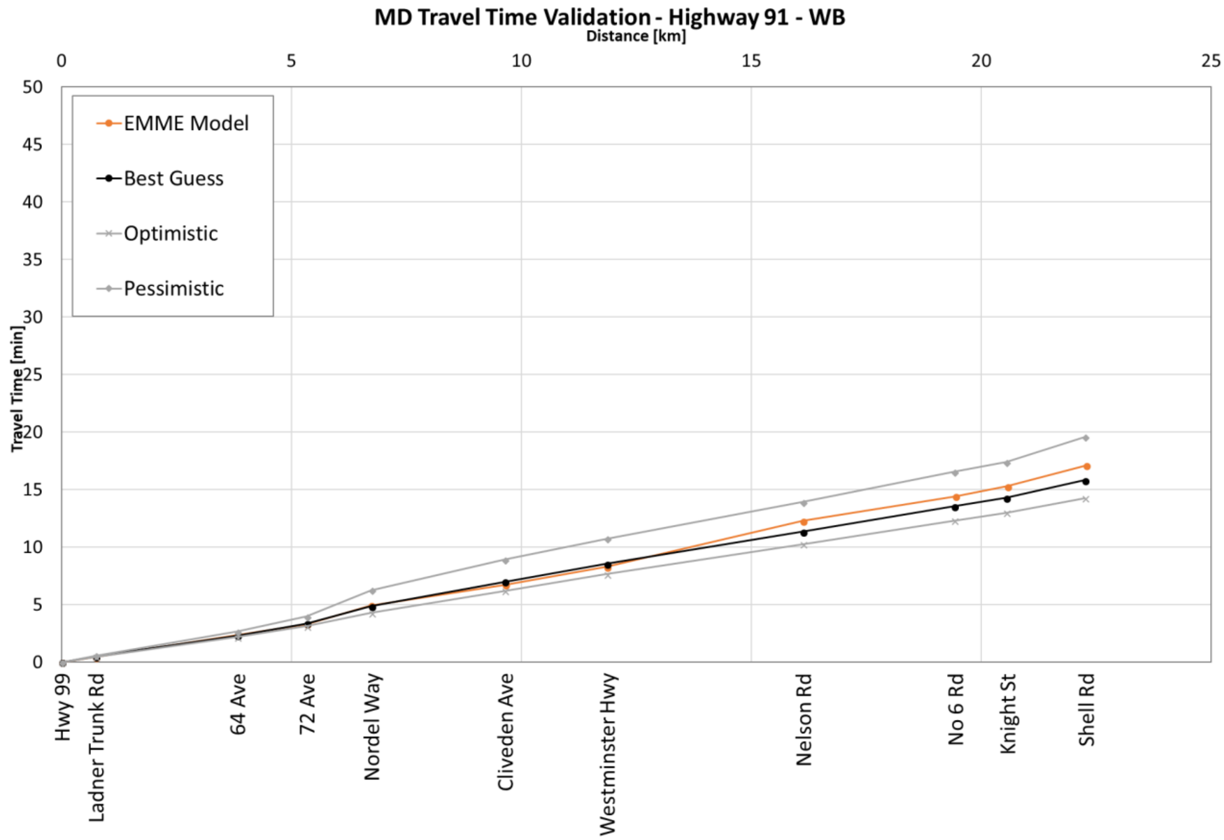
Nordel Way
72 Ave
64 Ave
Ladner Trunk Rd
Hwy 99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Distance [km]
Travel Time [min]
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Best Guess
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Pessimistic
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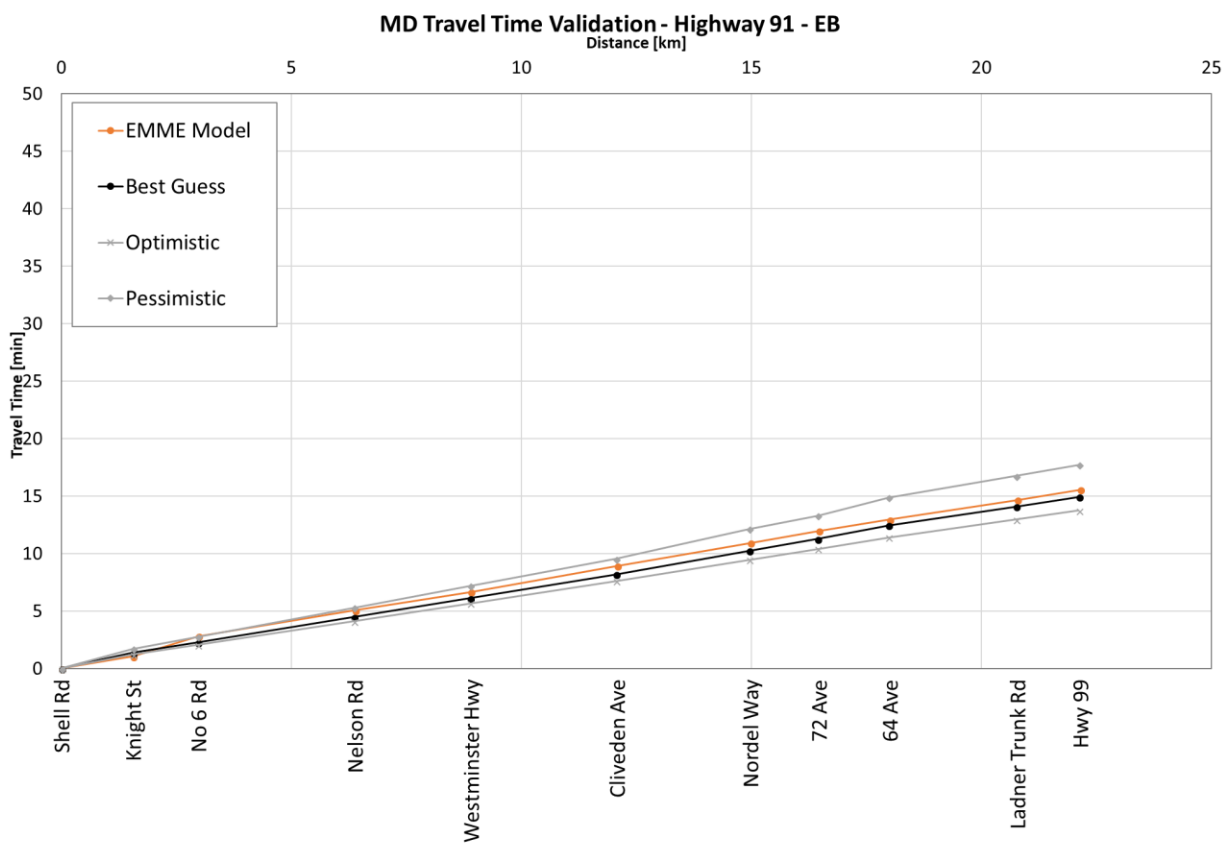
No 6 Rd
Knight St
Shell Rd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Distance [km]
Travel Time [min]
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Best Guess
Optimistic
Pessimistic
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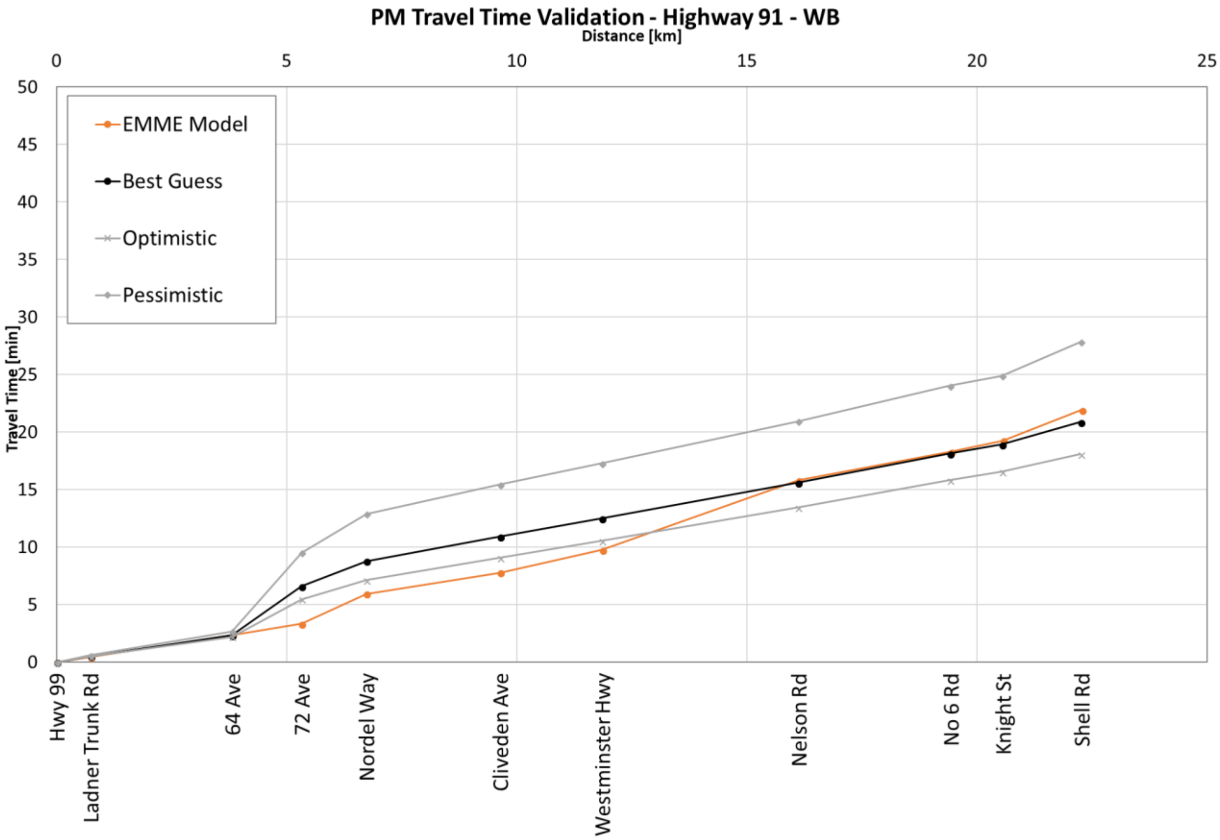
72 Ave
64 Ave
Ladner Trunk Rd
Hwy 99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Travel Time [min]
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Optimistic
Pessimistic
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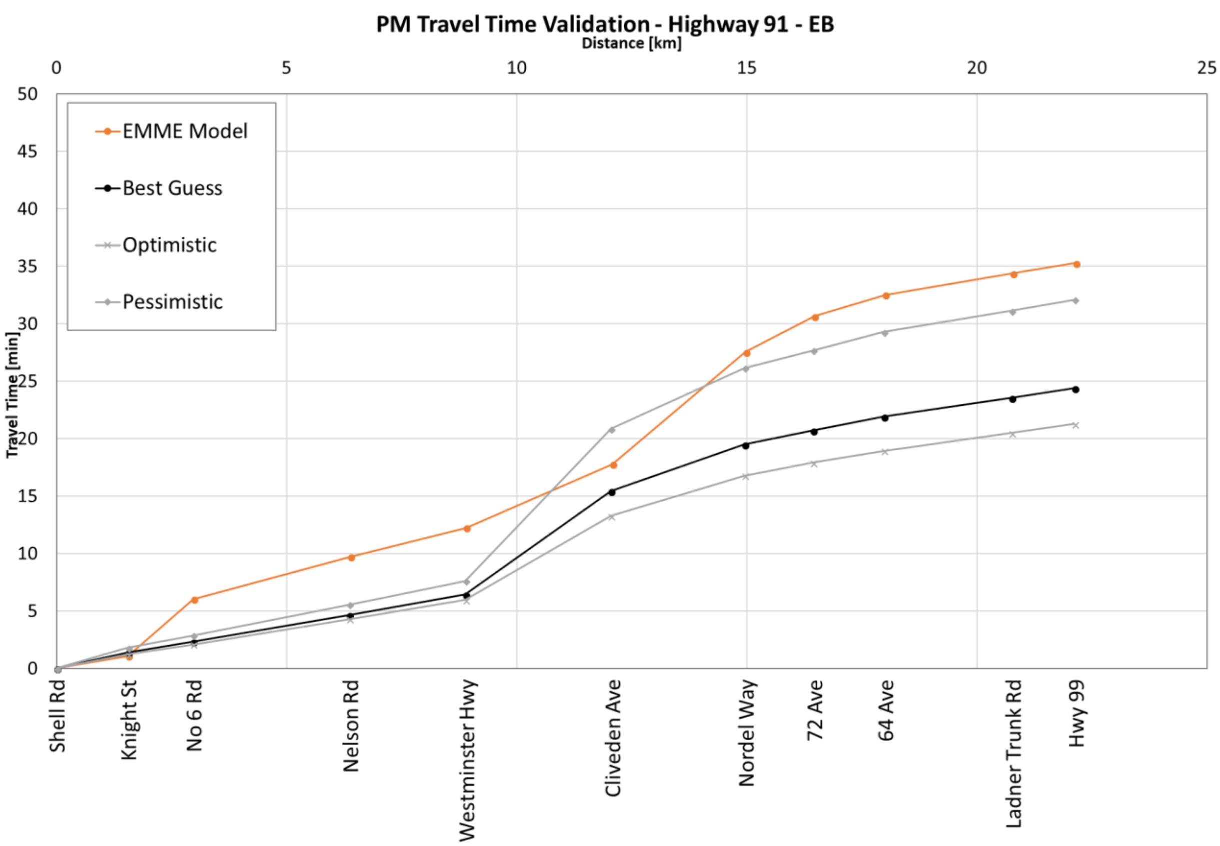
Shell Rd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Travel Time [min]
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Best Guess
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Pessimistic
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72 Ave
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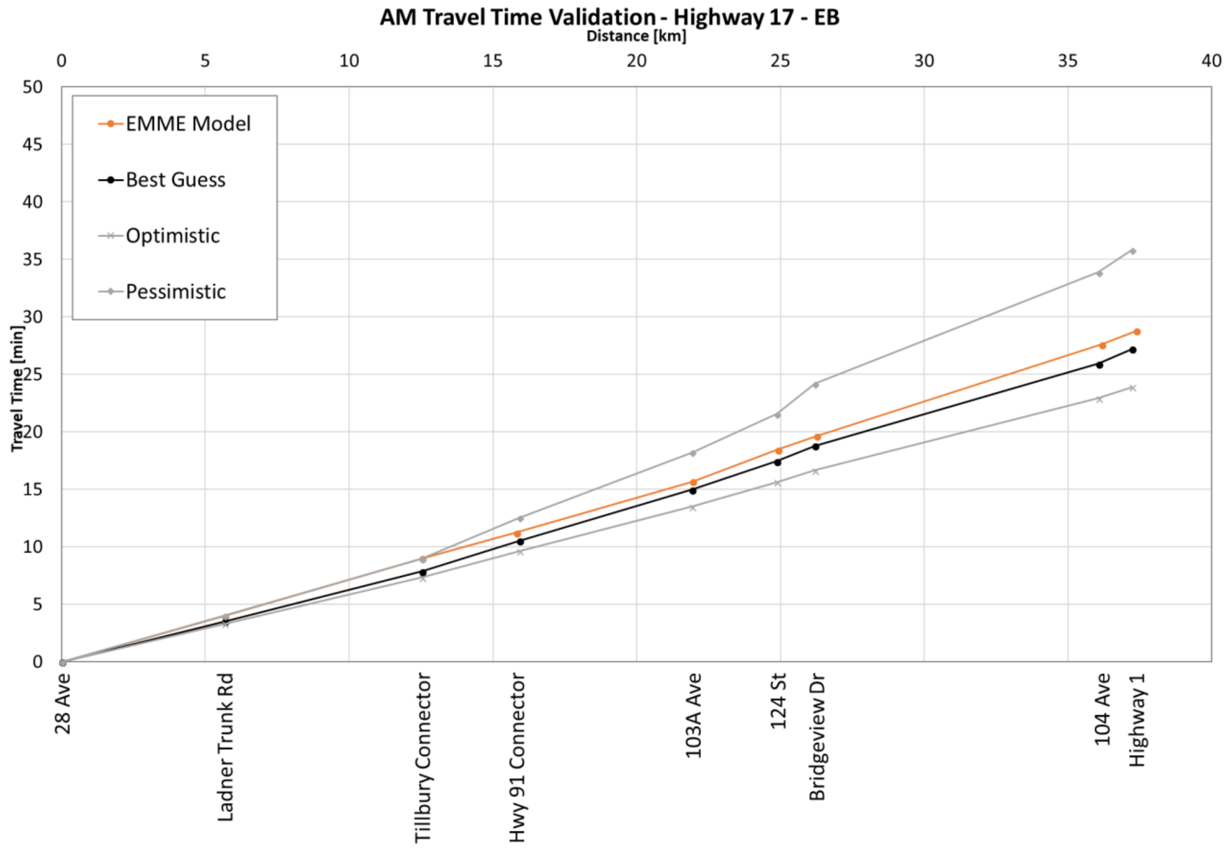
Ladner Trunk Rd
Hwy 99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Travel Time [min]
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Optimistic
Pessimistic
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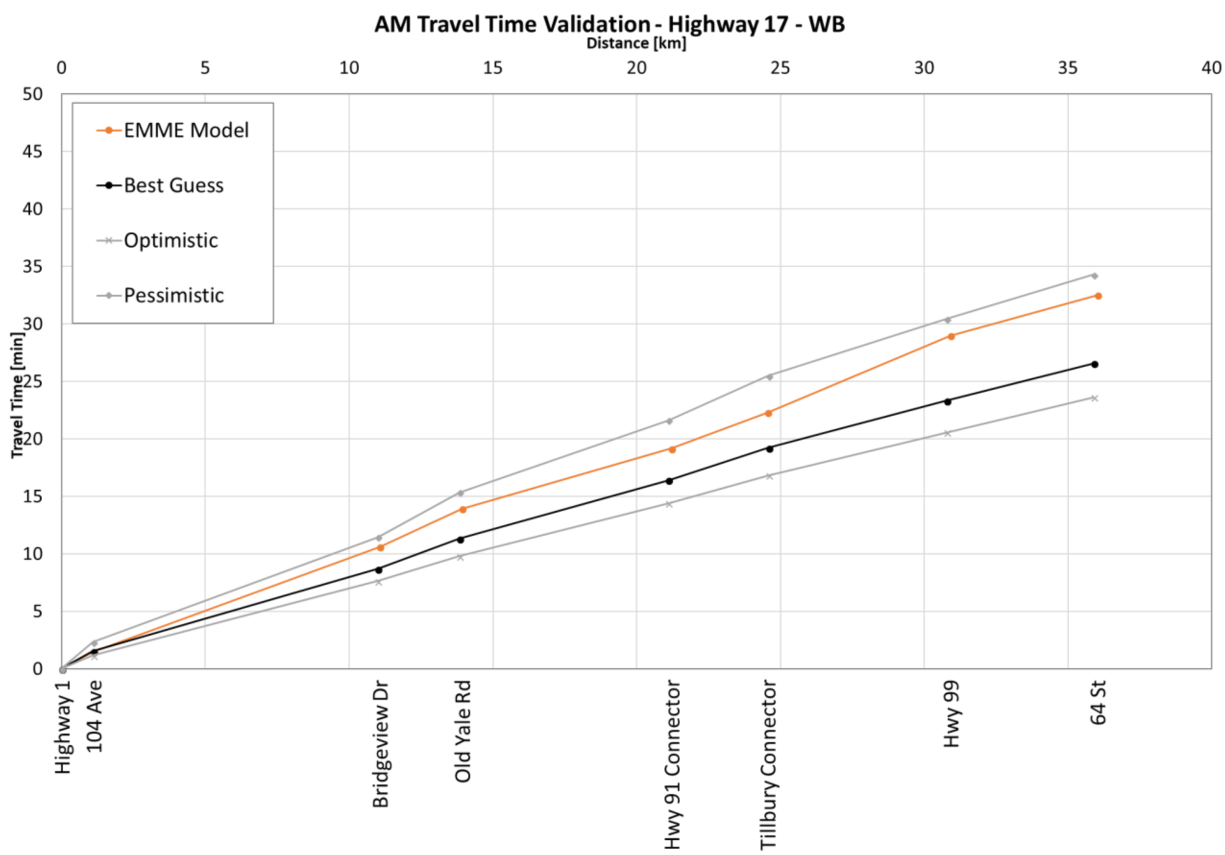
Hwy 91 Connector
103A Ave
124 St
Bridgeview Dr
104 Ave
Highway 1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Travel Time [min]
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Pessimistic
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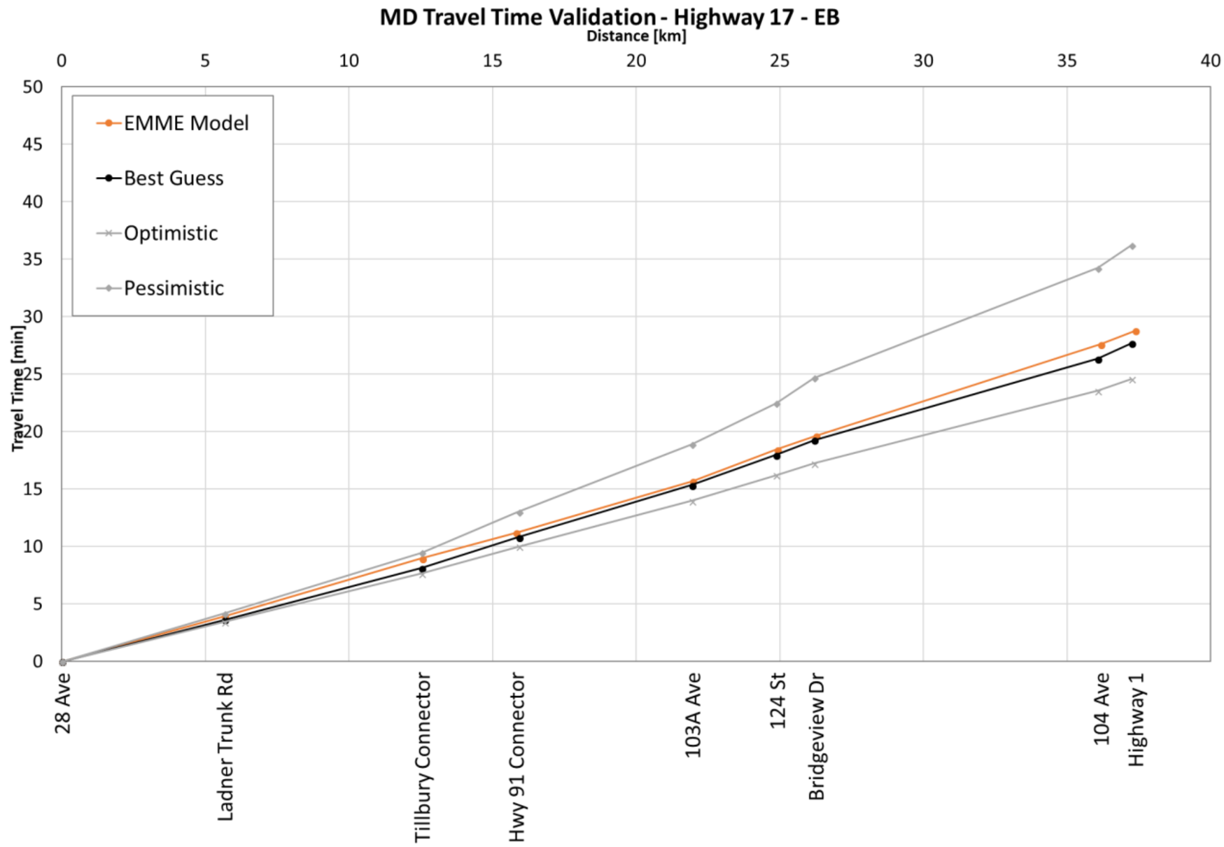
Old Yale Rd
Hwy 91 Connector
Tillbury Connector
Hwy 99
64 St



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Distance [km]
Travel Time [min]
EMME Model
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Pessimistic
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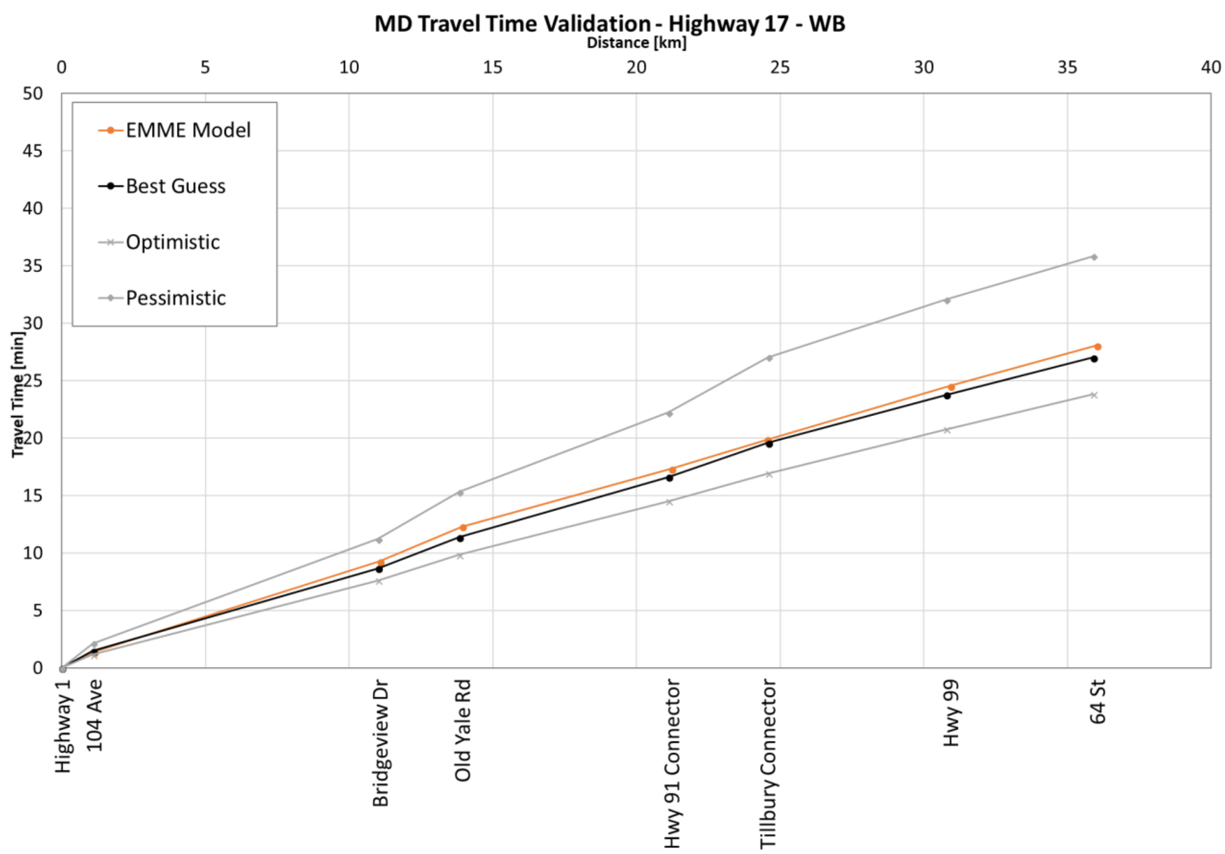
Hwy 91 Connector
103A Ave
124 St
Bridgeview Dr
104 Ave
Highway 1



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
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Pessimistic
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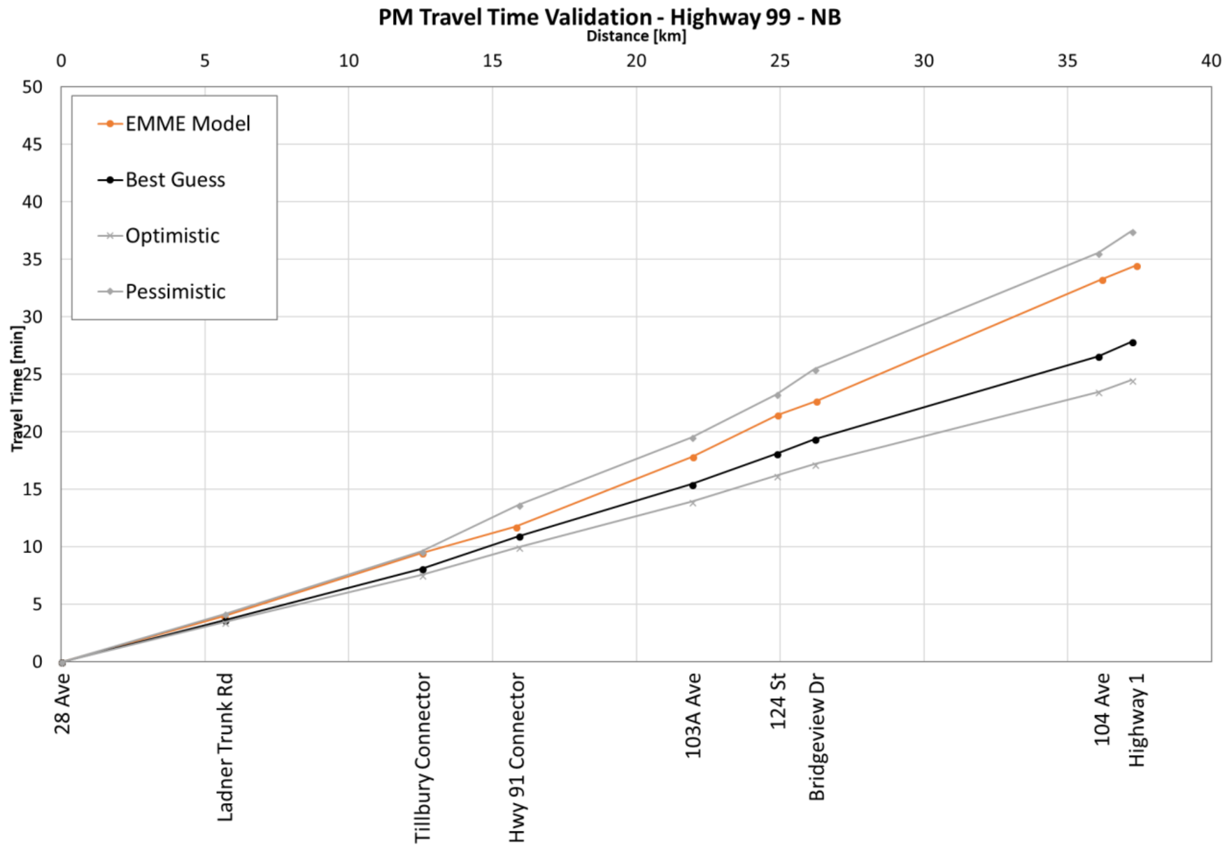
Hwy 99
64 St



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15
10
5
0
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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Hwy 91 Connector
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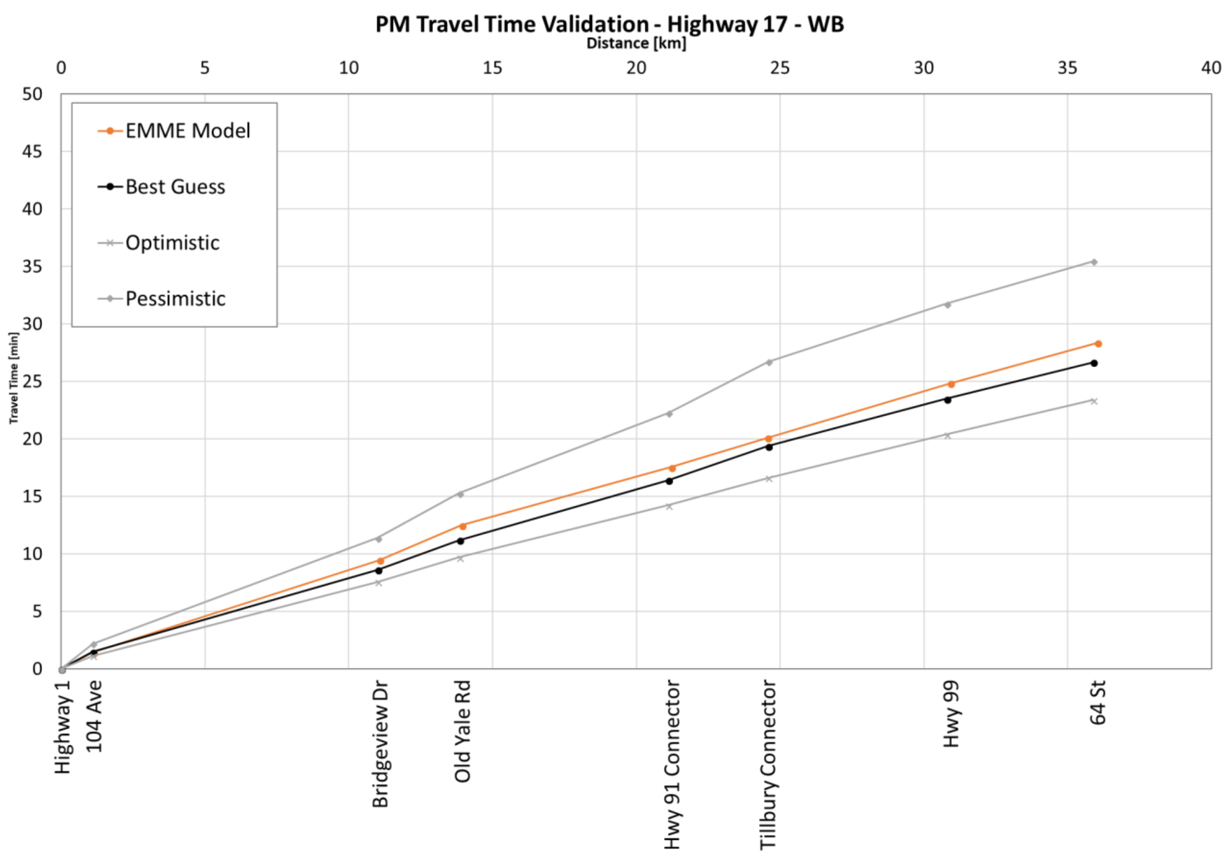
124 St
Bridgeview Dr
104 Ave
Highway 1



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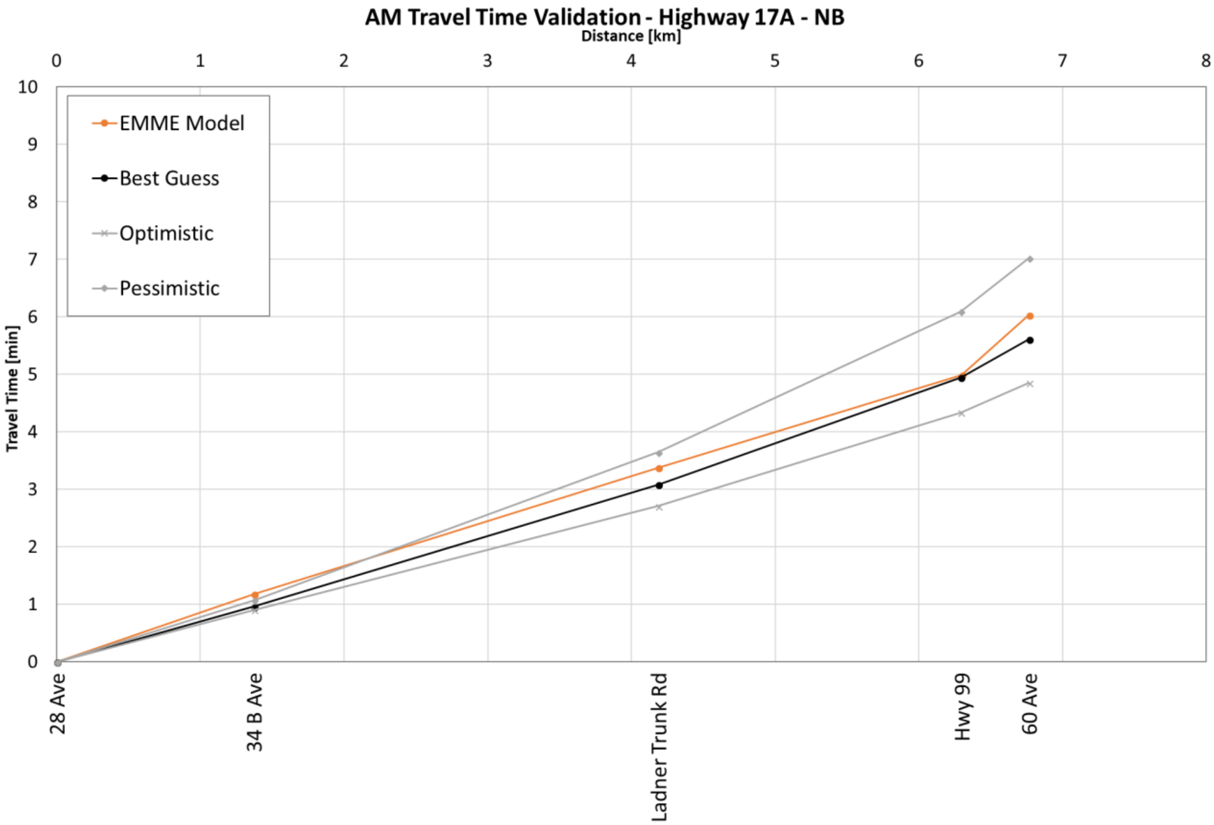
Hwy 99
64 St



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4
3
2
1
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Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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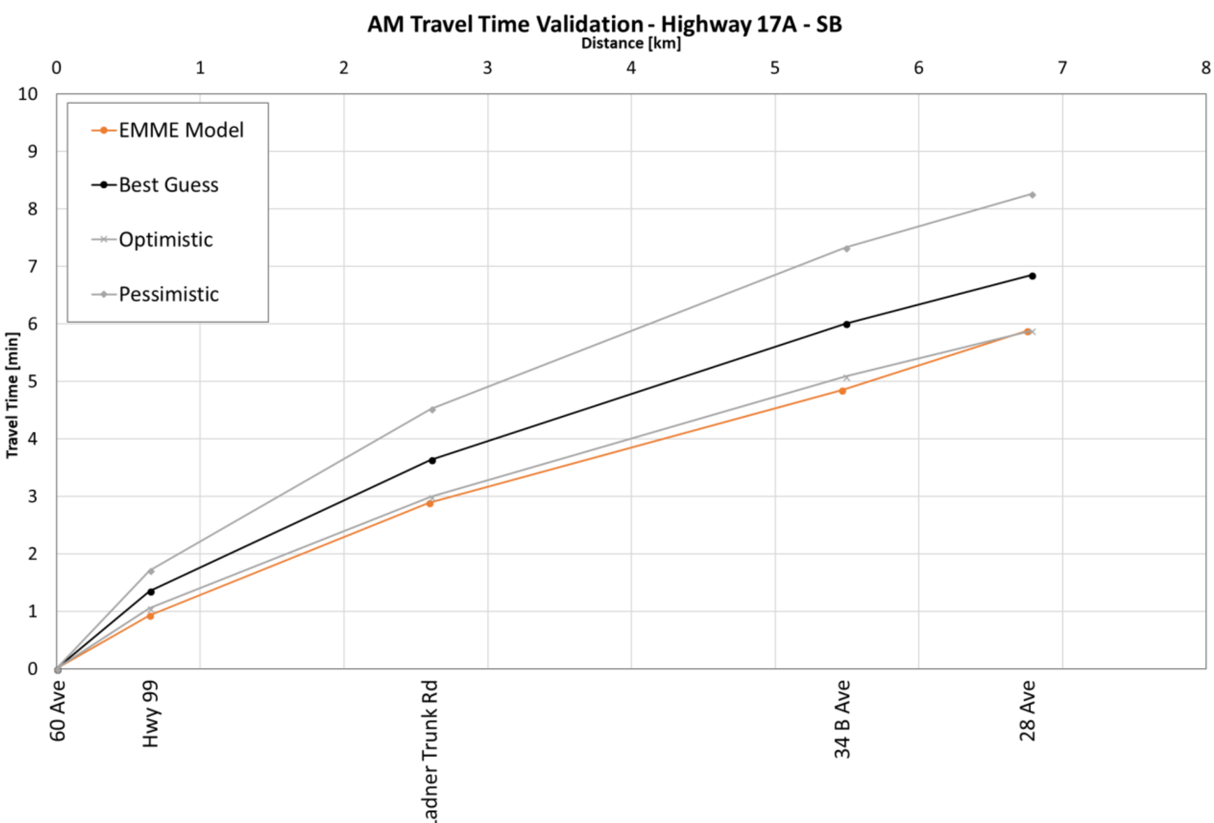
34 B Ave
Ladner Trunk Rd
Hwy 99
60 Ave



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6
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9
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6
5
4
3
2
1
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Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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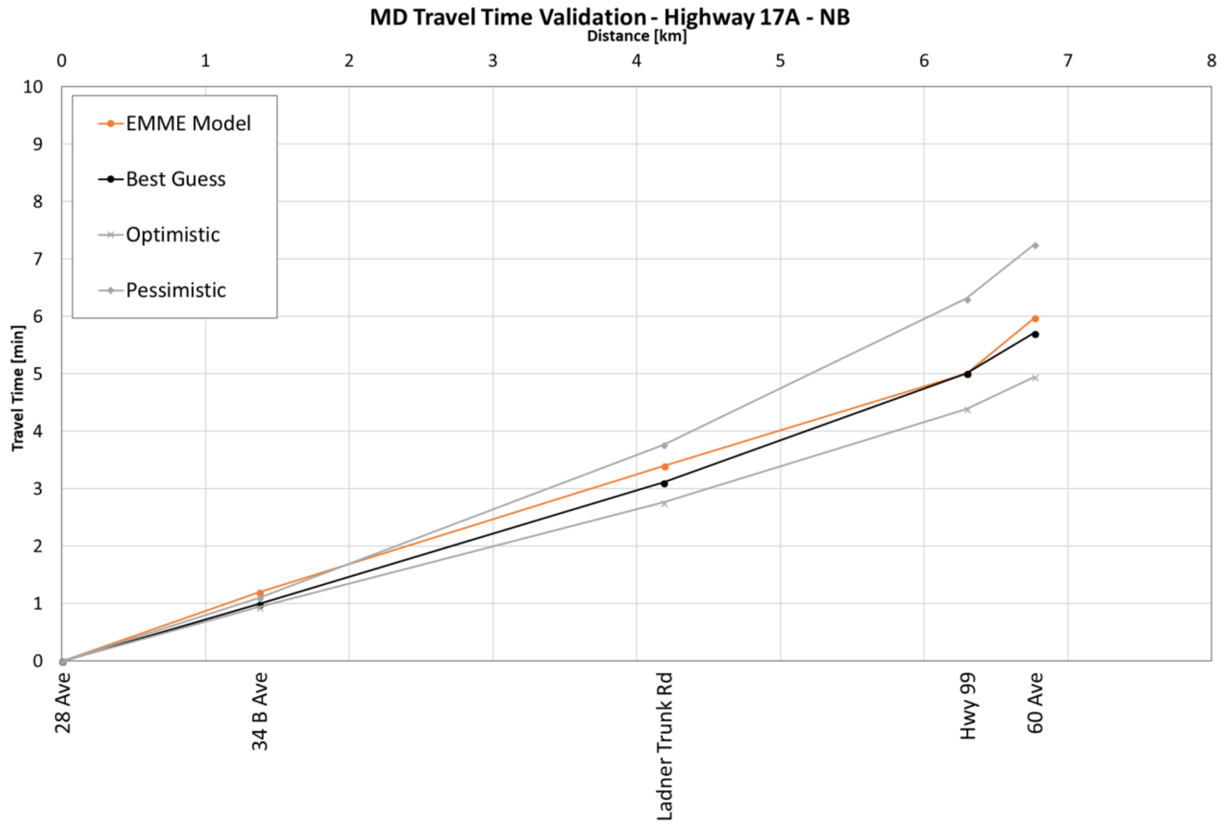
Hwy 99
Ladner Trunk Rd
34 B Ave
28 Ave



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Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
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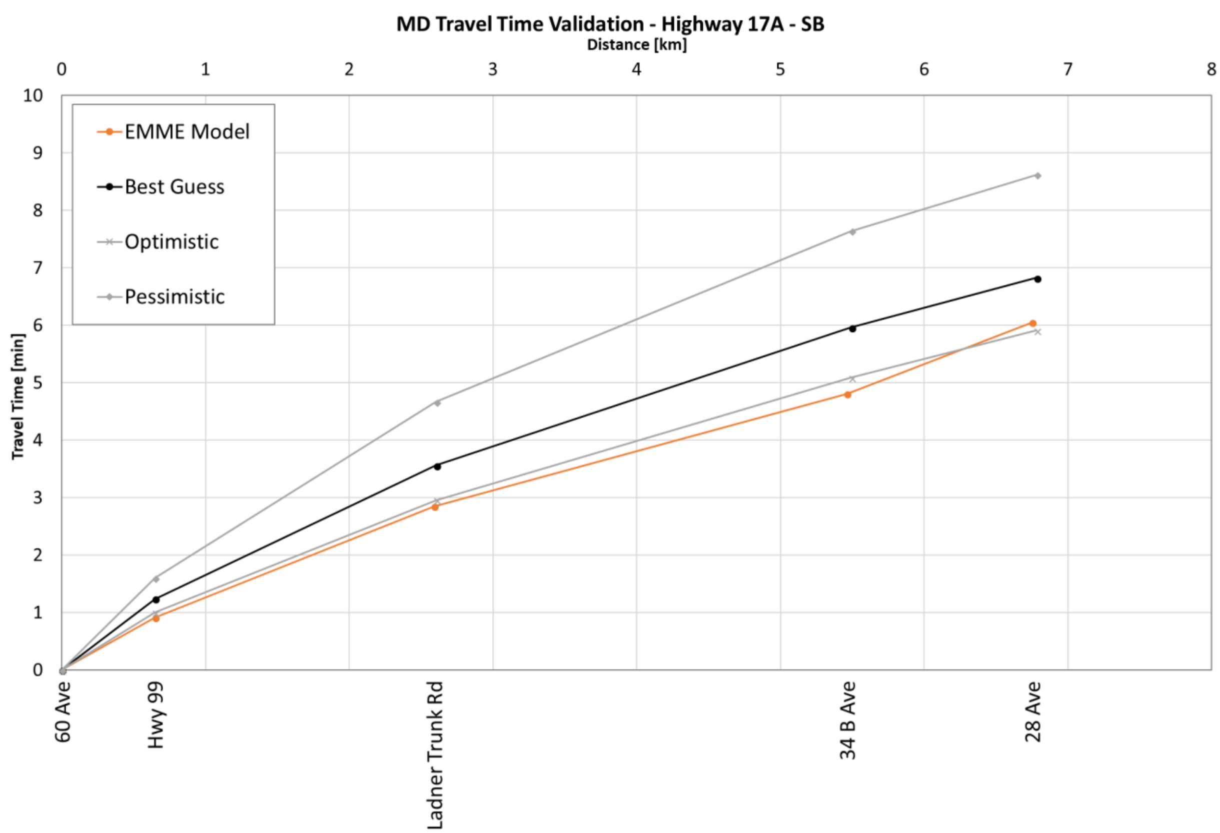
34 B Ave
Ladner Trunk Rd
Hwy 99
60 Ave



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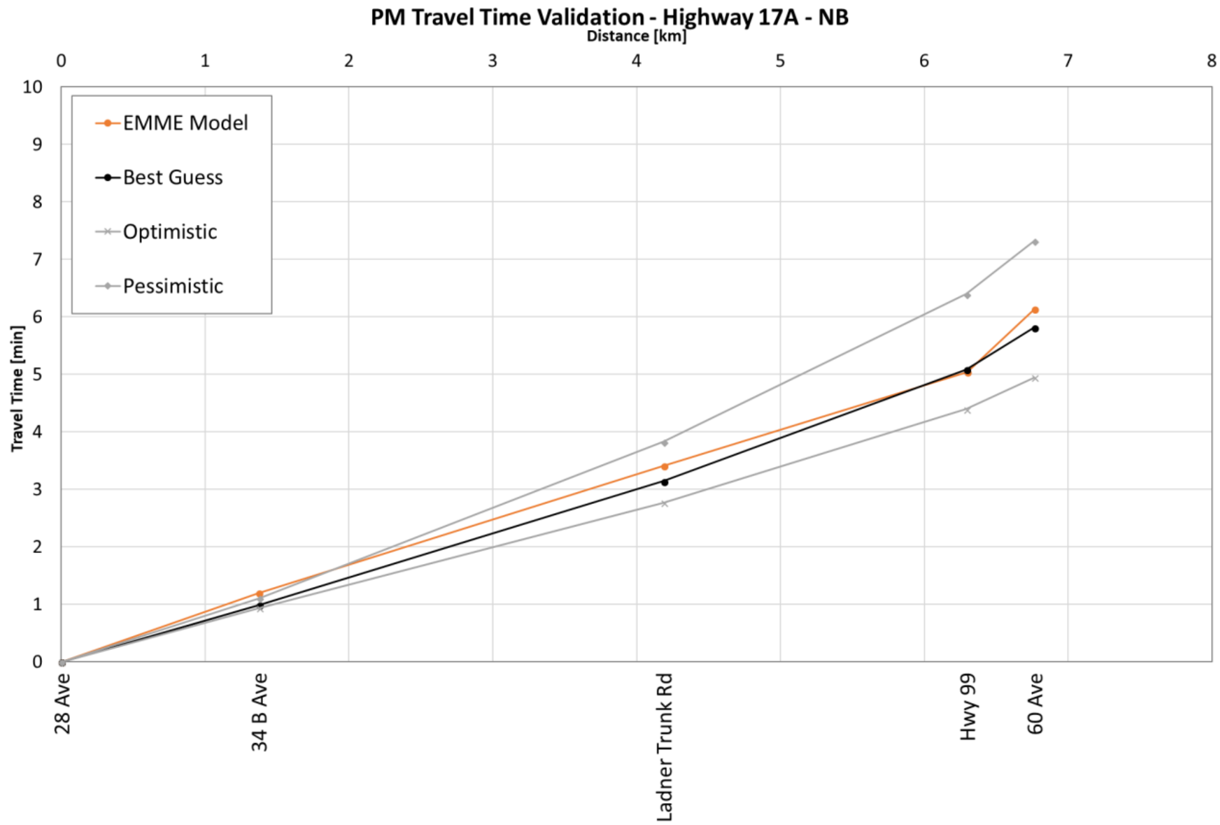
Distance [km]
Travel Time [min]
EMME Model
Best Guess
Optimistic
Pessimistic
60 Ave
Hwy 99
Ladner Trunk Rd
34 B Ave
28 Ave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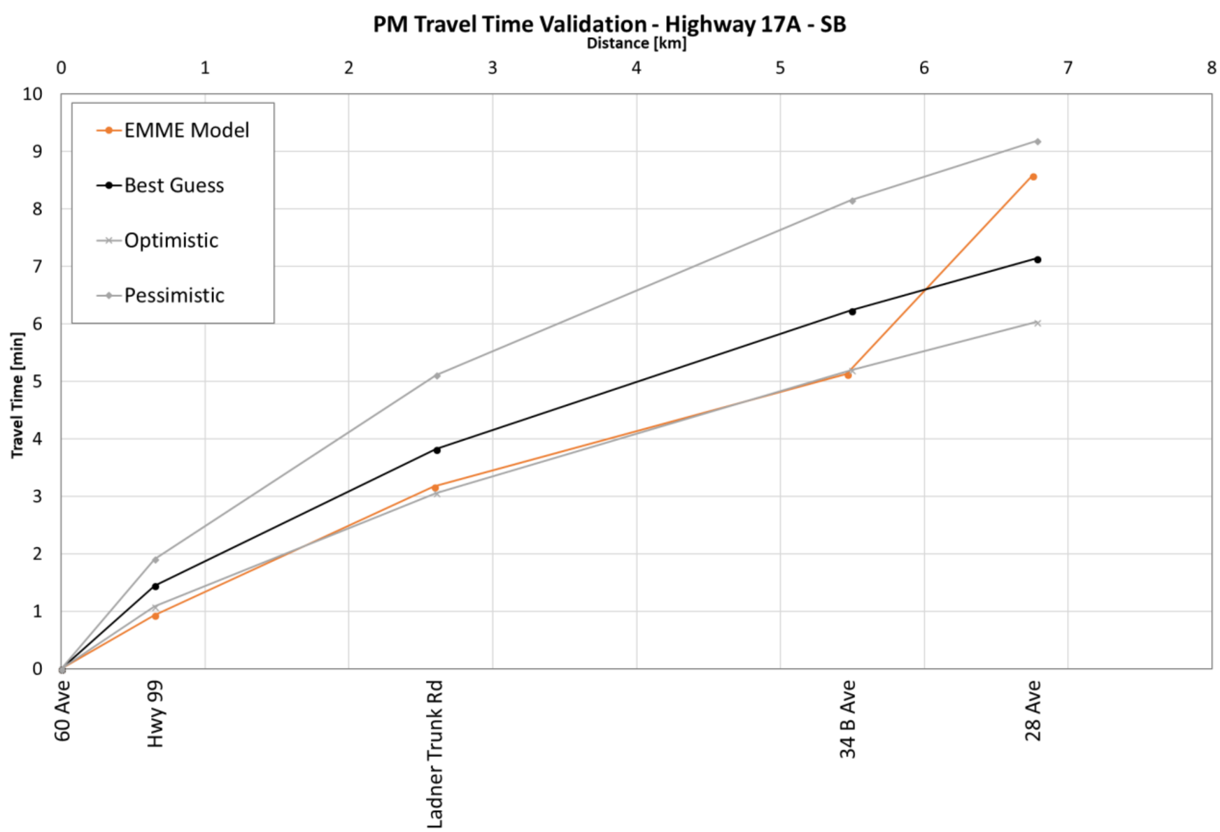
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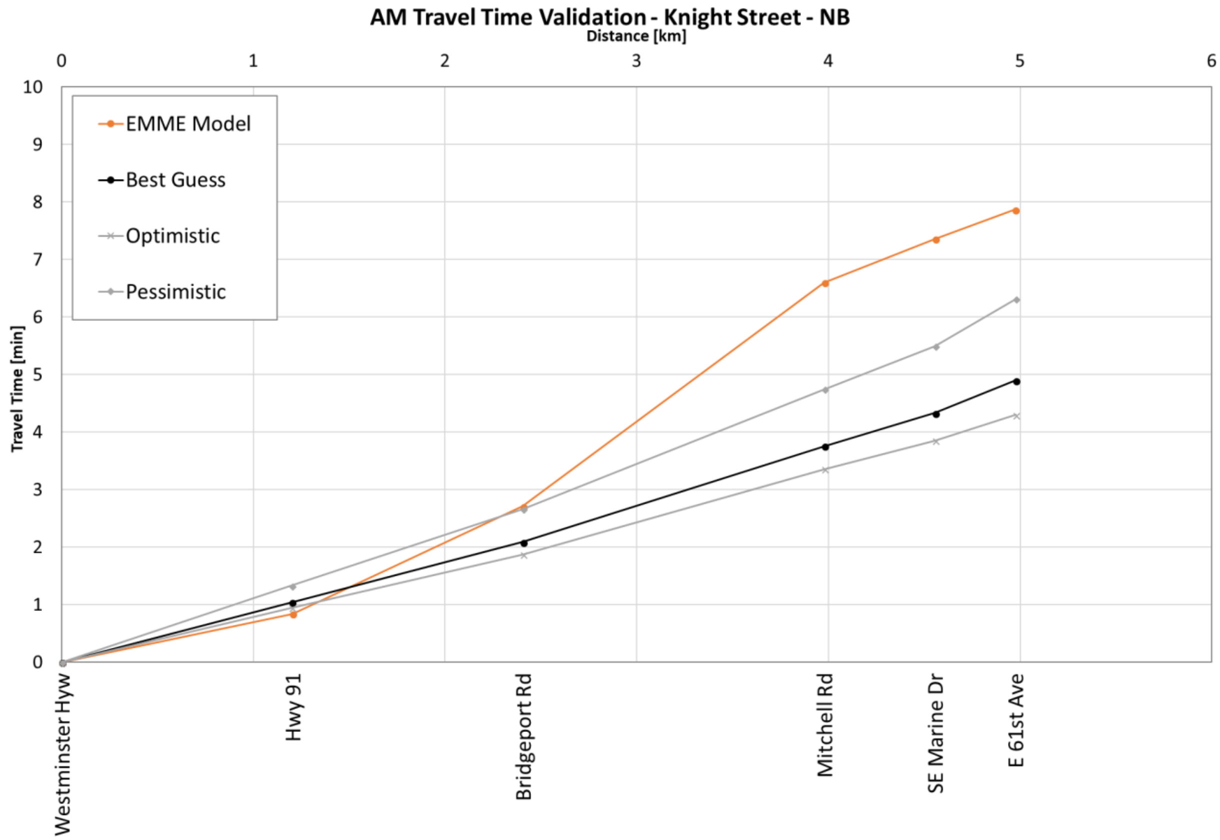
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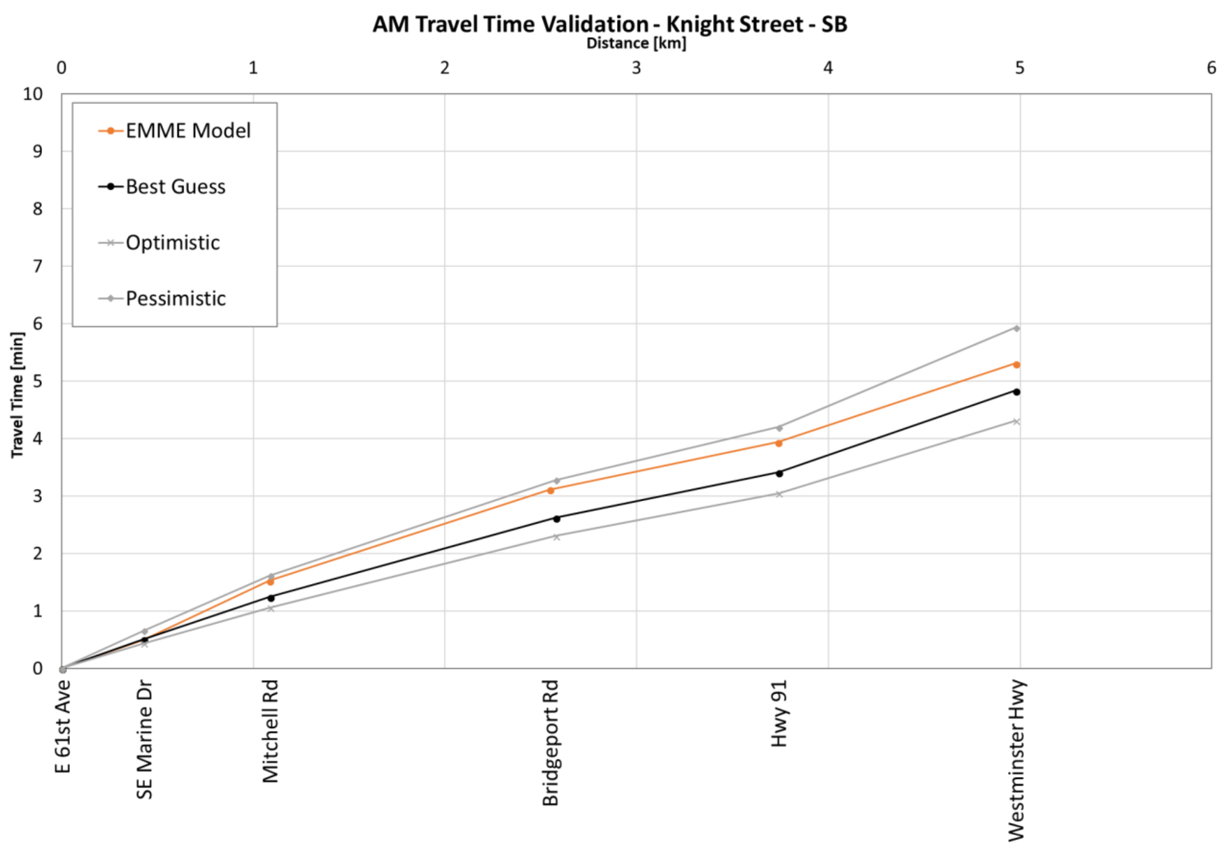
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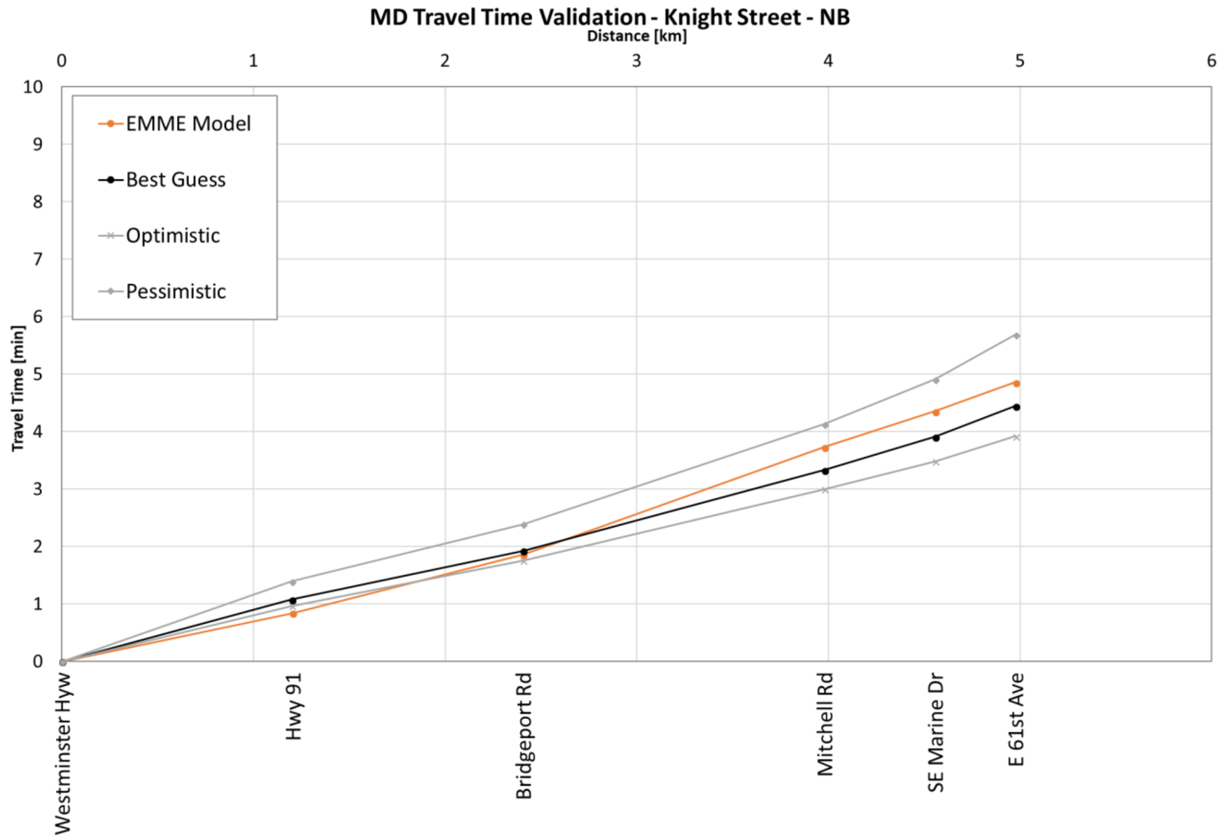
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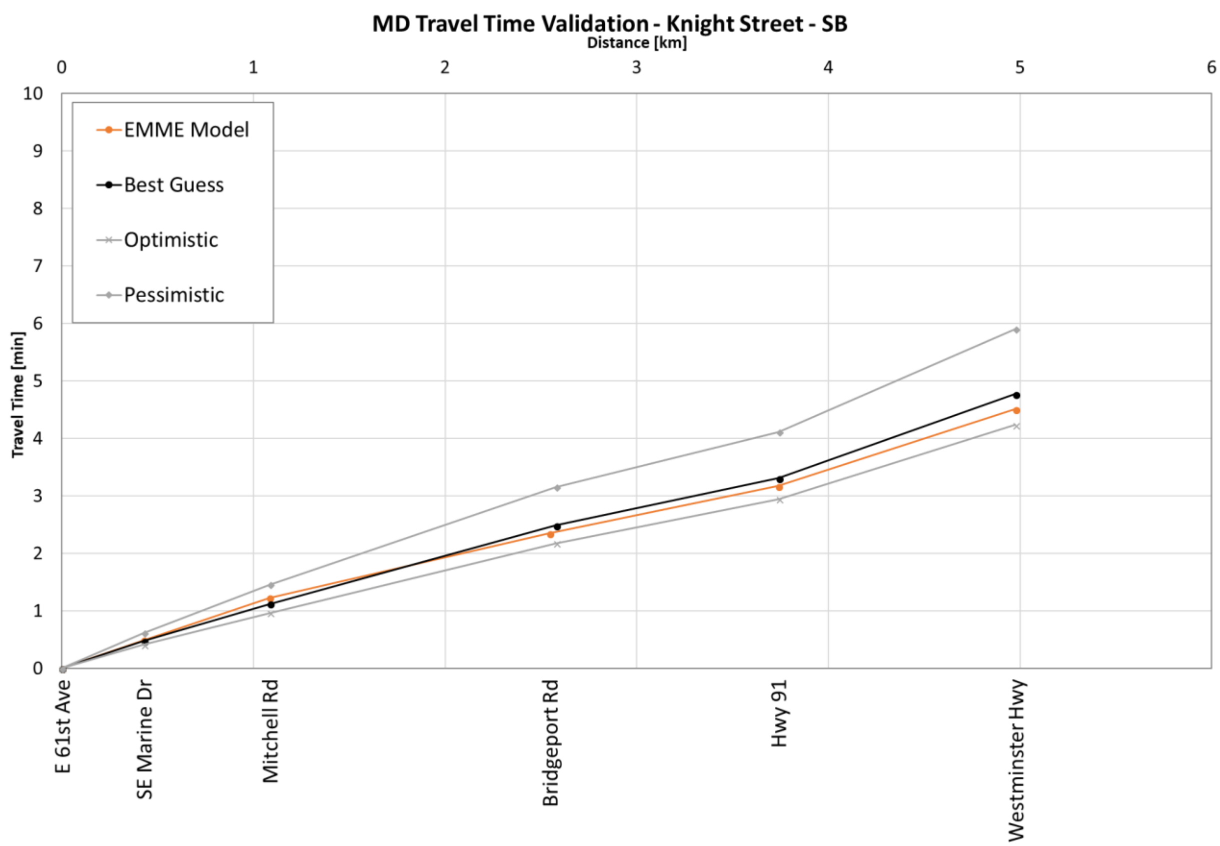
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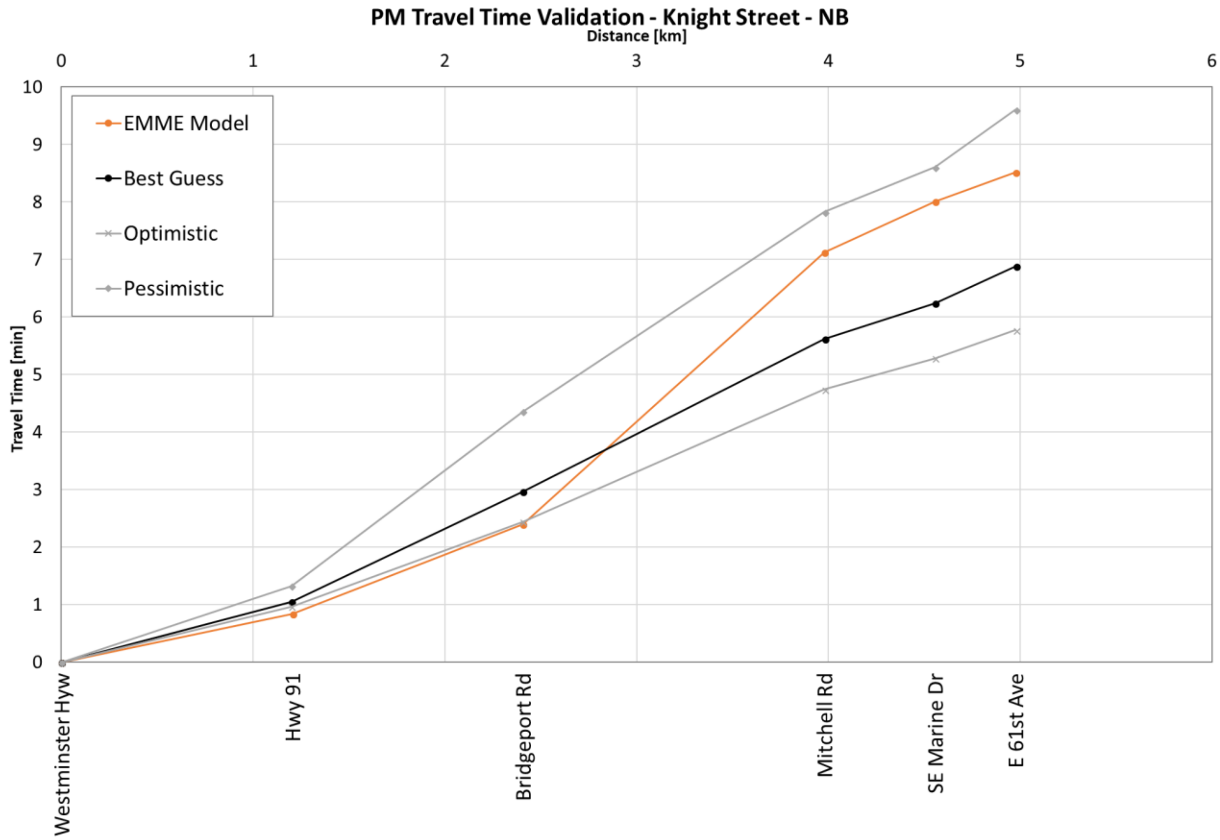

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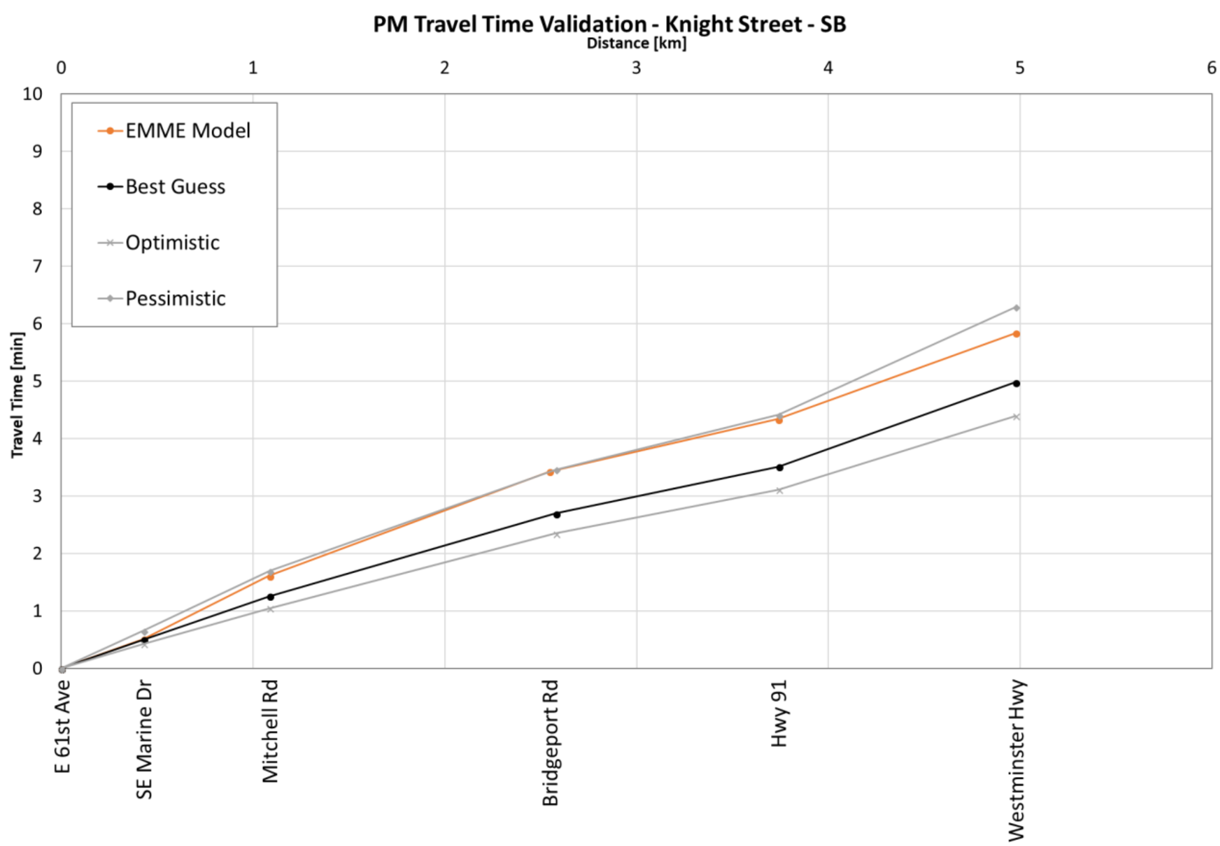

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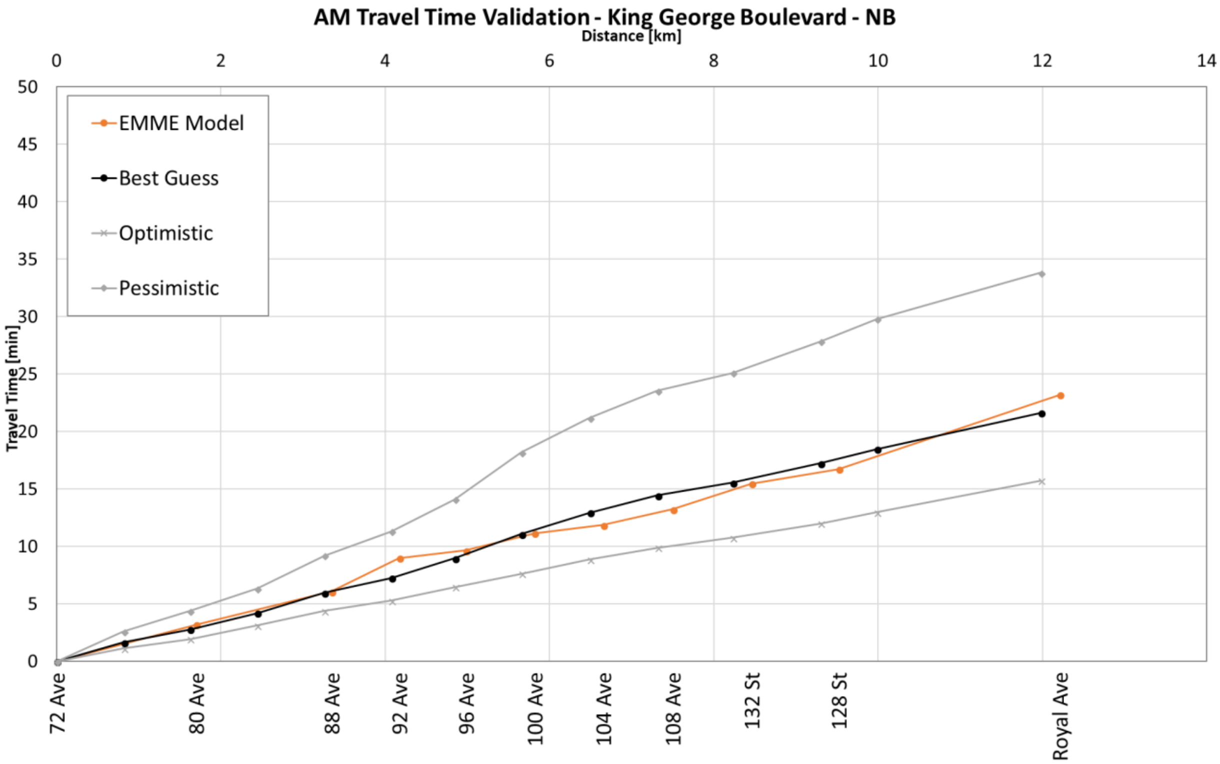
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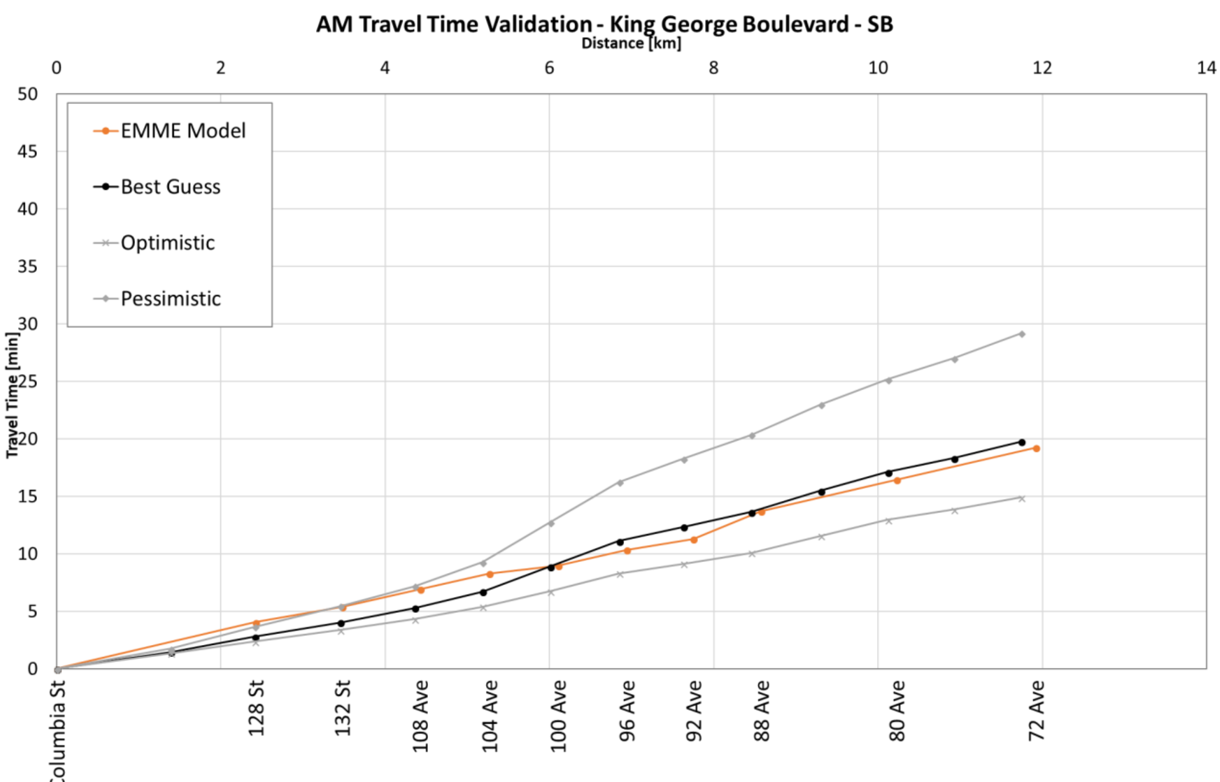
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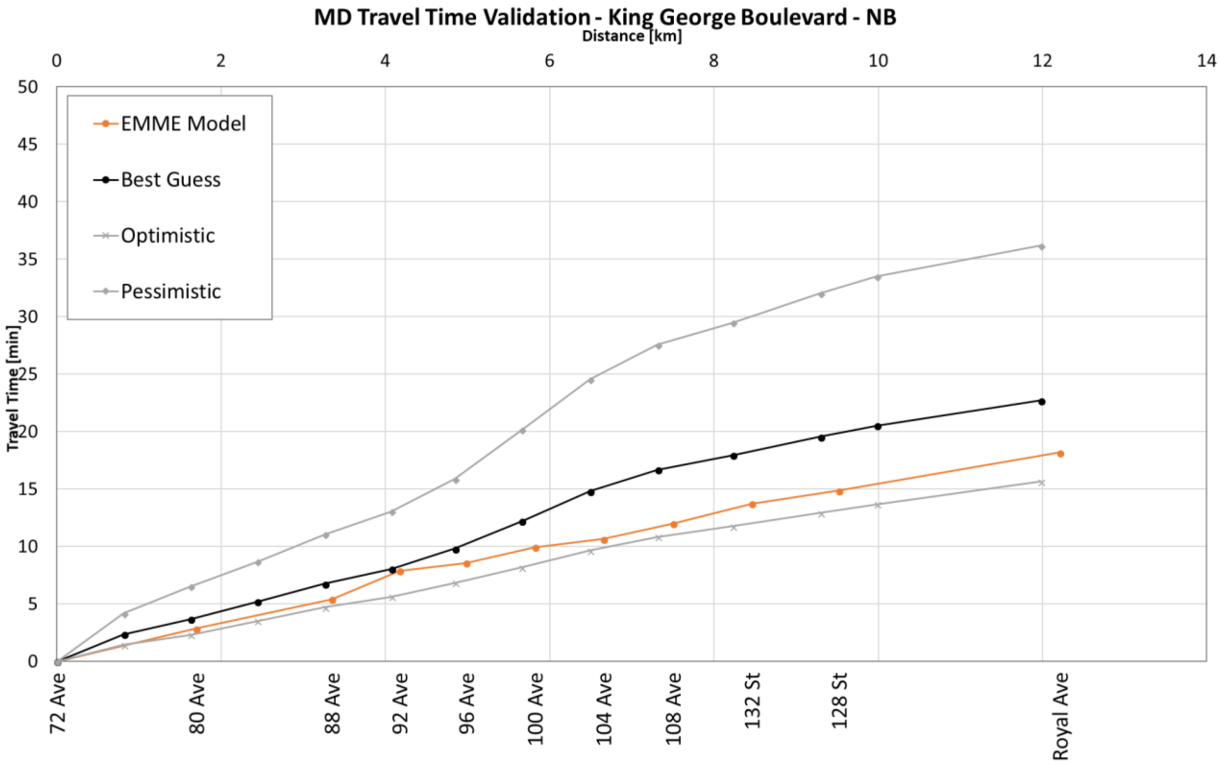
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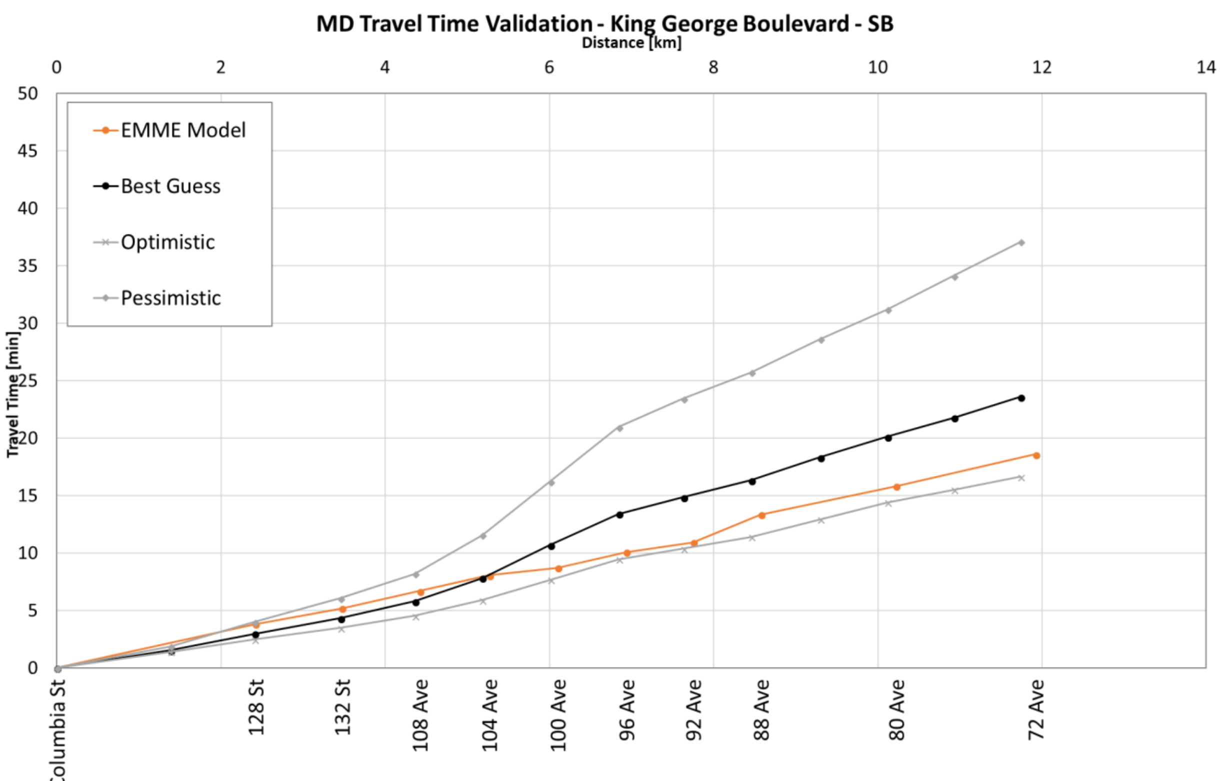
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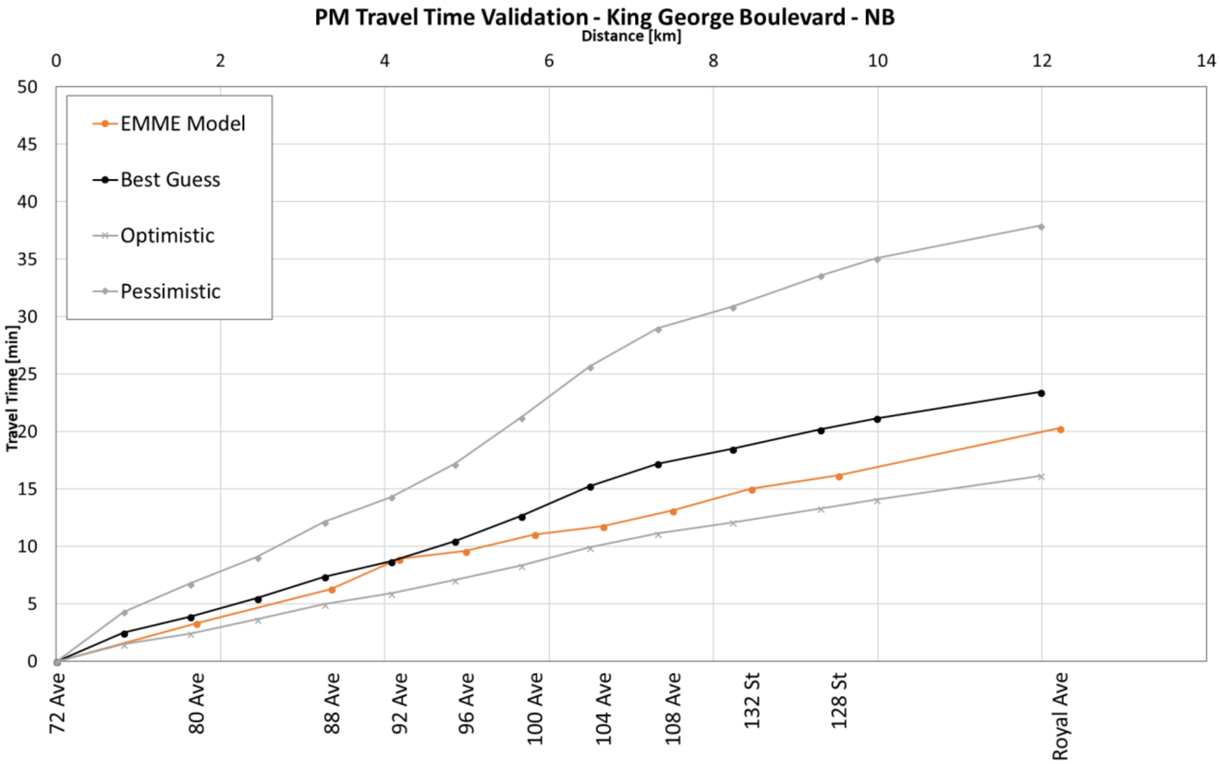

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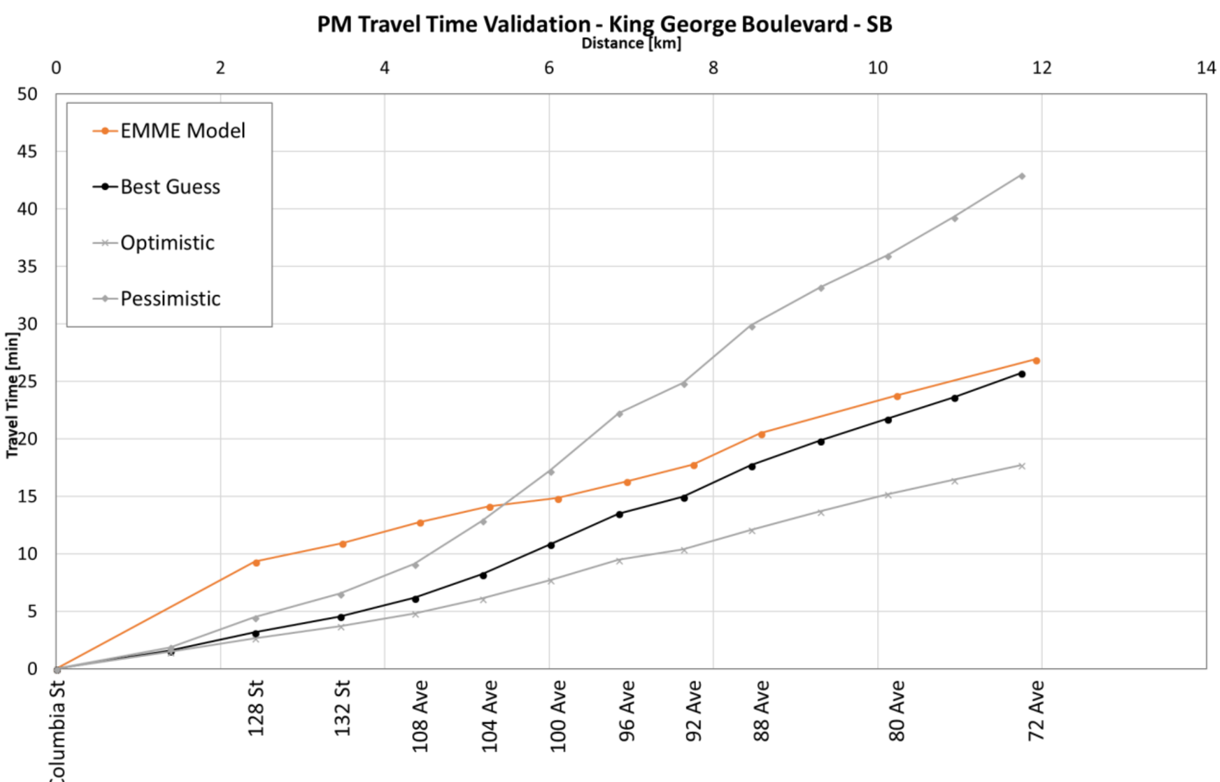

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Appendix D Tunnel Expert Panel Report

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

Suite 500 - 980 Howe Street
Vancouver, BC Canada V6Z 0C8
Telephone (604) 684-5900
Fax (604) 684-5909

June 8, 2018
Project No.: 0272027

Michael Cowdell, P.Eng., President
Westmar Advisors, Inc.
351 Bewicke Ave.
North Vancouver BC V7M 3B7

Dear Mr. Cowdell,

Re: George Massey Tunnel Replacement Project, Immersed Tube Tunnel Option – Independent Technical Review

1.0 INTRODUCTION

BGC Engineering Inc. (BGC) is pleased to provide Westmar Advisors (Westmar) with this report to support the Independent Technical Review (ITR) of the George Massey Tunnel Replacement project (GMTR). BGC's work was limited to studying feasibility and constructability of an immersed tube tunnel (ITT) at the George Massey Tunnel (GMT) site recognizing the geotechnical, seismic, navigation and environmental issues. Other technical issues such as required channel depth, land use and acquisition, traffic management, and geometric and interchange highway design were considered only to the extent that the brief project review of them informed the panel opinions presented here.

1.1. Scope of Review

The independent technical review of the feasibility of the ITT option for the GMTR project site consisted of a facilitated panel review of (a) the project requirements, (b) past experience with immersed tube tunnels as a particular means of tunnel construction, and (c) evaluation of the relevance of past experience with respect to the primary challenges and requirements of the GMTR project.

Benchmarking of past projects was initiated by Westmar prior to engaging BGC, and BGC continued to build a working catalogue of more than 20 ITTs, and learned of a record of others available on the web, and located here:

https://about.ita-aites.org/publications/wg-publications/content/16/working-group-11-immersed-and-floating-tunnels

This publication is by Working Group 11 of the International Tunneling Association (ITA-WG11), a working group dedicated to immersed and floating tunnels, and responsible for several online resources. For more recent tunnels, this online database is a valuable resource they provide:

https://cases.ita-aites.org/search-the-database?art_title=&project_country=&project_working_group%5B%5D=11&cck=project&project_state=2&search=projects&task=search

Through this literature review process, an initial understanding of the present state of practice for the design, construction and operation, and the versatility and limitations of the construction methodology was gained.

To improve understanding and develop an expert-informed opinion, a panel of experts was then convened to discuss what was identified through our searches, their own experiences, and other projects of which they are aware. This discussion was held in-person at the BGC office in Vancouver, BC, on May 3 and 4, 2018, and was facilitated by BGC in the structured and transparent way described here.

The panelists were chosen to represent experience on the Pacific Coast of North America as well as global experience, and they were identified to be independent from past work related to the GMT and its potential replacement. The North American experts brought especially valuable experience with North American contracting means and methods, local site conditions and construction, and bored tunnel alternatives, whereas experts from the United Kingdom and Netherlands brought global experience and perspective. The panel members were:

- Mr. Jonathan Baber: Project Director – Metros & Civil, Account Leader International Metros/Highway Tunnels, Mott MacDonald; Chair of International Tunnel Association Working Group 11: Immersed and Floating Tunnels; United Kingdom.
- Mr. Hans de Wit, M.Sc.: Managing Director Tunnel Engineering Consultants (TEC)/Leading Professional Tunnels, Royal HaskoningDHV; Member of International Tunnel Association Working Group 11: Immersed and Floating Tunnels Netherlands.
- Mr. Bob Bittner, PE: President, Bittner-Shen Consulting Engineers, Inc.; USA.
- Mr. Doug Grimes, P.Geo., PMP: Lead Associate, McMillen Jacobs Associates; Canada.

2.0 PANEL MEETING

The agenda for the panel meeting is attached as Appendix A. The meeting had three general objectives, the first of which was informing the panel of the project requirements and site conditions. This was done by Westmar and other professionals that have also been engaged by Westmar to support the ITR, and whom have specific understanding on geology, subsurface conditions, seismic setting, environmental sensitivity, physical constraints and the existing tunnel construction and condition.

The second objective of the meeting was to compare site conditions and requirements for an ITT at the GMTR project site to global experience. During this part of the meeting agenda, discussion became centred on the following eight key criteria and considerations that would likely determine the feasibility and practicality of a new ITT for the new crossing:

1. Strong Ground Motion from earthquakes.
2. Seismically induced liquefaction of deep foundation alluvium.
3. Strong channel current during construction.
4. Environmental sensitivity of dredging and in-water work.
5. Short in-water construction windows.
6. Requirements for deep sea vessel navigation and channel access during construction.
7. Proximity of new construction to existing structures.
8. Required tunnel width (lanes).

These considerations provided structure for the third meeting objective, which was achieved through the remainder of the meeting. The panel was asked to share their experiences and knowledge of where these issues have been previously addressed, and to comment on how well this previous experience related to the GMTR project site and needs. The meeting then concluded with brief discussion of other items and considerations that were generated from the meeting itself.

The following precedent ITTs were identified by the panel in relation to the eight key criteria. These lists are not exhaustive but taken from the panels' suggestions for high degree of relevance and being well known by the panel. It can be seen from these lists and the summary of the identified projects in Table 2-1 that multiple precedent projects have been identified for each technical challenge.

Ground Motion:

- Aktio-Preveza Tunnel, Greece
- Coatzacaolcos Tunnel, Veracruz, Mexico (2 earthquakes very soon after completion)
- Kobe Tunnel, Japan (earthquake while under construction)
- Bay Area Rapid Transit (BART), San Francisco, USA
- Posey & Webster Street Tubes, San Francisco, USA
- Marmaray Tunnel, Istanbul, Turkey.

Liquefaction:

- Marmaray Tunnel, Istanbul, Turkey (mitigation with compaction grouting)
- Aktio-Preveza Tunnel, Greece (mitigation with stone columns)
- Coatzacaolcos Tunnel, Mexico (mitigation by excavation)
- Posey & Webster Street Tubes (densified or grouted during retrofit)
- Kobe Tunnel, Japan (earthquake during construction in 1995).

Current:

- Marmaray Tunnel, Istanbul, Turkey (crossing Bosporus): discharge current dominates)
- Oosterweel Tunnel, Antwerp, Belgium (crossing river Schelt, tidal currents dominate river discharge)
- Coatzacaolcos Tunnel, Mexico (tidal + discharge, discharge currents dominate)

- Limerick Tunnel, Ireland (tidal currents)
- Kennedytunnel Schelt (3 m/s current, though immersion was done near neap tide at 1.5 m/s.- tidal currents dominate river discharge).

<u>Environment:</u>

- Marmaray Tunnel, Turkey (significant fish migration route)
- New Tyne Tunnel, Newcastle, UK (dredging restrictions to avoid interference with fish migration)
- Bay Area Rapid Transit (BART), San Francisco, USA
- Limerick Tunnel, Ireland (pristine estuary, no dredging windows during fish migration).
- Bjorvika Tunnel, Oslo, Norway (restrictions on blockage of river during fish migrations, and containment of contaminated bed sediments during dredging)
- Marieholm tunnel, Gothenburg, Sweden (now under construction, no dredging and immersion during fish season).

<u>Construction Windows:</u>

- Marmaray Tunnel, Turkey (immersion tunnel element per month, tunnel founded on gravel bed)
- Bjorvika Tunnel, Oslo, Norway (No work in water from July – Nov., tunnel founded on gravel bed, immersion cycle 4 weeks)
- New Tyne Tunnel, UK (dredging only permitted Nov.-Feb., tunnel on sand flow foundation bed, immersion cycle 2 weeks at neap tide)
- Piet Hein Tunnel, Amsterdam, The Netherlands (immersion every 1-2 weeks, tunnel on sand flow foundation)
- Hong Kong Zuhai Macao Link, China (gravel bed)
- Oresund Link (Denmark – immersion one element per month, tunnel founded on gravel bed).
- Coatzacoalcos Tunnel Mexico (dry season for element immersion, immersion cycle 2 weeks).

<u>Navigation:</u>

- Wijkertunnel, The Netherlands (Amsterdam Port Entrance)
- Elizabeth River Tunnels, Norfolk, USA (US Navy access requirement)
- Hong Kong Zhuhai Macao Link, China (very busy access channels to port of Hong Kong and port of Guangzhou, no blockage of navigation, working zone immersion restricted to 400x400m^2)
- BART, San Francisco (Oakland and Alameda ports)
- Blankenburg Tunnel, Rotterdam, The Netherlands (main access route to the Port of Rotterdam, passing ships while on temporary supports and during sand flowing)
- Caland Tunnel, Rotterdam, The Netherlands (busy narrow 240m wide water way in Port of Rotterdam).

- Oosterweel Tunnel, Antwerp, Belgium (ships passing while on temporary supports and during sand flowing)
- Coatzacoalcos Tunnel, Mexico (passing of oil tankers over tunnel roof immediate after immersion).

Proximity to Structures:

- Elizabeth River Tunnels, Norfolk, USA
- Second Coen Tunnel, Amsterdam, The Netherlands (beside existing immersed tunnel)
- Second Benelux Tunnel, Rotterdam, The Netherlands (beside existing immersed tunnel)
- BART (passes below San Francisco – Oakland Bay Bridge: estimated 80 m from a foundation)
- New Tyne Tunnel, Newcastle, UK (beside existing bored tunnel)
- Hampton Road expansion, USA (Virginia, Chesapeake Bay area, beside two existing immersed tunnels)
- Shatin-Centre Metro Link Hong Kong, cross harbor section (Western Harbor Crossing Immersed Tunnel beside) (Hong Kong).

Tunnel Width:

- ShenZhen - Zhongshan Crossing, (design phase-moving to construction, widest section 12 lanes, over 60 m width, standard section 8 lanes approx. 50 m)
- Drecht Tunnel, Dordrecht, The Netherlands (50 m width)
- Second Benelux Tunnel, Rotterdam, The Netherlands (45 m width)
- Kennedy Tunnel under the river Schelt, Antwerp, Belgium (48 m width).
- Bjorvika Tunnel, Oslo, Norway (45 m width).

Table 2-1. Key technical criteria and considerations identified and discussed in this review.

Precedent Projects	Key Technical Criteria and Considerations							
	Ground Motion	Liquefaction	Current	Environment	Construction Windows	Navigation	Proximity to Structures	Tunnel Width
Marmaray Tunnel, Turkey	x	x	x	x	x	x		
Coatzacaolcos Tunnel, Mexico	x	x	x		x	x		
Elizabeth River Tunnels P3 Project, USA						x	x	
Hong Kong Zhuhai Macao Link, China				x	x	x		
Shenzhen – Zhongshan Crossing, China	x		x					x

Precedent Projects	Key Technical Criteria and Considerations							
	Ground Motion	Liquefaction	Current	Environment	Construction Windows	Navigation	Proximity to Structures	Tunnel Width
Second Coen Tunnel, Netherlands						x	x	
San Francisco Bay Area Rapid Transit (BART) Transbay Tube Seismic Retrofit, USA	x			x		x	x	
New Tyne River Immersed Tunnel Crossing/Tunnel Twinning, Wallsend, UK			x	x	x	x	x	
Limerick Tunnel, Ireland			x	x				
Aktio – Preveza Tunnel, Greece	x	x						
Bjorvika Tunnel, Norway				x	x			x
Oosterweel Tunnel, Belgium			x			x		
Caland Tunnel (Rotterdam), Netherlands					x	x	x	x
Piet Hein Tunnel, Netherlands					x	x		
Oresund Link: Tunnel Section Under the Drogden, Sweden & Denmark					x			
Western Harbor Crossing Tunnel, Hong Kong							x	
Wijkertunnel, Netherlands						x		
Blankenburg Tunnel, Netherlands			x			x		
The Second Benelux Tunnel, Netherlands								x
Kennedy Tunnel Schelt, Belgium			x	x		x		
Kobe Tunnel, Japan	x	x						
Hampton Road Expansion, USA							x	
Posey & Webster Street Tubes, USA	x	x						
Marieholm tunnel, Gothenburg, Sweden				x				
Drecht Tunnel, Netherlands								x

Note: See text for greater discussion of criteria and basis of precedent.

3.0 REVIEW FINDINGS

The panel members shared their experience and knowledge with respect to the eight key considerations, one at a time. For each issue there was a recap of how the issue was framed by the broader ITR team earlier in the meeting and then the panel drew on their experience to identify projects that had addressed similar issues, and how they did so. Panelists were able to identify more than one project that addressed each issue and some projects that addressed multiple issues. Though conversation often went towards how they would address the issue for GMTR, the panelists were directed to simply judge the suitability of the precedent solution for the GMTR and to suggest alternative approaches, if any. Suitability was recorded as *High, Medium*, or *Low*.

3.1. Strong Ground Motion

The panel's first comment was that tunnels are inherently suitable for resisting ground motion from earthquakes, as tunnels experience less amplification of ground motions due to being buried. The precedent ITT projects in areas with potentially strong ground motion from seismic activity are listed in Section 2.0 and shown in Table 2-1, and the panel also notes that there are approximately 25 ITTs in Japan, all of which would be subject to strong ground motion. The panel stated that ground motion for ITTs is mitigated through their reinforcement design, built-in ductility through jointing at appropriate intervals (element length, typically around 100-125m), and robust sealing solutions at element joints (Gina and Omega gaskets, which are common solutions to seal and protect the immersion joints between elements).

The panel considered ITTs as *Highly* applicable to the proposed GMTR with respect to ground motion. Drawing upon their considerable experience, the panel was not aware of any poor performance or tunnel flooding from seismic events, and the panel estimated there are approximately 30 ITTs around the world in seismic areas. It was noted that it is standard practice for ITTs to have a backup power system for pumps.

The panel provided examples of existing ITTs that have experienced earthquakes of magnitude 6.4 and greater, and mentioned the Kobe Tunnel in Japan that survived the Hannshin earthquake of 1995 while under construction, and the Aktio-Preveza Tunnel in Greece that experienced an earthquake approximately one year following tunnel completion. After the meeting, it was confirmed that the Coatzacoalcos tunnel survived two earthquakes a couple of months after completion in September 2017 (Central Mexico earthquake and Chiapas earthquake). Movements were recorded, but quite small, and inspection showed no damage at all. The tunnel was reopened one day later.

The panel stated that segmental tunnels are designed to withstand earthquakes up to approximately magnitude 9.2, and that monolithic tunnels (only one element, and with no intermediate joints) are designed to withstand earthquakes stronger than magnitude 9.2. In the panel's opinion, ITT designers are comfortable with existing solutions.

3.2. Liquefaction

The precedent ITT projects that were constructed in areas with liquefiable soils are listed in Section 2.0 and shown in Table 2-1. The panel noted that several of the approximately 25 ITTs built in Japan likely have been designed in consideration of liquefaction. Four ITTs that had liquefaction mitigation were discussed further. The Coatzacaolcos Tunnel in Mexico had a few meters of liquefiable soil that was excavated and replaced with non-liquefiable soil. The Aktio-Preveza Tunnel in Greece was underlain by approximately 15 m of liquefiable soil which was mitigated with stone columns. The Marmaray Tunnel in Turkey, the tunnel bottom of which is located approximately 70 m below the water surface, mitigated about 15 m of liquefiable soil with compaction grouting. The Posey & Webster Street Tubes were retrofitted to resist liquefaction. The primary seismic retrofit consisted of jet grout columns (both sides of the Posey Street Tube) and pipe pile stone columns (both sides of the Webster Street Tube). The Shenzhen - Zhongshan Crossing in China, also included in Table 2-1, will mitigate liquefaction with a dense grid of sand compaction piles, but is not yet built.

The panel agreed on a *High* to *Medium* applicability of stone columns for the GMTR. The panel suggested that stone columns could be installed with a vibro probe while introducing gravel in the upper liquefiable sand layer, or alternatively, by advancing steel pipe piles, cleaning out the piles, filling the piles with sand and gravel, and then removing the piles by vibration, while maintaining sand and gravel backfill. Account should be made for the fact that the existing tunnel is close by and in the area very next to the tunnel, additional requirements may apply.

Panel members agreed that compaction grouting had a *Medium* applicability, and suggested compaction grouting would likely be appropriate for deeper layers, if analysis showed that such treatment was indeed needed, but not higher layers. Compaction grouting in higher layers would have limited applicability due to potential heaving of the adjacent existing tunnel.

The panel agreed that sub-excavation and replacement had a *Low* applicability due to the required depth of sub-excavation and proximity to the existing tunnel.

The panel discussed the use of tie down anchoring systems that are commonly used for offshore platforms, but have not been used on ITTs. Tie down anchors would be useful for resisting tunnel flotation during liquefaction and the panel thought they could have applicability here if liquefaction was not mitigated in other ways.

Cutoff walls constructed on either side of the tunnel to contain soil movement during liquefaction were suggested by the panel as a potential option to improve seismic resistance.

The panel was informed that the actual depth of liquefiable soils could be deeper than the 15 m that was reported in earlier studies. The panel also stated that ground improvement can typically be done to approximately 30 m depth below ground surface with routine methods, and noted that compaction grouting at the Marmaray Tunnel was as deep as 70 m below water surface.

3.3. Strong Current

The precedent ITT projects installed in waterways with a strong current are listed in Section 2.0 and shown in Table 2-1. The panel expressed that ITTs have been installed in river and marine environments with currents stronger than those experienced at the GMTR site (approximated as 2 m/s). ITT installation methods in current employ robust upstream and downstream anchoring systems for the installation equipment and tunnel elements. Lowering tunnel elements parallel to current direction and then turning the element near the bottom of the lift has been used to overcome flows 3 m/s or greater. The panel did not believe that lowering tunnel elements parallel to current direction would be required for an ITT at the GMTR site.

The panel agreed that ITTs have a *High* applicability for installation in river currents experienced at the GMTR site. The panel stated that a specialist subcontractor experienced in lowering ITTs would be required for that part of the work.

The panel suggested that the length and depth of tunnel elements would need to consider the effect of current during installation. They considered that the current is not all that strong, so element length may end up being controlled by geometrics, not current. Either way, lengths of approximately 100 m to 150 m are in the range of common element lengths, and appear reasonable here.

3.4. Environmental Sensitivity

The precedent ITT projects installed in areas with environmental sensitivity issues are listed in Section 2.0 and shown in Table 2-1. The panel was familiar with environmental sensitivity issues on many ITT projects, and the ITT examples provided included environmental issues such as fish spawning, shell fish and bird habitats. The panel stated that construction windows for fish movement, restrictions on dredging, and adjustments to methods for siltation and oxygen levels, are common. The panel stated that ITTs have been constructed in environmentally sensitive areas, and could not provide one example where environmental effects could not be mitigated.

The panel believed that ITTs have a *High* applicability in environmentally sensitive areas such as the GMTR site, as they grapple with these issues regularly, and standard procedures have been proven over time. More information is in the ITA-WG11 'Immersed Tunnels in the Natural Environment' paper available here:

https://about.ita-aites.org/publications/wg-publications/content/16/working-group-11-immersed-and-floating-tunnels

The panel suggested that side scan sonar to monitor fish movement, and bubble curtains to keep fish away, are options that could be considered during the construction period. Silt curtains would likely not be applicable due to anchoring in an environment where there are current reversals (tides).

The panel discussed suction dredging as being a favourable method because in any suction dredging operation the effluent can be managed to not create turbidity. The Fraser River Navigation channel is maintained annually using suction dredging equipment. It was recognized that although fish tend to avoid disturbances, efforts may be needed to minimize risk that some fish get picked up by the dredge. There are other methods, such as closed bucket clamshell dredgers, that are accepted to limit sediment spill and are often used in sensitive areas. A key point panel is that there is more than one method possible.

3.5. Construction Windows

The precedent ITT projects installed in areas with construction window constraints are listed in Section 2.0 and shown in Table 2-1. The panel agreed that a single tunnel could likely be placed within one construction season, during the current winter construction window for the Fraser River at the GMTR site, between June/July 16th to February 28th. The panel noted that the original GMT was placed within a four-month period (January to April), and that the time required for ITT element placement normally ranges between about one week and one month.

The panel discussed typical construction methodologies and stated that the placement of elements is normally the critical path. The staging of tunnel elements to be placed needs to be carefully planned. Elements should to be stored close to the site for staging, and can either be constructed remotely and shipped to site, or constructed on site in one of the tunnel approaches. ITT projects construct tunnel elements on a regular basis at the tunnel approaches, instead of at a dry dock. A tow distance of 10 to 15 km from a production or staging area to site is appropriate, and longer tow distances would benefit from a staging area. The panel mentioned that some elements have been towed hundreds of kilometers to the tunnel site. For example, the Bjorvika Tunnel contractor towed elements 600 km through the North Sea off the coast of Norway.

The panel recommended that immersion work be done by a specialist subcontractor familiar with placing ITTs, but casting and building of tunnel elements could be done primarily by local contractors.

The panel agreed that an ITT would have *High* applicability with respect to conforming to available construction windows.

The panel suggested that approximately 100 m elements would help meet construction window timelines due to them being more manageable and moveable, and would help manage schedule risk, and would help manage the infill cycle (infilling of dredged trenches with river sediment). The panel estimated ITT construction at the GMTR site would be a 3 to 4-year long program, including design, site preparation, ground improvement, element casting, tunnel finishing works (including tunnel systems and installations) and instream works, significantly less than the six years that was previously estimated. Arranging a casting yard would take about one year while design is being done. To compress the schedule, the panel was asked if element placement could be completed from both ends simultaneously, to meet in the middle, and the panel stated yes, but that having the last joint at the deepest point in the channel should be avoided.

3.6. Navigation Maintenance

The precedent ITT projects installed in areas that included significant navigable channels are listed in Section 2.0 and shown in Table 2-1. The panel understands that the existing navigable channel width is approximately 200 m. Dredging equipment and pile driving equipment would typically take about 50 m of channel width for equipment and perhaps another 50 m for anchorage, but more channel width would be needed during the placement of tunnel elements. Site preparation work often occurs within navigable channels while ship traffic is passing, and will often use equipment that can move out of the way quickly, if needed. During tunnel element placement, shipping channels have often been shut down, or have posted lower required speeds, at least for large vessels. This restriction or closure might be for two or three days, normally a weekend planned well in advance. The panel agreed that ITTs have *High* applicability for installation within navigable channels, and provided six examples of ITTs that were constructed at river crossings and port areas subjected to heavy ship traffic.

The panel suggested that using a suction dredge to dredge the shipping channel may be advantageous as suction dredges (especially self-propelled ship style dredges) are more maneuverable. These opportunities would be used to the extent possible. If it is not practical to provide anchors on each side of the river, anchoring platforms can be used, an approach which is more expensive but may be needed for a new ITT at the GMT crossing.

The panel understood that Transport Canada has a well-established system for instream works within navigable waters, and stressed that planning well in advance with Transport Canada would be important. Advanced planning with shipping authorities is standard practice on ITT projects.

3.7. Proximity to Structures

The panel was aware of seven ITTs that were constructed adjacent to existing structures. The precedent ITT projects in areas that were adjacent to existing structures are listed in Section 2.0 and shown in Table 2-1. The panel stated that alignment changes (horizontal curve), cut off walls (Second Coen Tunnel, Netherlands), documenting and monitoring of existing structures (Elizabeth River Tunnels), and designing dredging trenches that do not intersect adjacent tunnel covers (Second Benelux Tunnel), are common procedures when constructing adjacent to other structures. Examples were given of ITTs being constructed next to existing structures, such as the bottom of a new ITT tunnel being constructed within 5 ft (1.5 m) of a 100-year-old transit tube (Boston Central Artery Tunnel), and the Second Coen Tunnel (Netherlands) was constructed 13 m from the first Coen Tunnel.

The panel considered ITTs to have a *High* applicability for construction next to existing structures.

The panel suggested that the approaches may require sheet piles to contain excavations, and possibly press-in sheet piles (separation walls) could be considered to isolate a new ITT from the GMT. The panel also discussed the use of sonic methods for installing pipe piles for stone column ground improvement, to reduce vibration and settlement below the GMT. The panel considered using a horizontal curve to separate a new tunnel from the GMT as the most practical solution.

3.8. Required Tunnel Width

The panel had five examples of tunnels (approximately 50 m wide) that support eight lanes of traffic; however, 10-lane ITTs have not been constructed yet. The precedent ITT projects that have a similar number of lanes (8 vs.10) as required for the GMTR project are listed in Section 2.0 and shown in Table 2-1. The panel is aware of a current project in China (Shenzhen – Zhongshan Crossing), being designed, that will contain a widening section of 12 lanes close to the shore (resulting in one or two tunnel elements with a width of over 60 m. The issue with ITTs wider than 50 m is torsional stiffness during transportation, and the Shenzhen – Zhongshan project is considering temporary internal walls for transport.

The panel considered the applicability of ITTs to be *High* if an eight-lane tunnel is considered. There are currently no ITTs wider than eight lanes, however, there will soon be some precedent for wider ITTs. Wider elements will require larger equipment, and larger construction and staging areas, and may require internal walls for stiffness or support.

3.9. Other Topics Briefly Discussed with Panel

Upon concluding our discussion of key criteria with the panel, other topics deemed important by the panel were briefly discussed, and are summarized in this section.

3.9.1. Bored Tunnel Option

An incidental outcome of this review was recognition that a technical feasibility study of a bored tunnel would also be valuable as it would identify whether bored tunnel construction warrants continued consideration as a viable alternative.

The review panel considered the construction of two (2) 17 m diameter bored tunnels as potentially feasible, with two lanes stacked per tunnel (eight lanes total), constructed approximately 30 m below grade beneath the river, a depth assumed to be below zones of liquefaction, but resulting in a significant increase in tunnel length and deep approaches. Geometry was stated as more of an issue than technical. The panel was informed that a challenge of bored tunnels would be untangling the traffic lanes at the portals, maintaining maximum 5% grades and the required tunnel depth within the tunnel approaches and connecting to interchange locations, and that the portals themselves would create more interference with the existing highway during construction. A report generated after the panel meeting and providing the bored tunnel concept is provided in Appendix B.

3.9.2. Operation and Maintenance of a New ITT

An ITT would have operation costs of some on-going pumping, lighting (which is now low power LED) and ventilation. Past reports have stated that maintenance costs for an ITT would be more than for a bridge. The panel disagreed with that conclusion. If leakage in an ITT became an issue due to poor construction, that could be a maintenance issue, but if built properly, an ITT should be less expensive to maintain than a bridge. An ITT would be about 1.2 km shorter than a bridge, and there are normally small amounts of pumping required during rain events, but relatively minimal pumping requirements otherwise.

3.9.3. Retrofitting of George Massey Tunnel

The ITT panel experts noted that the Maas Tunnel in Rotterdam, an ITT older than the GMT, is still in service and stated that retrofitting the existing tunnel should be considered carefully. It was understood by the panel that one of the issues is the current height of the tunnel, and the panel suggested that ballast concrete could be removed from the road base and moved into the ventilation tubes, and then have ventilation at the portals only. The panel estimated a three or four-month study would be required for a 10% conceptual design for the ITT or for the retrofit of the existing tunnel.

3.9.4. Cost Considerations

No cost estimates were prepared or evaluated as part of this work. The experience of the panel is that a cost of 750 to 1,500 Euros (approximately $1,100 to $2,300 Canadian) per cubic meter of tunnel is typically referred to at the earliest stages of feasibility evaluation. They did not expect anything different at this site and for these project requirements.

4.0 CONCLUSION AND RECOMMENDATIONS

Eight key considerations and criteria were identified as most important to evaluate the suitability of a new ITT crossing at the GMTR project site. Though no single past or current project served as a benchmark for all eight key considerations and criteria, there were variously between six and thirteen existing benchmark projects discussed for each. The panel believes even more projects could be identified.

The panel's opinion was that the conditions of the project site and the needs of the project are similar to those that have been addressed within successful past design and construction experience with ITTs. Based on the panel's opinion, BGC recommends that the ITR carry forward a recommendation to Ministry of Transportation and Infrastructure (MoTI) that a more thorough exploration of the ITT approach be considered. Additionally, the possible suitability of a bored tunnel (or two) was discussed, and this idea appears warranted, though the attached report suggests that when compared to the ITT, the benefit may be in terms of other criteria, rather than cost.

The panel's observations on the comparability of technical aspects of ITT design and construction at the GMTR project site with precedent elsewhere, and the suitability of approaches to address key considerations, are based only on the level of information conveyed through this process. As such, these observations, and the summary and recommendation here by BGC, are limited by the short duration of review and discussion, and the material conveyed in that period. The findings presented here are considered to be sufficient to assist MoTI with their decision on whether to proceed with further tunnel evaluations, but not for other purposes. A more in-depth review could be conducted if desired.

5.0 CLOSURE

BGC Engineering Inc. (BGC) prepared this document for the account of Westmar Advisors, Inc. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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Yours sincerely,

BGC ENGINEERING INC.
per:

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Attachments: Appendix A – Meeting Agenda
Appendix B – Memo – Bored Tunnel Concepts

APPENDIX A
MEETING AGENDA

BGC	MEETING AGENDA	
	Project: 0272027 Independent Technical Review for George Masset Tunnel Replacement Project	FINAL

Venue: BGC Office, Vancouver BC **Date:** May 3-4, 2018

Attendees: **BGC Engineering:** Scott Anderson, Martin Devonald, Matt Thibeault

Expert Panel: Mr. Robert Bittner, Mr. Doug Grimes, Mr. Hans de Wit, and Mr. Jonathan Baber

Westmar Advisors: Stan Cowdell, Michael Cowdell, Daniel Jennings, Daniel Leonard, Colleen Ackermann

Other Guests: Mr. Blair Gohl, Wood; Gary Williams, GL Williams & Assoc.

Subject: Independent Technical Review for George Masset Tunnel Replacement Project: Focus on the Immersed Tube Tunnel Alternative

Day 1 - Morning Session (8:00 AM – 12:00 PM)

1. PROJECT BACKGROUND (75 min – led by BGC then Westmar)
   1.1. Introductions, agenda review and general business, safety (BGC)
   1.2. Project history through contracting of ITR (Westmar)
   1.3. Conduct of the ITR – and where this effort contributes (Westmar)

2. MEETING PURPOSE (15 min – led by BGC)
   2.1. Expectations from this meeting
   2.2. Expectations after this meeting

3. SITE UNDERSTANDING (90 minutes – led by Westmar and Guests)
   3.1. Geology/Geotechnical (Blair Gohl – 15 min)
   3.2. Seismic (Blair Gohl – 15 min)
   3.3. Environment (Gary Williams – 10 min)
   3.4. Physical Constraints (Daniel Leonard – 15 min)
   3.5. Existing GMT technical issues (Colleen Ackermann, Daniel Jennings (15 min)
   3.6. Other (20 min)

4. RECAP (15 minutes – led by BGC)
   4.1. Morning ‘parking lot’ items, Q&A

Lunch (12:00 PM – 1:00 PM) (brought in)

Day 1 - Afternoon Session (1:00 PM – 5:00 PM)

5. GLOBAL ITT EXPERIENCE (60 min - led by BGC)
   5.1. Review of Experience Table
   5.2. Completion of updated Experience Table

6. PRECEDENT FOR GMTR ITT (120 min - led by BGC)
   6.1. Within world experience
   6.2. North American considerations
   6.3. Risk Factors
   6.4. Options to Mitigate Risks
   6.5. Cost Factors

7. PLANNING FOR TOMORROW (30 min - led by BGC)
   7.1. Recap of the day
   7.2. Review of ‘parking lot’ items
   7.3. Identification of questions and data needs
   7.4. Considerations for final panel work product

Day 2 - (8:00 AM – 12:00 PM)

8. WELCOME
   8.1. Recap of Day 1 (15 minutes – led by BGC)
   8.2. Answers to questions and inquiries (30 min – led by Westmar)
9. CONTINUATION OF PRECEDENT DISCUSSION
   9.1. Reevaluate prior day work (45 minutes – led by BGC)
   9.2. Further questions (15 minutes – led by BGC)
10. PANEL RECOMMENDATION DISCUSSION
11. FUTURE PLANS AND CLOSURE FOR NEW ITT
12. OPEN DISCUSSION ON EXISTING TUNNEL WITH EXPERT PANEL (led by Westmar)
    -As time allows

APPENDIX B
MEMO – BORED TUNNEL CONCEPTS

Memorandum

To:	Scott Anderson, BGC	Project: George Massey Crossing
From:	Doug Grimes	cc: Stan Cowdell, Westmar Project Advisors
Date:	June 05, 2018	Doc. No.: 58360_001_MO_GL_0
Subject:	Bored Tunnel Concepts	

Revision Log

Rev. No.	Date	Revision Description
A	May 18, 2018	Issued for review
0	June 5, 2018	Final

1.0 Introduction

McMillen Jacobs Associates (MJ) participated in an expert panel workshop to review Immersed Tube Tunnel concepts as part of the George Massey Tunnel Replacement project (Project). As follow up to the workshop, MJ has completed a conceptual design and class 5 cost estimate for two Bored Tunnel alternatives for the project. This memo presents a discussion of these alternatives, their potential benefits and the estimated construction costs.

2.0 Objectives

The bored tunnel alternatives aim to address the feasibility of designing and constructing a seismically resilient highway crossing of the Fraser River through loose fluvial sand deposits, while addressing environmental, operational and logistical constraints at a competitive cost.

3.0 Bored Tunnel Design Concepts

3.1 Bored Tunnel Design and Construction

The bored tunnel features a double lined structure, with each lining working together to maximize seismic resistance. The initial lining is the concrete segmental lining, installed by the Tunnel Boring Machine (TBM), and the final lining is the road deck and vertical structure associated with ventilation and pedestrian walkways isolated from the roadway installed inside the bored tunnel. The TBM excavates the tunnel through a predetermined alignment, in this case down to about 35m below the average Fraser River water level, into presumed non-liquefiable soil. The final lining will be designed to resist seismic induced ground displacements, while the initial lining will be placed in preferable soil, so that the ground displacements are manageable.

Environmental impacts of bored tunnels are relatively small compared to the alternatives for this crossing. It is anticipated that an Earth Pressure Balance (EPB) TBM would be used, due to the nature of the soil. EPB Tunneling is well suited to the project geology, thus boring operations are expected to proceed efficiently (e.g. good production rates) with a low probability of unforeseeable delays due to boulders, obstructions or high-abrasion (e.g. cutter-head wear). EPB TBMs use low concentrations of biodegradable soil conditioners to create texture and consistency in the spoil and providing support to the tunnel face, allowing the TBM to bore underneath the Fraser River and Deas Slough without settlement induced impacts to the existing George Massey Tunnel and adjacent properties.

TBM driven road tunnels require a decline structure with a portal head wall (portal structure) for launching and receiving the TBM. These portal structures are built using open cut methods. They are typically about 200m long and wide enough for the permanent roadway configuration (including ventilation chambers/walkways). At the proposed site, the portal structures will need to accommodate a high ground water table that has unlimited recharge. To address this, we've assumed slurry walls will be used along the perimeter of each cut, and a jet grout slab will be installed to a depth of about 20m below the base of the excavation. The structures would then be excavated, and a base slab (working slab) would be cast on top of the jet grout slab. Additionally, jet grout would be installed immediately in front of the portal walls for the TBM break-out/break-in.

For building roadway transitions from Highway 99 into the tunnels, there will be two sections: the u-section and the cut-and-cover section. Beginning from the Highway 99 grade, the transitions will be constructed in u-sections, deepening as they approach the tunnels. At the outer edge of the portal structures, the roadways enter the cut-and-cover sections, which continue for the extent of the portal structures, and end at the tunnel portal walls.

3.2 George Massey Crossing Concept Design Inputs

The following are the key design inputs assumed for this process:

- Provide a minimum of 8 lanes of traffic.
- Ground conditions consist of loose fluvial sand deposits overlying marine silt deposits.
- Ground improvement is required to cut-off groundwater for construction of the portal structures and to improve the liquefiable soils intersected by the roadways.
- The minimum seismic performance level is that of a Lifeline bridge, as defined in the *Bridge Standards and Procedures Manual* (BC MOTI, 2016), supplement to the *Canadian Highway Bridge Design Code* (CSA, 2014).
- Design life is 100 years.
- The depth of the existing river channel is 15m not accounting for future scour.
- No disruption to traffic in the existing 4 lane Immersed Tube Tunnel is permitted during bored tunnel construction.

- Limit environmental and community impacts associated with construction and operation of the crossing.

4.0 Alternative A - Twin 4 Lane Tunnels

This twin 4 lane tunnel alternative includes two bored tunnels, each with capacity for four traffic lanes, a pedestrian walkway, utilities and ventilation. For simplicity of interchanges, each tunnel carries traffic in one direction only, through upper and lower decks. Although multi directional traffic is feasible, the interchanges involved are more complex and beyond the scope of this conceptual study. The result would be 8 lanes of traffic crossing the Fraser River, Deas Island and Deas Slough below grade. Figures 1 and 2 (attached) show the plan and profile of this design.

The tunnels would be bored by a 17m diameter TBM, similar to that used for the recently completed Alaska Way Viaduct (SR 99) replacement project in Seattle, WA. The proposed vertical alignment is along the inferred interface between liquefiable and non-liquefiable soils. This will embed the tunnels deep enough into the non-liquefiable soils to achieve a seismically resilient design, capable of meeting the anticipated seismic design criteria for this structure. It will also ensure that scour and tunnel confinement criteria are addressed.

At the tunnel portals, the road decking begins vertical and horizontal transitions, to merge with the existing Highway 99. The two staggered road decks transition horizontally, becoming side-by-side, and at the same time, transitioning vertically, to merge with the Highway 99 at grade, at about 450m from the tunnel portals.

The portal structures provide ground support for constructing about 225m of the transitions, while the remaining 225m require a u-section to house the transitions beyond the launch/receiving pits. The u-sections are about 12m below grade at their deepest points, and taper off to nil as the transitions reach the existing grade.

The work sequence is as follows:

1. Construct portal structures for the North and South portals, including slurry wall initial lining.

2. Install jet grout blocks for break-in/break-out of the TBM.

3. Launch the TBM at the launch pit, bore the tunnel, and disassemble the TBM at the receival pit.

4. Transfer the TBM to the adjacent launch pit, bore the second tunnel, and disassemble the TBM.

5. Fit-out the tunnels with road decking and utilities. This step can be partially concurrent with tunneling.

6. Build u-sections for the roadway transitions beyond the portal structures. This step can be concurrent with tunneling.

7. Build the road decking transitions. This step can be partially concurrent with tunneling.

8. Construct the ventilation and operations buildings. This step can be partially concurrent with tunneling.

9. Transition traffic from the George Massey Tunnel into the new tunnels.

Once the tunnels are operational, the Highway 99 crossing under the Fraser River and Deas Slough will have 8 lanes in operation. The George Massey Tunnel can then be decommissioned and the bridge over Deas Slough can be removed, opening green space on Deas Island. Note, no concept design or cost estimating has been completed for the decommissioning.

5.0 Alternative B - Twin 2 Lane Tunnels with Retrofit of George Massey Tunnel

The twin 2 lane Tunnels alternative includes two bored tunnels, each with the capacity for two traffic lanes. Each tunnel carries two lanes of traffic on a single deck, with adequate space for a separated pedestrian walkway, utilities and ventilation. Road tunnels of this size and layout are common in the bored tunnel industry and require about a 12m diameter TBM. To meet the 8-lane requirement, this alternative would include the rehabilitation of the George Massey Tunnel to bring it up to current seismic and operational standards, although the nature of such upgrades is outside the scope of this exercise and is described at a basic level only. The result would be 4 lanes of traffic crossing the Fraser River, Deas Island and Deas Slough below grade, and 4 lanes of traffic using the existing infrastructure. Figures 3 and 4 (attached) show the plan and profile of this concept design.

Like Alternative A, the vertical alignment of the tunnel will be at the interface of liquefiable and non-liquefiable soils. Each tunnel would have a decline structure, installed as shown on the drawings. At the tunnel portals, the road deck would begin a vertical transition to merge with the existing Highway 99 at grade. The distance to make the vertical transition up to the grade of Highway 99 is about 340m from the tunnel portals. This distance varies with the road grades, and depth of tunnel at the portals. Typically, it is preferred to launch/receive the TBM close to the ground surface, to minimize the depth of shoring and excavation for the pits.

The portal structures provide ground support for constructing about 200m of the transitions, while the remaining 140m require a u-section to construct the transitions beyond the launch/receiving pits. The u-sections are about 12m below grade at their deepest points, and taper off to nil as the transitions reach the existing grade.

The work sequence is as follows:

1. Construct portal structures for the North and South portals, including slurry wall initial lining.

2. Install jet grout blocks for break-in/break-out of the TBM.

3. Launch the TBM at the launch pit, bore the tunnel, and disassemble the TBM at the receival pit.

4. Transfer the TBM to the adjacent launch pit, bore the second tunnel, and disassemble TBM.

5. Fit-out the tunnels with road decking and utilities. This step can be partially concurrent with tunneling.

6. Build u-sections for the roadway transitions beyond the portal structures. This step can be concurrent with tunneling.

7. Build the road decking transitions. This step can be partially concurrent with tunneling.

8. Construct the ventilation and operations buildings. This step can be partially concurrent with tunneling.

9. Open the two new bored tunnels.

10. Close one half of the existing George Massey Tunnel while stone columns or jet grout columns are installed along the perimeter. For this step, a total of 6 lanes will remain in operation.

11. Open the newly retrofitted side of the existing George Massey Tunnel and close the other side, while stone columns or jet grout columns are installed along the perimeter. Six lanes will remain in operation during this step.

12. Finally, open all four lanes of the existing George Massey Tunnel, providing a total of 8 lanes of traffic.

6.0 Cost Estimate

For determining project feasibility, a cost estimate consistent with concept level design definition and AACE Class 5 was prepared, based on quantities shown in the drawings. A Class 5 cost estimate typically carries an accuracy range of minus 20 to 50% and plus 30 to 100%. It is a tool for understanding order of magnitude costs, and is typically used for comparison with other alternatives which have been developed to a similar degree of design definition. All prices are in 2018 Canadian dollars.

The cost estimate is based on unit rates derived from actual contractor costs for similar sized road traffic tunnels, and takes the form of an expected bid price. It does not include Owner’s costs such as design, permitting, project and construction management - in our experience these costs can total 15-20% of the construction cost. It also does not include Owner’s contingency, which at this stage would be approximately 35%. For a further breakdown of costs, see the Class 5 cost estimate attached. A summary of the cost estimates follows.

- The estimate includes costs for: bored tunnels; tunnel fit-out; entry and exit ramps; electrical, mechanical and ventilation works; and operations facilities.

- For Alternative A, the cost estimate is $1.8B, exclusive of at-grade upgrades to Highway 99, Right of Way (RoW) acquisition and decommissioning of the existing George Massey tunnel.

- For Alternative B, the cost estimate is $1.2B, exclusive of at-grade upgrades to Highway 99, RoW acquisition and upgrades to the existing George Massey tunnel.

7.0 Benefits of Bored Tunnel Alternatives

The benefits of bored tunnels include the elimination of impacts to the current roadway/traveling public (they can be built entirely off line), the low environmental impact of the structures and their construction, and the flexibility to install tunnels deep enough below the ground surface to reduce the costs associated with achieving adequate seismic resistance. A list of the primary benefits for the two bored tunnel alternatives is provided below.

Alternative A - Twin 4 Lane Tunnels

- Selection of the vertical and horizontal alignment of the tunnel which eliminates conflicts with the existing Highway 99 infrastructure and traffic during construction.
- Placement of the tunnels below the depth of liquefaction, in soil that would exhibit relatively small ground displacements during a seismic event.
- Low environmental impact during construction and potentially (depending on ventilation) through the life of the structure. Bored tunnel construction is done underground, with support at the tunnel portals.
- Flexibility to dredge to Fraser River to increase the allowable vessel size.
- At completion of the project, 8 new lanes of traffic will be in operation.
- Reclamation of Deas Island by removal of existing Highway 99 infrastructure.

Alternative B - Twin 2 Lane Tunnels with Retrofit of George Massey Tunnel

- Traffic conflict avoidance, seismic resiliency and low environmental impact, as mentioned above.
- Upgrades to the George Massey Tunnel eliminate the cost and environmental impacts associated with removing it.
- While upgrades to the George Massey Tunnel are being done, 6 lanes of traffic can be operational.
- At completion of the project, 8 lanes of traffic will be in operation.

The issue that is often seen as a disadvantage to bored tunnels is the concentration of gasses at the end of the tunnel. The current industry approach to this issue is to collect exhaust fumes at a single point, so that if required it can be cleaned/filtered prior to release into the atmosphere. Alternatives to this approach include placement mid-tunnel ventilation structure/fan plant which exhausts over Deas Island. However, this is contrary to where industry is at today. Our work has not investigated this, nor the size, extent scope of ventilation needed. It assumes horizontal ventilation, fan plants on both ends of each tunnel, and no mid-tunnel shaft/plant.

8.0 Closure/Recommendations

We have developed two bored tunnel alternatives for upgrading the George Massey crossing. A summary of the results of this study is as follows:

- Alternative A consists of two 17m diameter bored tunnels, at an estimated cost of $1.8B, exclusive of at-grade upgrades to Highway 99, RoW acquisition and decommissioning of the existing George Massey tunnel. It would provide 8 lanes of traffic and an opportunity to reclaim Deas Island.

- Alternative B consist of two 12m diameter bored tunnels, and seismic retrofit of existing George Massey Tunnel, at an estimated cost of $1.2B, exclusive of at-grade upgrades to Highway 99, RoW acquisition and seismic upgrades to the George Massey Tunnel. It would provide 8 lanes of traffic and avoid costs and environmental impacts associated with decommissioning of the existing tunnel.

Both concepts presented provide long term seismic resiliency, are within the range of successfully constructed projects and rely on conventional construction methodology.

Attachments:

- Alternative A - Twin 4 Lane Tunnels Plan. Figure 1.

- Alternative A - Twin 4 Lane Tunnels Profile. Figure 2.

- Alternative B - Twin 2 Lane Tunnels with Retrofit of George Massey Tunnel Plan. Figure 3.

- Alternative B - Twin 2 Lane Tunnels with Retrofit of George Massey Tunnel Profile. Figure 4.

- Class 5 Cost Estimate. Document No. 58360_002_ID_GL_0.

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PLAN VIEW
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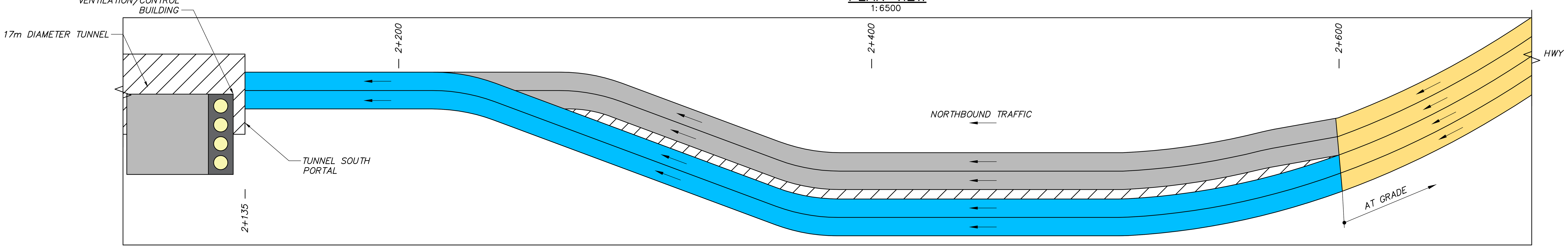
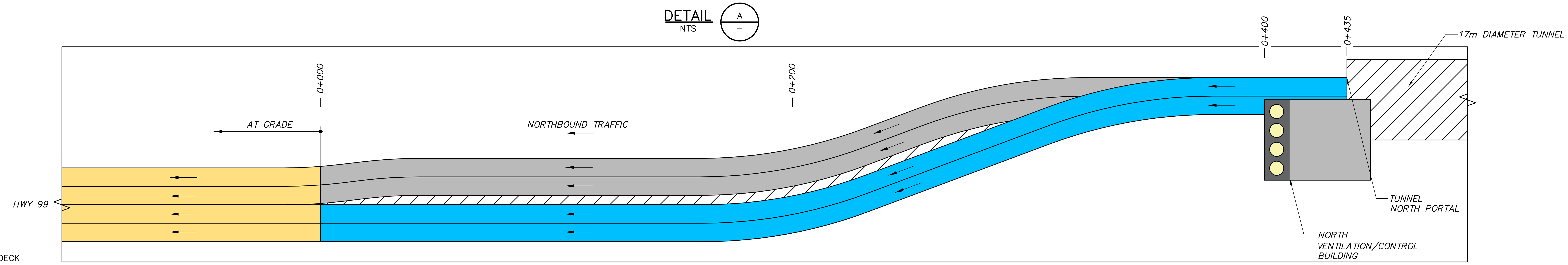


NORTHBOUND TRANSITION INTO TUNNEL

DETAIL A
NTS



NORTHBOUND TRANSITION OUT OF TUNNEL

DETAIL B
NTS

LEGEND:

- UPPER ROAD DECK
- LOWER ROAD DECK
- ALL LANES AT GRADE

PREPARED BY:
McMILLEN JACOBS ASSOCIATES
1188 W GEORGIA STREET, SUITE 1850
VANCOUVER BC V6E 4A2

Professional Seal

Issue	Date	Des'n	Dr'n	Chkd	App'd	Description
P1	JUN 2018	GE	EP	DG	–	ISSUED WITH BORED TUNNEL CONCEPTS MEMO

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Design: GE
Drawn: EP
Checked: DG
Approved
Manager

GEORGE MASSEY CROSSING

BORED TUNNEL STEVESTON – DELTA
TWIN 4 LANE TUNNELS
CONCEPTUAL PLAN

SCALE: AS SHOWN
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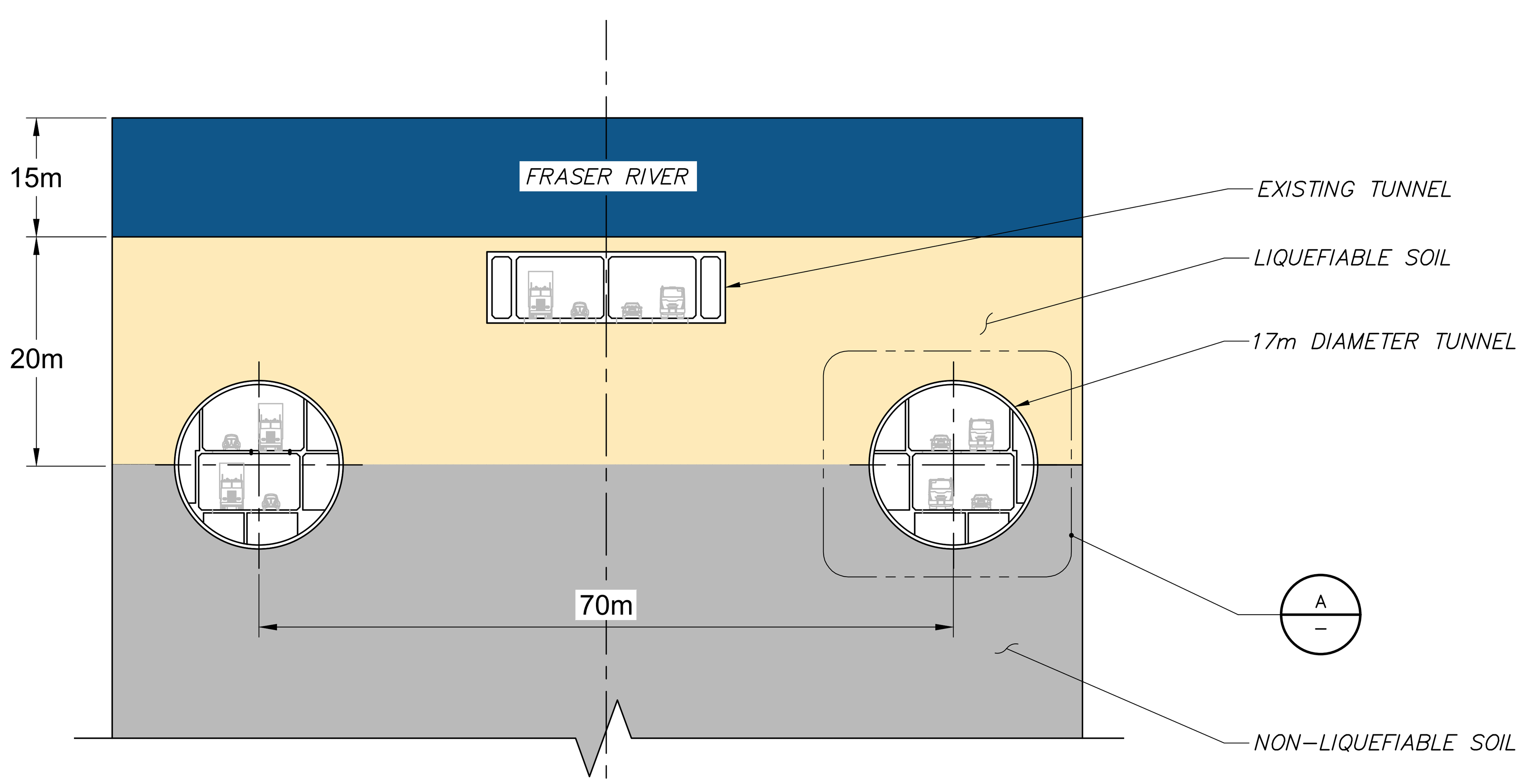
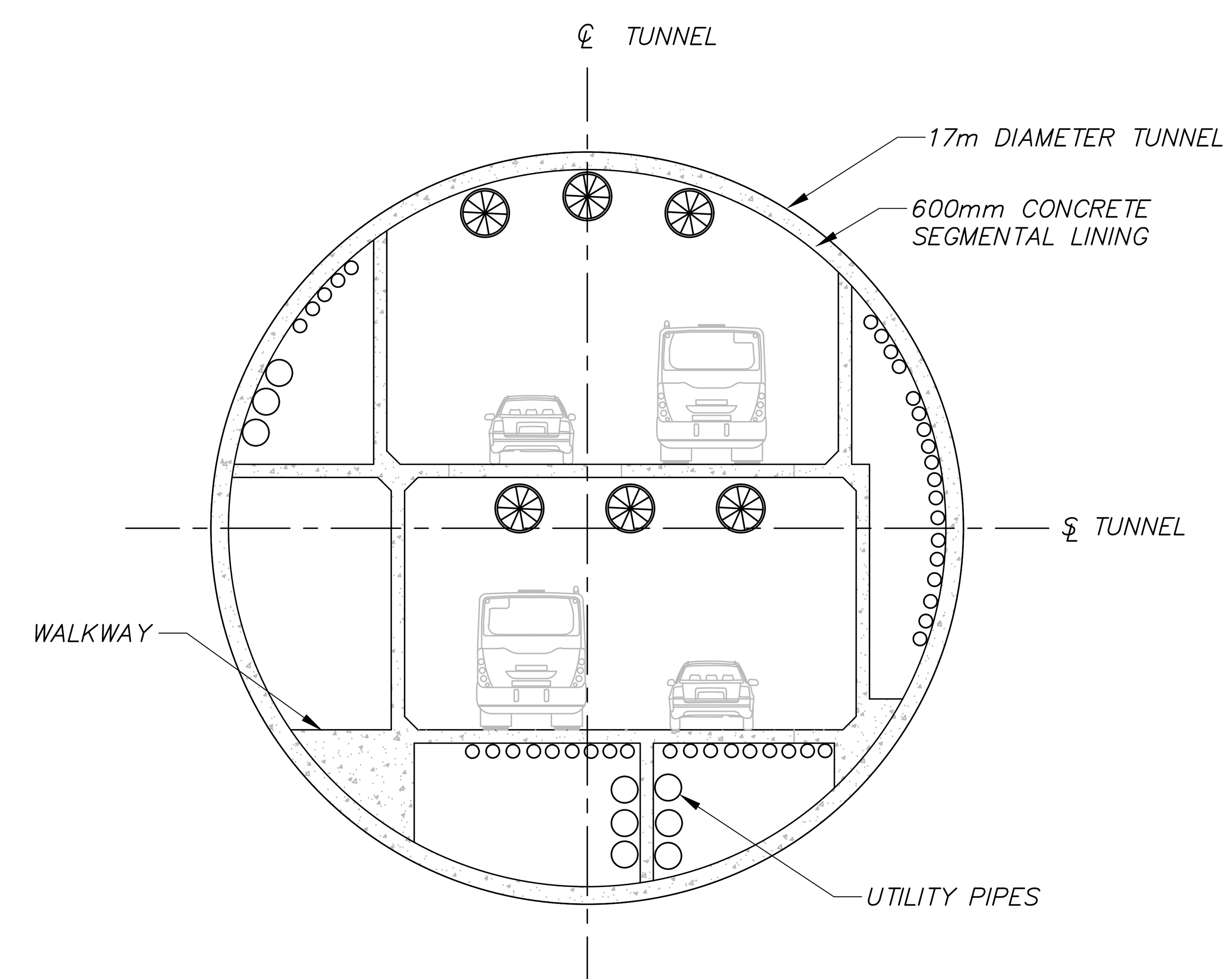
ELEVATION VIEW
NTS



SECTION 1
1:500



DETAIL A
1:125

WORK SEQUENCE:

1) INSTALL SLURRY WALLS AND JET GROUT AT NORTH AND SOUTH PORTALS.
2) EXCAVATE NORTH AND SOUTH PORTALS.
3) EXCAVATE TUNNELS BY 17m DIAMETER TBM.
4) FIT–OUT TUNNELS WITH TRAFFIC DECKS AND UTILITIES.
5) BUILD TRANSITIONS FROM HWY 99 INTO NEW TUNNELS.
6) TRANSITION TRAFFIC INTO TUNNELS (8 LANES IN OPERATION).
7) DECOMMISSION GEORGE MASSEY TUNNEL.
8) REMOVE BRIDGE OVER DEAS SLOUGH.

10m 0 25m
SCALE IN METERS
SCALE 1 = 500

2.5m 0 5m
SCALE IN METERS
SCALE 1 = 125

PREPARED BY:
McMILLEN JACOBS ASSOCIATES
1188 W GEORGIA STREET, SUITE 1850
VANCOUVER BC V6E 4A2

Professional Seal

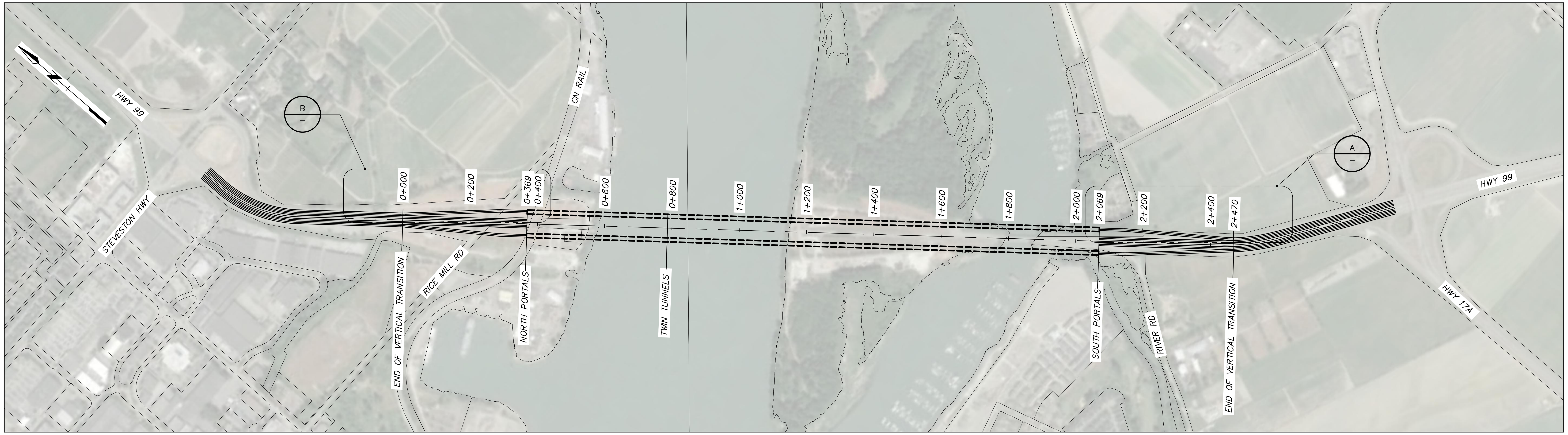
Issue	Date	Des'n	Dr'n	Chkd	Appd	Description
P1	JUN 2018	GE	EP	DG	–	ISSUED WITH BORED TUNNEL CONCEPTS MEMO

0 20 Bar is 20mm On Original Drawing. If Not On This Sheet, Adjust Scales Accordingly.

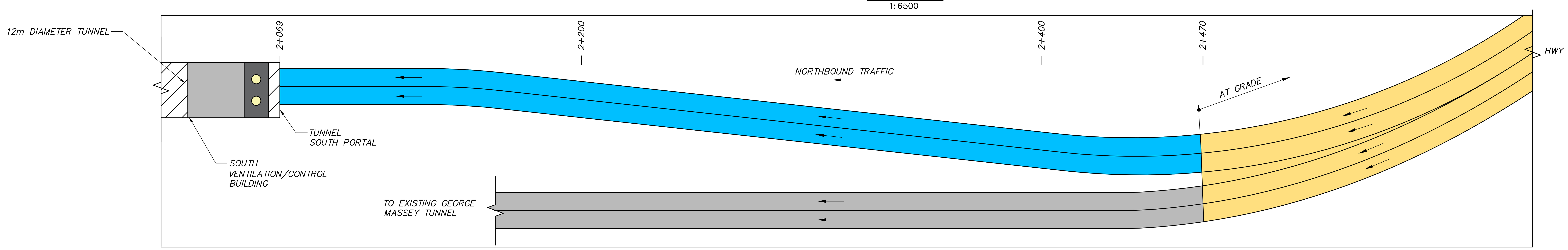
Design: GE
Drawn: EP
Checked: DG
Approved –
Manager –

GEORGE MASSEY CROSSING
–
BORED TUNNEL STEVESTON – DELTA
TWIN 4 LANE TUNNELS
CONCEPTUAL PROFILE

SCALE: AS SHOWN
DISTRICT FILE –
DRAWING NUMBER –
SUPERSEDES PRINTS OF THIS DRAWING NUMBER WITH LETTERS PREVIOUS TO P1

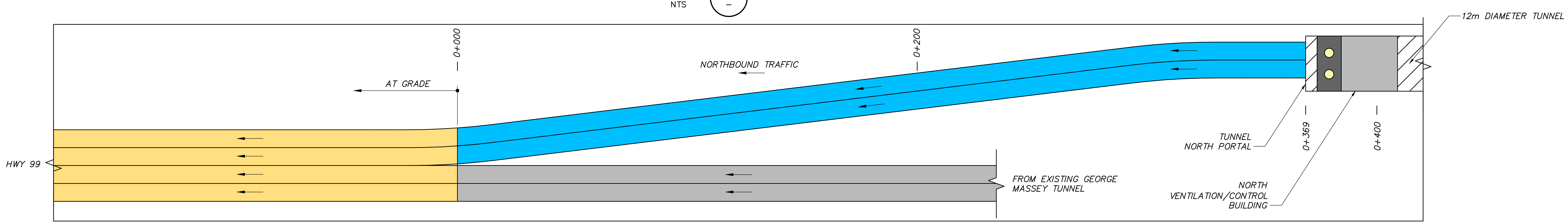


PLAN VIEW
1:6500



NORTHBOUND TRANSITION INTO TUNNEL

DETAIL A
NTS



LEGEND:

- HWY 99
- TRAFFIC ENTERING/EXITING NEW TUNNELS
- TRAFFIC ENTERING/EXITING GEORGE MASSEY TUNNEL

NORTHBOUND TRANSITION OUT OF TUNNEL

DETAIL B
NTS

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VANCOUVER BC V6E 4A2

Professional Seal

Issue	Date	Des'n	Dr'n	Chkd	App'd	Description
P1	JUN 2018	GE	EP	DG	–	ISSUED WITH BORED TUNNEL CONCEPTS MEMO

0 20 Bar is 20mm On Original Drawing. If Not On This Sheet, Adjust Scales Accordingly.

Design: GE
Drawn: EP
Checked: DG
Approved
Manager

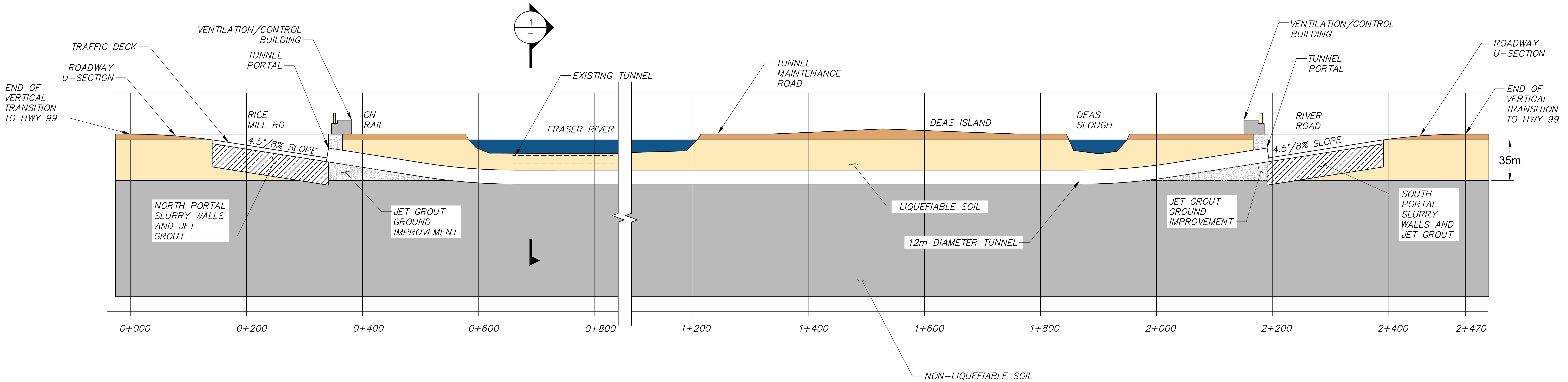
GEORGE MASSEY CROSSING

BORED TUNNEL STEVESTON – DELTA
TWIN 2 LANE TUNNELS
CONCEPTUAL PLAN

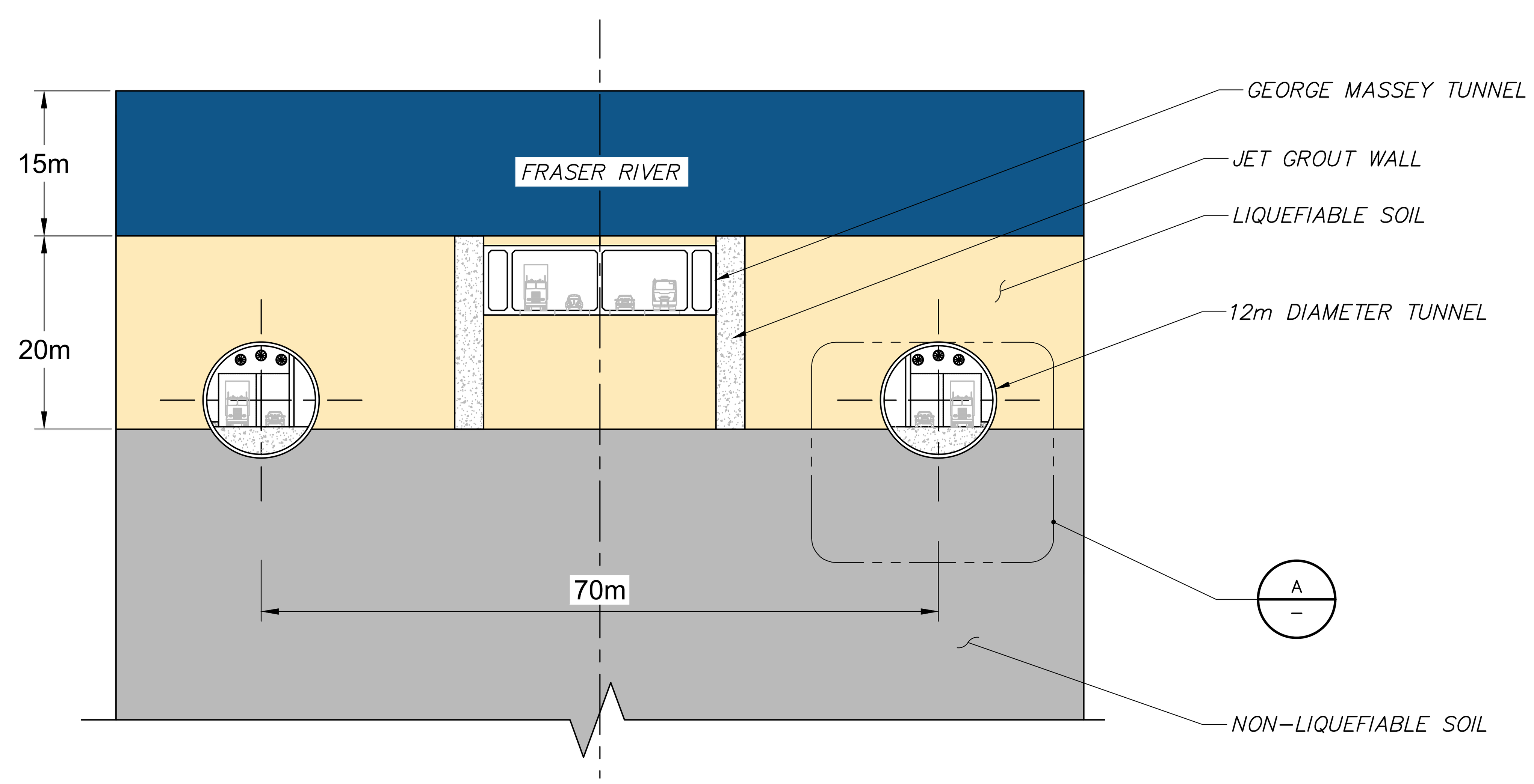
SCALE: AS SHOWN
DISTRICT FILE –
DRAWING NUMBER –

SUPERSEDES PRINTS OF THIS DRAWING NUMBER WITH LETTERS PREVIOUS TO P1

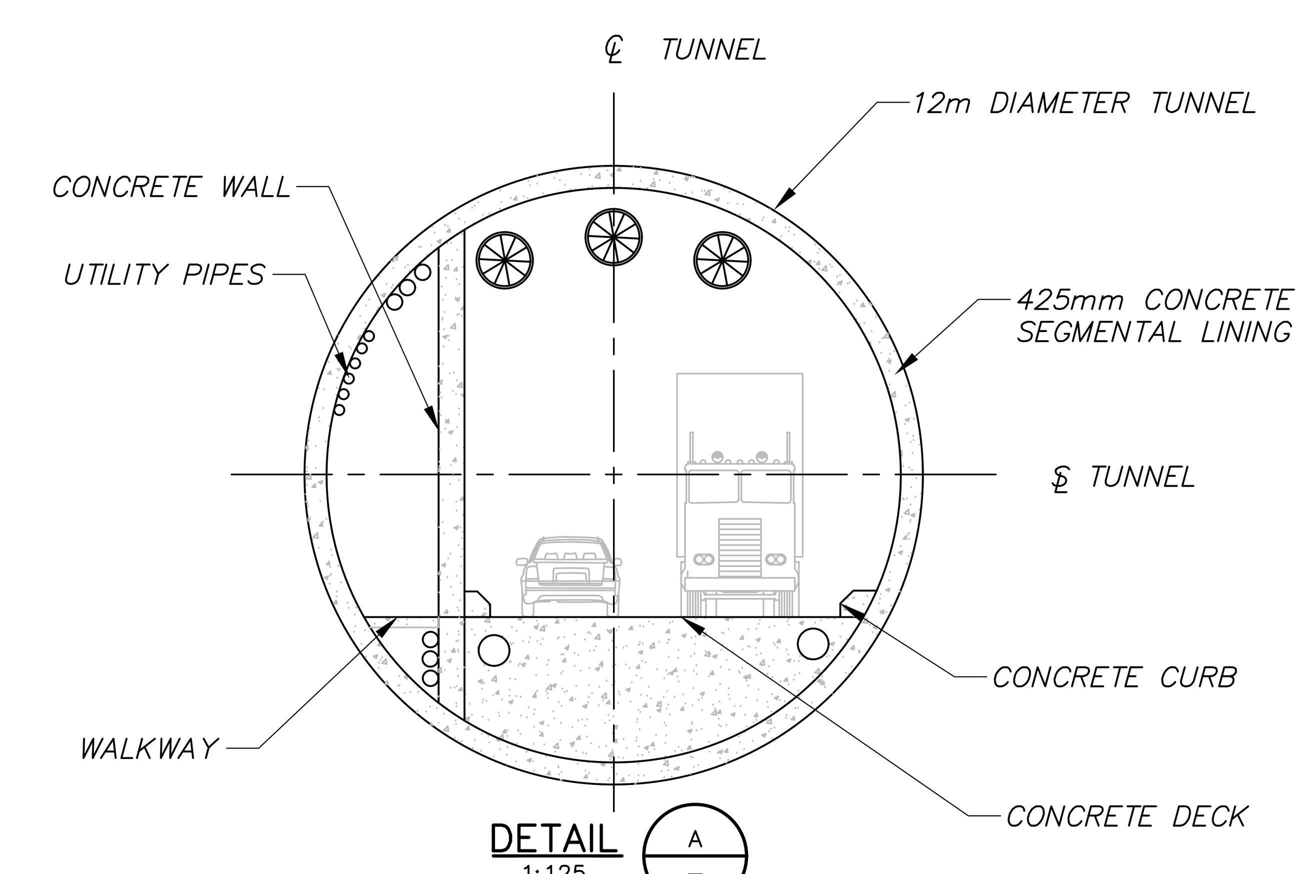
???.DWG



ELEVATION VIEW
NTS



SECTION 1/–
1:500



DETAIL A/–
1:125

WORK SEQUENCE:

1) INSTALL SECANT PILES AND JET GROUT AT NORTH AND SOUTH PORTALS.
2) EXCAVATE NORTH AND SOUTH PORTALS.
3) EXCAVATE TUNNELS BY 12m DIAMETER TBM.
4) FIT-OUT TUNNELS WITH ROADWAY SYSTEMS.
5) BUILD TRANSITIONS FROM HWY 99 INTO NEW TUNNELS.
6) TRANSITION TRAFFIC INTO NEW TUNNELS.
7) CLOSE WEST SIDE OF MASSEY TUNNEL (6 LANES REMAIN IN OPERATION).
8) INSTALL JET GROUT WALL ALONG WEST SIDE OF GEORGE MASSEY TUNNEL.
9) OPEN WEST SIDE OF GEORGE MASSEY TUNNEL AND CLOSE EAST SIDE (6 LANES REMAIN IN OPERATION).
10) INSTALL JET GROUT WALL ALONG EAST SIDE OF GEORGE MASSEY TUNNEL.
11) OPEN EAST SIDE OF GEORGE MASSEY TUNNEL (8 LANES IN OPERATION).

10m 0 25m
SCALE IN METERS
SCALE 1 = 500

2.5m 0 5m
SCALE IN METERS
SCALE 1 = 125

PREPARED BY:
McMILLEN JACOBS ASSOCIATES
1188 W GEORGIA STREET, SUITE 1850
VANCOUVER BC V6E 4A2

Professional Seal

Issue	Date	Des'n	Dr'n	Chkd	App'd	Description
P1	JUN 2018	GE	EP	DG	–	ISSUED WITH BORED TUNNEL CONCEPTS MEMO

0 20 Bar is 20mm On Original Drawing. If Not On This Sheet, Adjust Scales Accordingly.

Design: GE
Drawn: EP
Checked: DG
–
Approved
–
Manager

–
GEORGE MASSEY CROSSING
–
BORED TUNNEL STEVESTON – DELTA
TWIN 2 LANE TUNNELS
CONCEPTUAL PROFILE

SCALE: AS SHOWN
DISTRICT FILE –
DRAWING NUMBER –

SUPERSEDES PRINTS OF THIS DRAWING NUMBER WITH LETTERS PREVIOUS TO P1
???.DWG

Class 5 Cost Estimate Document No. 58360_002_ID_GL_0

George Massey Crossing
BORED TUNNEL STEVESTON - DELTA - TWIN 4-LANE TUNNELS

JMS
6/1/2018

CONCEPT (CLASS 5) ESTIMATE - $CAD 2018									$1,800M
North Approaches									**$344M**
Slurry Walls	40,596	m2			$292	/m2	$11.8M		
Jet Grout Invert	196,460	m3			$486	/m3	$95.5M		
Excavation	235,329	m3			$123	/m3	$28.8M		
Bracing	21,956	m2	171	kg/m2	$9	/kg	$35.3M		
Break-in/out Structure	120,564	m3			$486	/m3	$58.6M		
Added Jet Grout Improvement	49,810	m3			$680	/m3	$33.9M		
Base Slab	14,735	m3			$490	/m3	$7.2M		
Rice Mill Rd. Crossing	800	m2			$2,451	/m2	$2.0M		
Elevated Concrete Roadway		LS			$60.0M	/LS	$60.0M		
Laid-back excavation	68,684	m3			$98	/m3	$6.7M		
Roadway slab	2,810	m3			$943	/m3	$2.6M		
Ancillary VMS, striping etc		LS			$2.0M	/LS	$2.0M		
South Approaches									**$327M**
Slurry Walls	45,540	m2			$292	/m2	$13.3M		
Jet Grout Invert	218,080	m3			$486	/m3	$106.0M		
Excavation	271,660	m3			$123	/m3	$33.3M		
Bracing	24,124	m2	171	kg/m2	$9	/kg	$38.8M		
Break-in/out Structure	62,050	m3			$486	/m3	$30.1M		
Added Jet Grout Improvement	29,410	m3			$680	/m3	$20.0M		
Base Slab	16,568	m3			$490	/m3	$8.1M		
Elevated Concrete Roadway		LS			$66.2M	/LS	$66.2M		
Laid-back excavation	69,916	m3			$98	/m3	$6.9M		
Roadway slab	2,860	m3			$943	/m3	$2.7M		
Ancillary VMS, striping etc		LS			$2.0M	/LS	$2.0M		
Tunnels 2 x 17m dia	**3,406**	**m**			**$331,062**	**/m**			**$1,128M**
TBM Job Cost	1	ea			$123.2M	/ea	$123.2M		
Tunnel Construction	3,406	m			$227,007	/m	$773.2M		
Interior Concrete	3,406	m			$32,663	/m	$111.2M		
Operations Building/FLS	4	ea			$30.0M	/ea	$120.0M		

VARIABLES

1.3	CAD/USD EXCHANGE RATE
45%	OVERHEAD (PRIME)
15%	OVERHEAD (ON SUBS)

CALCS

Excavation Support

Pipe Struts 36"dia x 3/4" thick x 20m long @ 6m V x 5m H OC x 50% each side

30.6 lb/sf   4300 kg/ea/side   143 kg/m2/side

Wales W36x359 @ 6m levels

27 kg/m2/side

North Approach

Upper Deck within Approach - Stacked Configuration x 2 tunnels:					
Slab: 150m long x 14m wide x 1.0m x 2 tunnels	8400	m3	$2,828	/m3	$23.8M
Beams: 150m @ 6m OC x 20-27m long x 2m x 2m	4888	m3	$3,299	/m3	$16.1M
Corbels: 1 x 1.5 x 2m x 150m @ 6m OC x 2 sides	312	m3	$2,262	/m3	$0.7M
Parapets: 2m x 0.5m x 150m x 2 sides	600	m3	$754	/m3	$0.5M
Upper Deck within Approach - Ramp to Grade Configuration:					
Slab: 60m long x 14m wide x 1.0m x 2 tunnels	3360	m3	$2,828	/m3	$9.5M
Beams: 60m @ 6m OC x 18m long x 2m x 2m	2376	m3	$3,299	/m3	$7.8M
Posts: 2m x 2m x 4m avg H x 2/set x 11 sets	704	m3	$2,356	/m3	$1.7M
Layback Exc.: 23m D max x 47m w @ 2.5H:1V x 223m	68684	m3			
Roadway Slab: 42m w x 223m	2810	m3			

South Approach

Upper Deck within Approach - Stacked Configuration x 2 tunnels:					
Slab: 145m long x 14m wide x 1.0m x 2 tunnels	8120	m3	$2,828	/m3	$23.0M
Beams: 145m @ 6m OC x 20-27m long x 2m x 2m	4731	m3	$3,299	/m3	$15.6M
Corbels: 1 x 1.5 x 2m x 145m @ 6m OC x 2 sides	302	m3	$2,262	/m3	$0.7M
Parapets: 2m x 0.5m x 145m x 2 sides	580	m3	$754	/m3	$0.4M
Upper Deck within Approach - Ramp to Grade Configuration:					
Slab: 85m long x 14m wide x 1.0m x 2 tunnels	4760	m3	$2,828	/m3	$13.5M
Beams: 85m @ 6m OC x 18m long x 2m x 2m	3276	m3	$3,299	/m3	$10.8M
Posts: 2m x 2m x 4m avg H x 2/set x 15 sets	960	m3	$2,356	/m3	$2.3M
Layback Exc.: 12m D max x 47m w @ 2.5H:1V x 227m	69916	m3			
Roadway Slab: 42m w x 227m	2860	m3			

George Massey Crossing | **JMS**
BORED TUNNEL STEVESTON - DELTA - TWIN 2-LANE TUNNELS | **6/1/2018**

CONCEPT (CLASS 5) ESTIMATE - $CAD 2018									**$1,210M**
North Approaches									**$229M**
Slurry Walls	30,960	m2			$292	/m2	$9.0M		
Jet Grout Invert	112,000	m3			$486	/m3	$54.4M		
Excavation	90,412	m3			$123	/m3	$11.1M		
Bracing	28,260	m2	161	kg/m2	$9	/kg	$42.9M		
Break-in/out Structure	43,632	m3			$486	/m3	$21.2M		
Added Jet Grout Improvement	115,296	m3			$680	/m3	$78.4M		
Base Slab	8,400	m3			$490	/m3	$4.1M		
Rice Mill Rd. Crossing	560	m2			$2,451	/m2	$1.4M		
Laid-back excavation	24,440	m3			$98	/m3	$2.4M		
Roadway slab	2,251	m3			$943	/m3	$2.1M		
Ancillary VMS, striping etc		LS			$1.5M	/LS	$1.5M		
South Approaches									**$205M**
Slurry Walls	30,960	m2			$292	/m2	$9.0M		
Jet Grout Invert	112,000	m3			$486	/m3	$54.4M		
Excavation	90,412	m3			$123	/m3	$11.1M		
Bracing	13,812	m2	161	kg/m2	$9	/kg	$21.0M		
Break-in/out Structure	43,632	m3			$486	/m3	$21.2M		
Added Jet Grout Improvement	115,296	m3			$680	/m3	$78.4M		
Base Slab	8,400	m3			$490	/m3	$4.1M		
Laid-back excavation	24,267	m3			$98	/m3	$2.4M		
Roadway slab	2,244	m3			$943	/m3	$2.1M		
Ancillary VMS, striping etc		LS			$1.5M	/LS	$1.5M		
Tunnels 2 x 12m dia	**3,406**	**m**			**$227,890**	**/m**			**$776M**
TBM Job Cost	1	ea			$46.6M	/ea	$46.6M		
Tunnel Construction	3,406	m			$164,276	/m	$559.5M		
Interior Concrete	3,406	m			$14,706	/m	$50.1M		
Operations Building/FLS	4	ea			$30.0M	/ea	$120.0M		

VARIABLES

1.3	CAD/USD EXCHANGE RATE				
45%	OVERHEAD (PRIME)				
15%	OVERHEAD (ON SUBS)				

CALCS

Excavation Support

Pipe Struts 24"dia x 1" thick x 14 long @ 6m V x 5m H OC x 50% each side

40.8	lb/sf	4013	kg/ea/side	134	kg/m2/side

Wales W36x359 @ 6m levels

27	kg/m2/side

North Approach

Layback Exc.: 10m D max x 27m w @ 2.5H:1V x 141m	24440	m3
Roadway Slab: 22m w x 341m	2251	m3

South Approach

Layback Exc.: 10m D max x 27m w @ 2.5H:1V x 140m	24267	m3
Roadway Slab: 22m w x 340m	2244	m3

Appendix E Tunnel History

George Massey Crossing

Original Design and Construction Details

September 2018

WESTMAR ADVISORS

Original Design and Construction Details

This appendix supplements the Review by providing additional detailed information about the original design and construction of the George Massey Tunnel (Tunnel).

The Tunnel has been in service since 1959. Designed with a great deal of care and attention to detail by Christiani & Nielsen of Canada Ltd. (Christiani & Nielsen), together with Foundation of Canada Engineering Corporation (FENCO), it was the second pre-fabricated rectangular cross-section tunnel in the world to be installed using immersed tube technology. The first such tunnel, the Maastunnel in Rotterdam, Netherlands, which opened in 1942, is still in use today – it is a National Monument – and is currently undergoing a maintenance retrofit to extend its life well into the future.

Both a bridge and a tunnel were considered for the original crossing which was installed to replace a ferry service. A tunnel was selected because it would not interfere with shipping, it had a much-improved vertical profile at only half the offset distance from the river's surface compared to a bridge, and its estimated cost was 25% to 30% lower than that of a bridge[1,2,3].

The tunnel portion of the crossing consists of six precast rectangular concrete elements, each 105 metres (m) long, which were constructed in a purpose built dry dock next to the site. The concrete units, with temporary bulkheads at each end, were floated into the river and lowered into a prepared trench. The units were connected end to end employing a pneumatic perimeter sealing gasket which allowed the joint chamber to be drained of water between the bulkheads so the workers could enter to the space to complete the construction of the permanent joints.

Once the elements were in place, the following steps were taken to secure them into the river bed:

- Sand was pumped under the elements to provide continuous bearing under the tunnel floor.
- Gravel was placed partially up the sides of the tunnel and protected with a 915 millimetres (mm) layer of 225 kilograms (kg) rock.

[1] ASCE Journal (1957, November) *Deas Island Tunnel* [Magazine article].
[2] Popular Mechanics Magazine (1959, March) *A Prefab Tunnel Conquers a Tough River* [Magazine article].
[3] British Columbia Ministry of Transportation and Infrastructure (1979, July) *George Massey Tunnel Information Manual* [Manual].

- Scour mats (flexible concrete mats, 38 mm thick, reinforced with stainless steel wire) were placed on the side slopes of the trench to protect it from scour during the period when the trench was allowed to backfill naturally. The overall width of scour mats varied (typically 38 m to 46 m on each side of the tunnel).
- A 1,065 mm layer of 225 kg rock was placed over the scour mats.
- A layer of 680 kg rock was placed over and beside the tunnel. The rock over the tunnel acts as ballast to help hold the tunnel down.
- The remaining portion of the trench which had been excavated for the placement of the tunnel elements was left to fill in naturally.

The overall construction period was three and a half years; however, the placement of the six tunnel elements in the river took less than 5 months, placement was scheduled to take place during the low flow months. The first unit placed on January 6, 1958, the central units placed on January 26, February 21, March 9, and April 5. The last unit was placed on April 17, 1958 just as river flows were starting to increase significantly. Figures AE-1 and AE-2 show cross sections through the Tunnel as originally constructed and Figure AE-3 and AE-4 show its profile.

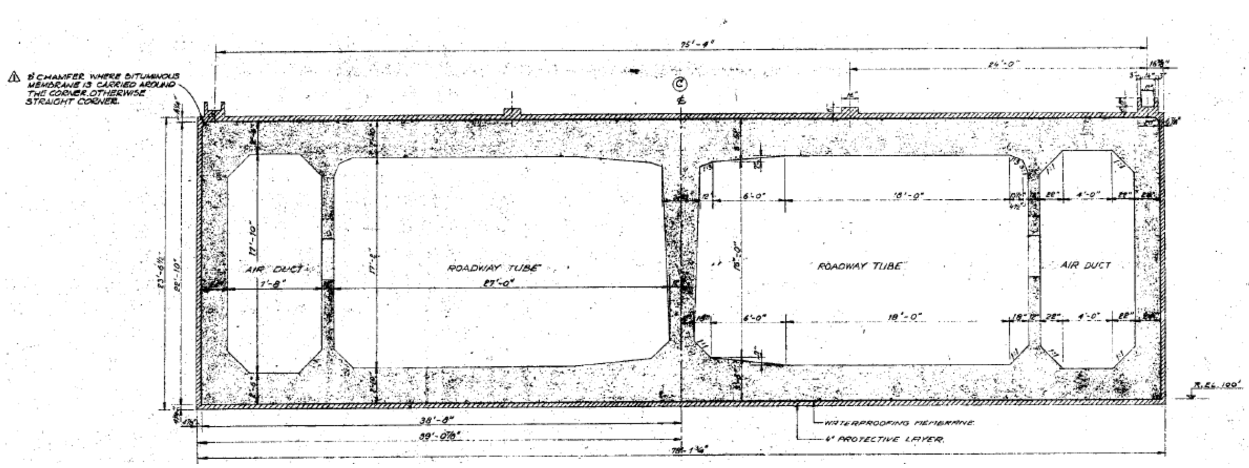


Figure AE-1 Original Tunnel element cross section[4].

[4] Extracted from Christiani & Nielsen /FENCO Drawing No. 3 J 3046 Rev 1.

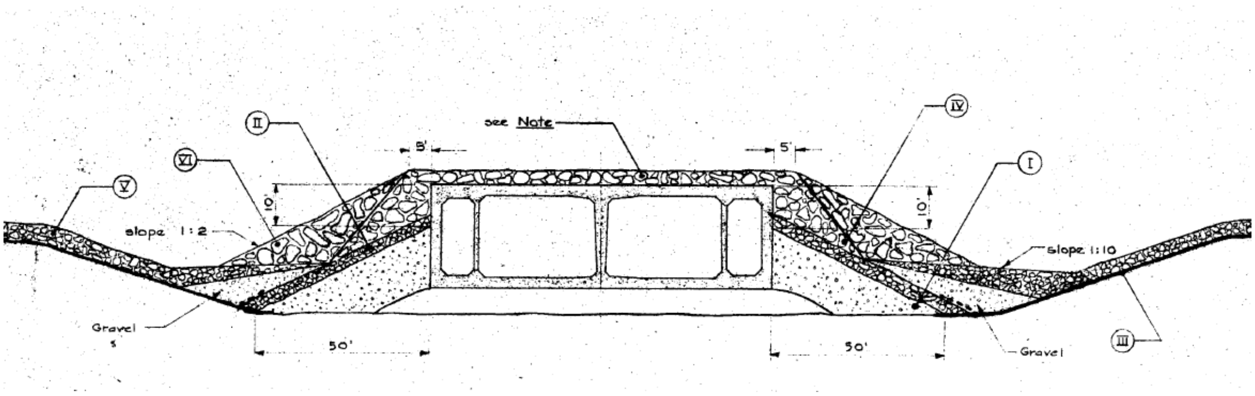


Figure AE-2 Original Tunnel element in place (prior to placement of natural sand backfill)[5].

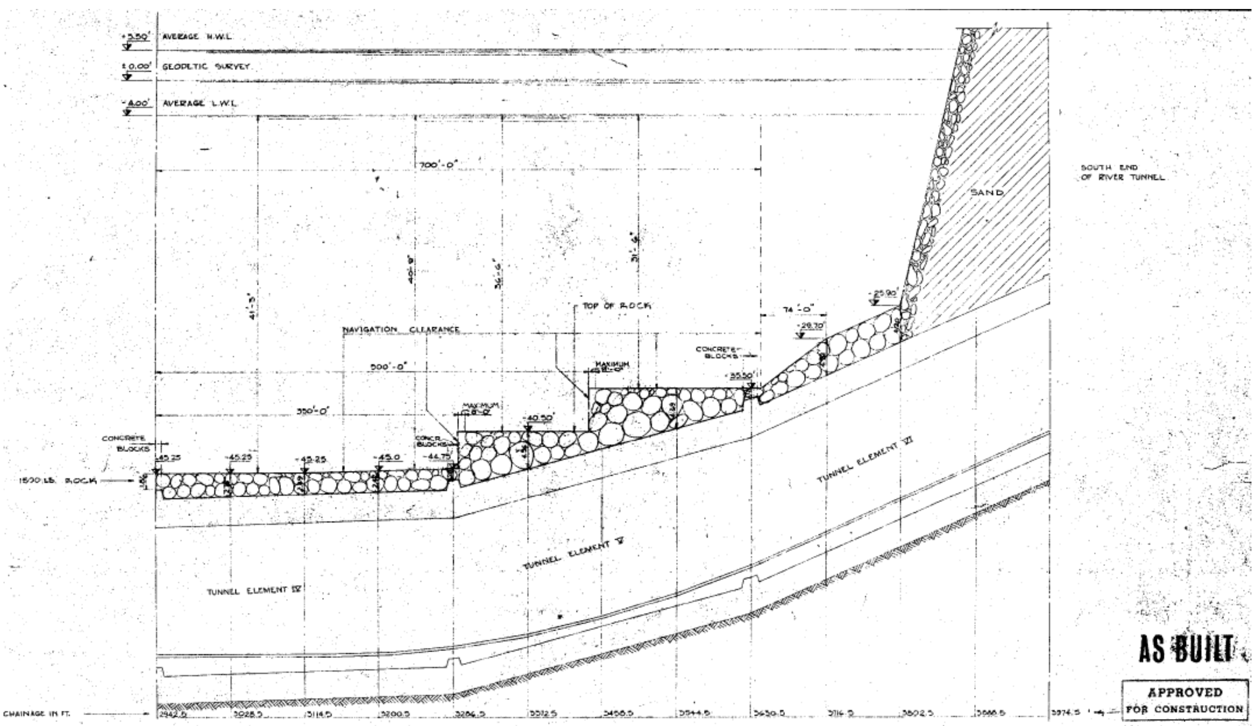


Figure AE-3 Tunnel profile – three elements[6].

[5] Extracted from Christiani & Nielsen /FENCO Drawing No. 14 J 1710 As Built.
[6] Extracted from Christiani & Nielsen /FENCO Drawing No. 14 E 1618 As Built.

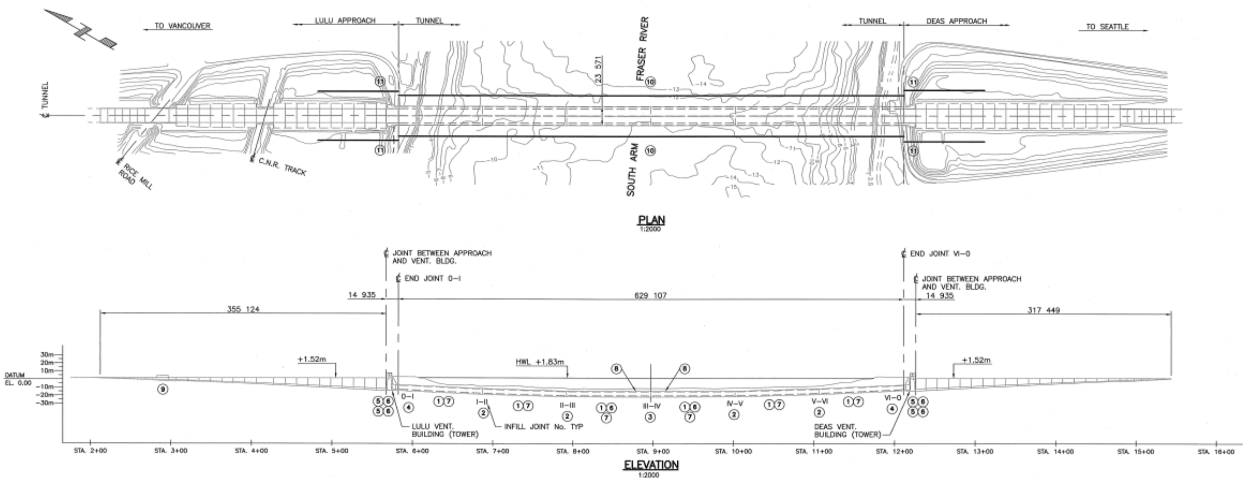


Figure AE-4 Tunnel profile – overall[7].

Significant design effort was made to detail the tunnel to be watertight and to protect its outer surface from damage. In addition to the basic reinforced concrete structure at the core of the tunnel elements, the following components were provided:

- **Below the Bottom Slab:** continuous 4.8 mm (3/16 inch) steel plate waterproofing membrane plus 100 mm (4 inches) of reinforced concrete. This protection also extended around the bottom corners and 400 mm up the exterior walls.
- **Over the Top Slab:** a multilayered bituminous membrane (asphalt emulsion prime coat, 1 layer of Glasfab, 4 layers of Coromat alternating with 5 layers of hot asphalt, 1 layer of roofing felt) plus 100 mm of reinforced concrete. This protection extended around the top corners and 300 mm down the exterior walls.
- **Over the Exterior Side Walls:** a multilayered bituminous membrane identical to and continuous with the membrane over the top slab plus 100 mm of horizontal timber planks held in place between full height vertical 100mm deep I-beam steel sections.

At the joints between the elements and for a distance of 3.35 m either side of each joint, a 6.4 mm (1/4 inch) continuous steel plate waterproofing membrane was provided around the top, bottom, and sides of the concrete core.

[7] Extracted from B&T Project No. 11469-0001, Drawing No. 1509-02 Rev 1.

The outer layer of protective concrete over the structural core was thickened to 440 mm over a 1.8 m distance at each segment end to create the structural collar that would facilitate the high pressures on the pneumatic gasket and which constituted the temporary joint when the elements were initially placed.

Figure AE-5 is a schematic representation of the waterproofing and protective components of the tunnel elements.

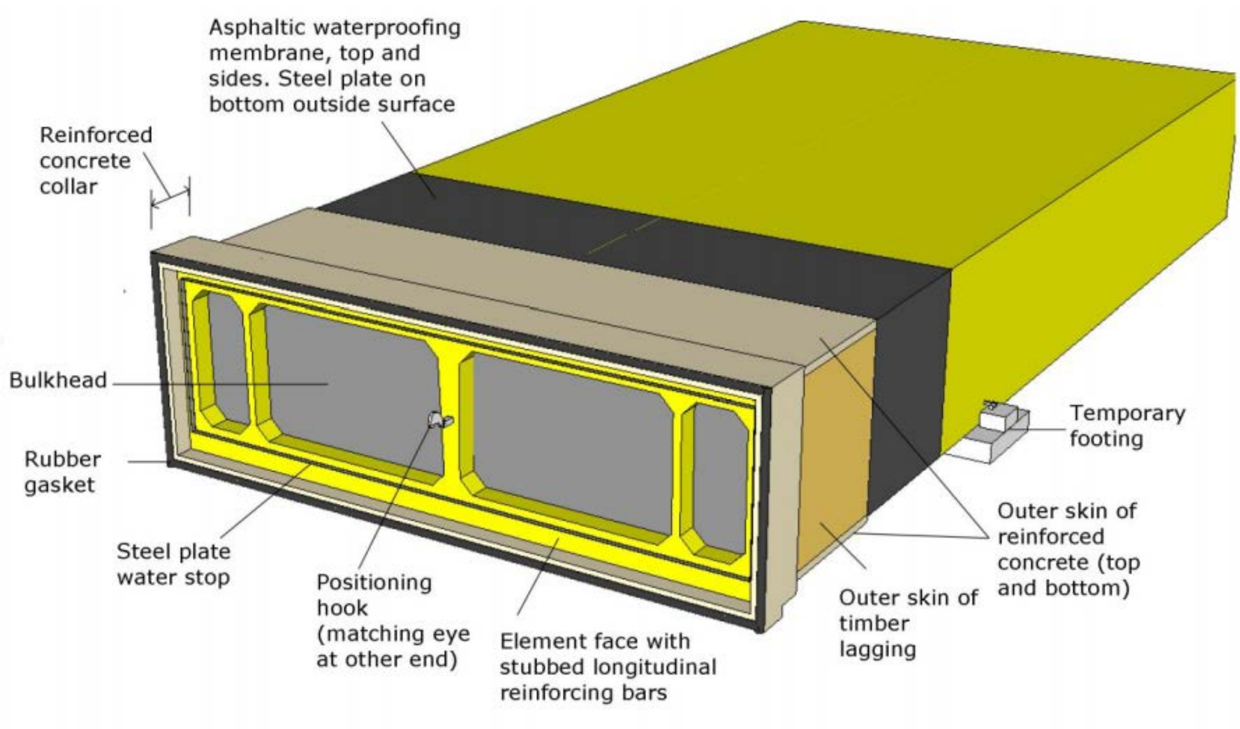


Figure AE-5 Tunnel waterproofing schematic[8].

[8] WSP | MMM Group (2017, February) *George Massey Tunnel Replacement Project –Tunnel Decommissioning Options* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2017/02/GMT-Tunnel-Decommisioning-Options-Feb-2017.pdf

After the elements were placed, the permanent joints were constructed between the ends of the elements:

- Steel plate was welded between the steel waterproofing membranes on each side to make the waterproofing membrane continuous across the joints;
- Lengths of rebar were welded to the rebar that had been left projecting at the ends of each element to make the rebar continuous;
- Concrete was cast into the gaps between the ends of the top slabs, the bottom slabs and all the walls to make the concrete core of the tunnel continuous across the joints; and
- The roadway ballast concrete was then installed, and the tunnel interior finishing completed.

Originally called the Deas Island Tunnel, the crossing was unofficially opened on Saturday, May 23,1959. Thousands of cars lined up to be amongst the first to go through; more than 136,000 cars used the tunnel on that first toll free opening weekend. Queen Elizabeth II officially opened the tunnel on July 16, 1959.

On September 26, 1969, the tunnel was officially renamed the “George Massey Tunnel” to honour the Ladner resident who had helped form the Lower Fraser Crossing Improvement Association and had been the proponent of a tunnel at the location for twenty years.

Appendix F Tunnel Seismic Retrofitting

George Massey Crossing

Tunnel Seismic Retrofitting

September 2018

WESTMAR ADVISORS

1 Introduction

This appendix supplements the Review by providing additional detailed information about the geotechnical investigative work and seismic retrofitting work that has been completed to date.

2 Geotechnical Conditions

As the new tunnel and retrofitting of the existing tunnel were not progressed to a full concept design, there was no additional geotechnical analysis completed to estimate the extent of soil liquefaction around these structures since the code requirements for design seismic event changed in the National Building Code of Canada in 2010 (NBCC 2010). To provide an opinion on the feasibility of either option the Review completed a concept level analyses to estimate the potential extent of liquefaction around these structures.

This following describes the history of the investigations and analysis of the geotechnical conditions at the Tunnel site, the reference information that was utilized by the Review, the analyses that were completed, the findings from the analyses, and further geotechnical work that could be undertaken if further studies related to tunnel options are completed.

2.1 Previous Site Investigations & Findings

A significant number of geotechnical site investigations have been completed at the Tunnel starting in 1956 for the original Tunnel and then in 1991, 2006, and 2103/2014. The details of these investigations are provided in the related reports.

The above geotechnical site investigation data indicate the following typical soil profiles:

- On the river banks, there is up to 4 metres (m) of river sand fill over floodplain silts extending up to 4 m depth underlain by post-glacial (Holocene) Fraser River sands and silty sands extending to the 20 to 32 m depth. These are followed by deep post-glacial marine sediments extending to approximately the 300 m depth followed by dense glacial deposits. Other geophysical test data provided by the Geological Survey of Canada in the Richmond and South Delta area indicates that bedrock is encountered at the 600 to 700 m depth.

- Within the river channel, post-glacial (Holocene) Fraser River sands and silty sands extend to 7 to 20 m depth below river bed. These are followed by deep post-glacial marine sediments extending to approximately 300 m depth, followed by dense glacial deposits and bedrock.

The Fraser River sand deposits are typically very loose to medium dense and consequently have a high susceptibility to seismically induced soil liquefaction. The post-glacial marine deposits consist of interlayered sands, silty sands and sandy silts with lenses of clayey silt. The cohesive silt/clay deposits are generally considered to be normally to lightly over-consolidated (normally consolidated deposits have never been subjected to vertical effective stresses greater than existing effective overburden pressures). The marine silts and clayey silts typically have moisture contents close to the liquid limit above approximately the 100 m depth. The sand and silty sand layers are loose to medium dense. The latter properties suggest seismic liquefaction potential to large depth, depending on the intensity and duration of seismic shaking.

2.2 Design Seismic Input Motions

The studies completed by Buckland & Taylor Ltd., now COWI North America, Ltd. (COWI), in the early 2000s used a relatively small suite of input seismic ground motions in the seismic modeling; representative of motions at the top of the dense glaciated deposits. Two shallow crustal earthquakes (with moment magnitude M7) and one offshore interplate subduction earthquake (magnitude M8.2) were selected for use. The crustal input motions (two orthogonal horizontal records were considered) were filtered and scaled to approximately match a target elastic response spectrum for dense soil deposits (Site Class C) at the site based on the probabilistic seismic hazard model adopted by the NBCC (2000). The subduction records were approximately matched to a target spectrum developed deterministically and considered a M8.2 earthquake at a closest distance of 120 km to the Tunnel site using an attenuation relationship proposed by Youngs et. al. (1997)[1].

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[1] Youngs, R.R., Chiou, S.-J., Silva, W.J., Humphrey, J.R. (1997). Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes. *Seismological Research Letters, 68 (1): 58-73*.

Seismic input ground motions used for the Project were based on the NBCC (2015) probabilistic hazard model considering a 1 in 2,475-year return period (RP) event. Target elastic response spectra were developed and a suite of seismic input motions for Site Class C soil conditions were filtered and scaled to approximately match the target spectrum[2]. Input motions representative of shallow crustal, deep inslab and long duration, offshore Cascadia subduction earthquakes were developed for various earthquake magnitude scenarios. The crustal and inslab design earthquakes were considered to have moment magnitudes typically in the range of M6 to M7.5 and the Cascadia subduction event to have a magnitude of up to M9.

It is noted that the target spectrum for the 1 in 475-year RP seismic event specified by the NBCC (2000) is very similar to that given by the NBCC (2015) for the shallow crustal and deep inslab earthquakes. The target spectrum is not similar for the Cascadia subduction earthquake event for structural periods in excess of 2 seconds.

The significantly higher amplitudes of input ground shaking for the 1 in 2,475-year RP event compared to the 1 in 475-year RP event indicates that greater depths of soil liquefaction than previously predicted could develop. In addition, the earlier COWI study did not consider potential soil liquefaction effects in the deeper marine silt and clayey silt deposits. Recent published test data on cyclic response of these low to non-plastic materials indicates they are also susceptible to transient liquefaction during shaking, depending on amplitudes and durations of shaking.

2.3 Estimated Soil Liquefaction Depths

The Review has made preliminary calculations of potential depths of soil liquefaction using cyclic shear stress demands versus the depths presented in the 2001 COWI study considering the influence of shallow crustal and deep inslab earthquakes. The cyclic shear stress demands were found by COWI to be higher compared to the influence of the offshore Cascadia subduction event. Seismic liquefaction triggering was evaluated using methods proposed by Idriss and Boulanger (2008, 2014)[3,4] for granular soils (e.g. the Fraser River sand and silty sand deposits) and based on available electronic cone penetration data in the river and along the river banks.

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[2] Golder Associates Ltd. (2016, March 7). *Earthquake Scenario Spectra and Acceleration Time-Histories 2,475-YR, 975-YR and 475-YR Return Periods, Massey Tunnel Replacement Project* [Memorandum].

[3] Idriss, I. M., and Boulanger, R. W. (2008). Soil liquefaction during earthquakes. *Monograph MNO-12, Earthquake Engineering Research Institute, Oakland, CA, 261 pp.*

[4] Idriss, I. M., and Boulanger, R. W. (2014). CPT and SPT Based Liquefaction Triggering Procedures. *Center for Geotechnical Modeling, Report No. UCD/CGM-14/01.*

This Review assessed that liquefaction over the full depth of the Fraser River sand deposits to about elevation -27 m (geodetic datum) should be expected for the 1 in 475-year RP event. Based on available cyclic laboratory test data presented by Sanin (2010) for low plasticity, normally to lightly over-consolidated Fraser River silt, it is considered that seismic liquefaction could occur in these materials to about 20 m depth below river bed (elevation -35 m geodetic datum) or about 13 m below the base of the deepest portion of the existing Tunnel. Liquefaction is also considered possible in thin sand seams within the deeper marine deposit to approximately 40 m below river bed, or about 33 m below the base of the deepest portion of the existing Tunnel.

The Review evaluated cyclic shear stress demand for the 1 in 2,475-year RP seismic event, again considering only the influence of crustal and deep inslab earthquakes, by scaling the cyclic shear stress demand for the 1 in 475-year RP event to represent higher peak ground accelerations versus depth for the 1 in 2,475-year RP event. The latter peak ground accelerations versus depth were estimated from SHAKE analyses carried out by EXP Services Inc. (2012)[5] for the South Fraser Perimeter Road Project, Highway 99 Interchange and considering crustal and deep inslab earthquake input motions. A soil profile and dynamic soil properties broadly similar to those for the Tunnel site were used in the EXP Services Inc. modeling.

Using the scaled shear stress demands versus depth for the 1 in 2,475-year RP event, liquefaction over the full depth of the upper Fraser River sand deposits and liquefaction in the deeper marine silt and clayey silt deposits to approximately the 50 m depth blow river bed (elevation -65 m) is estimated (or about 43 m below the base of the deepest portion of the existing Tunnel). Liquefaction in thin sand silty sand seams in the deeper marine deposit is also considered possible down to about 60 m depth below river bed (53 m below the base of the deepest portion of the existing Tunnel).

2.4 Key Seismic Geotechnical Issues for Immersed Tube Tunnels

The results of the COWI seismic geotechnical modeling carried out using both one dimensional (1D) (equivalent linear modeling using the program SHAKE-91) and two-dimensional (2D) seismic wave propagation modeling (considering nonlinear soil response and the program FLAC-2D) indicated the that several geotechnical issues are important to seismic response of the existing Tunnel or to another potential crossing of the river using ITT.

[5] EXP Services Inc. (2012, October 17). Geotechnical Design Memo No. 64 – Seismic Ground Response Analyses, Segment 2, Highway 99 Interchange, Rev. A [Memorandum].

These issues included the following:

- Liquefaction causing tunnel heave during shaking. This results from a reverse bearing capacity failure due to imbalanced vertical pressures over the width of the tunnel (higher pressures external to the tunnel, reduced pressure under the tunnel which is nearly buoyant). In other words, the liquefied soil and water mixture has a higher density than water and so the tunnel will tend to be pushed upwards much like a buoyant item will sit higher in mercury than it will in water.
- Soil reconsolidation following pore pressure dissipation after seismic shaking and resultant post-seismic differential settlement along the tunnel. The extent of differential settlements depends on soil variability, the depth of soil liquefaction and the intensity and duration of earthquake shaking. Given variability in soil types and depths of liquefaction over the tunnel, prediction of differential settlement is very difficult.
- Differential lateral ground movements along the length of the tunnel occurring during and after shaking. Prior to soil liquefaction, out of phase, travelling seismic wave effects should be considered but have relatively small amplitudes compared to the post soil liquefaction case. After liquefaction, lateral soil movements increase progressively during shaking and are increased if non-level river bed conditions (due to scour) exist.
- River bank flow movements causing axial loading on the tunnel and tunnel heave. River bank failures could also cause significant water ingress at the tunnel portals and could also result in large masses of soil flowing into the river and overtop of the tunnel.

The 2001 COWI study indicated that ground improvement (GI) should be considered to mitigate the above effects on the existing Tunnel. GI is a process whereby the foundation and related soils are modified to improve their design properties and capacities for various design conditions. There are wide range of different alternatives for GI that need to be evaluated based on specific site conditions and existing soil characteristics. A combination of vibro-replacement (stone columns) and gravel drains were proposed as a cost-effective GI solution. It is likely that some form of GI would be required to seismically retrofit the existing Tunnel or for other tunnel or bridge crossing options. GI technologies are advancing globally and should be surveyed before selecting a methodology.

2.5 Further Geotechnical Work Required

The above estimates of liquefaction depth should be confirmed by more detailed 1D or 2D nonlinear site response modeling which can take into account progressive soil softening during shaking and base isolation effects. A larger suite of input earthquake ground motions should be used than was previously considered by the 2001 COWI study.

The deep drill hole data available has provided basic soil property testing. However, no undisturbed tube samples of the deeper marine silts and clayey silts has been obtained. Therefore, additional drilling and sampling of these marine deposits is recommended in order to carry out cyclic laboratory testing on these materials and investigate their cyclic liquefaction behaviour.

Also, there may be some benefit in performing three dimensional (3D) seismic modeling of the existing Tunnel–soil interaction, including the effects of localized river bed slope (due to scour), considering the 1 in 2,475-year RP input ground motions and the previously conducted structural retrofit of the existing Tunnel. 3D effects may indicate a lessening of seismic demand on the Tunnel compared to 2D modeling and may permit refinements in seismic retrofit solutions, including the requirements for GI.

3 Concepts to Seismically Retrofit the Tunnel

3.1 Part 2 - Ground Improvement Retrofit

The *Part 2 - Ground Improvement Retrofit* consisted of densifying the granular soils and installing seismic drains along the sides of the tunnel and the approaches. Densification of the Fraser River sands and silty sand subsoils would be achieved by installing bottom feed vibro-replacement (stone columns) over a width of 10 m on each side of the tunnel within the river. The densified zone would extend about 6 m below the underside of the deepest part of the tunnel (i.e. to Elevation -27 m). A single row of seismic drains was to be installed on the outside edges of the densified zones within the river (see Figure AF-1). The plan also included varying widths of stone columns and two outer rows of seismic drains alongside the north and south ends of the tunnel closest to the river dike. Further inland, beyond the dyke, two to three rows of seismic drains were proposed.

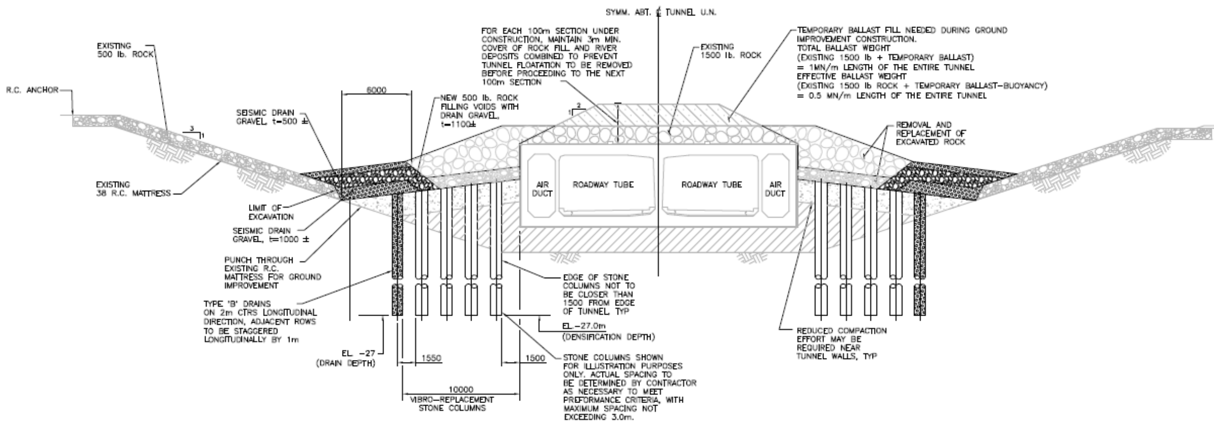

Figure AF-1 GMT geotechnical retrofit (ground improvement) – not constructed[6].

During the meeting with COWI at which the *Part 2 - Ground Improvement Retrofit* was discussed in detail, potential liquefaction in the marine silt/clay layer below the densified zone was identified as a potential deficiency that would have to be assessed in a future retrofit design.

3.2 The 2007 VE Recommendations

In 2007, the Province decided to undertake a VE study to determine if the *Part 2 - Ground Improvement Retrofit* proposed represented the most cost-effective solution to the project objectives. A team of experts in seismic design and densification, marine structural engineering, and investment risk analysis was assembled, and 22 VE concepts were generated for review; of these, eight were put forward to MoTI for further consideration[7].

The VE Study concluded that the GI design as prepared represented extensive, state-of-the-art analyses by a wide range of specialists and researchers. The VE study stated that, considering the importance of the tunnel to the Regional network and the uncertainty of the timing of a planned replacement, spending in the order of magnitude of the estimated cost of $25 million was justified. The VE team stated that it was limited in its ability to provide effective comments on risks and alternatives given the lack of an available analysis of the expected seismic performance of the tunnel as it existed at the time of the study, i.e. with the structural retrofit program completed but without the completion of the proposed GI program.

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[6] Buckland & Taylor Ltd. (2001, March 26). *George Massey Tunnel No. 1509 – Seismic Safety Retrofit and Rehabilitation - Project No. 11469-0001, Drawing No. 1509-133 Rev PA* [Drawing].

[7] EVM Project Services Limited. (2007, April 20). *Value Engineering Study - Project 11469-0002: George Massey Tunnel Seismic Densification* [Report]. Retrieved from https://engage.gov.bc.ca/app/uploads/sites/52/2016/04/2007-04-20_George_Massey_Tunnel_Seismic_Densification_VE_Report1.pdf

Eight value engineering concepts were put forward for further consideration:

- Investigate mass concrete buttresses;
- Investigate anchoring with large diameter pipe piles;
- Limit densification to joint locations;
- Accommodate structural movement with additional jointing;
- Eliminate densification in the middle third of river;
- Increase pumping capacity to meet expected water ingress;
- Allow proprietary drains; and/or
- Further strengthen the tunnel to withstand liquefaction.

The planned *Part 2 - Ground Improvement Retrofit* designed by COWI for the Tunnel was cancelled before the recommendations of the 2007 VE Study were formally considered.

3.3 Independently Developed Concept

The Review Team, for the purpose of further exploring the potential for continued use of the Tunnel, developed a concept to improve the seismic performance of the Tunnel in a 475-year event which addresses the risk of the installation of stone columns immediately adjacent to the Tunnel as well as the existence of deeper potentially liquefiable marine silt/clay layers below the Tunnel. The Review notes that the concept development was based on order of magnitude calculations and the detailed geotechnical analysis and computer modelling necessary to fully assess the feasibility has not been completed. In addition to confirming the feasibility additional design work would optimize the scope of the retrofit.

The preferred concept has similarities to one of the 2007 VE concepts, shown in Figure AF-2, but with additional components:

- Pipe piles driven along each side of the Tunnel;
- Removal of the ballast over the tunnel and installation of low profile steel beams and/or straps and precast concrete ballast over the Tunnel and secured to the piles;
- Scour protection rock installed on either side of the Tunnel; and
- Stone column GI installed along the sides of the Tunnel but with a clear distance of at least 15 m to the Tunnel to minimize potential tunnel settlements caused by stone column installation.

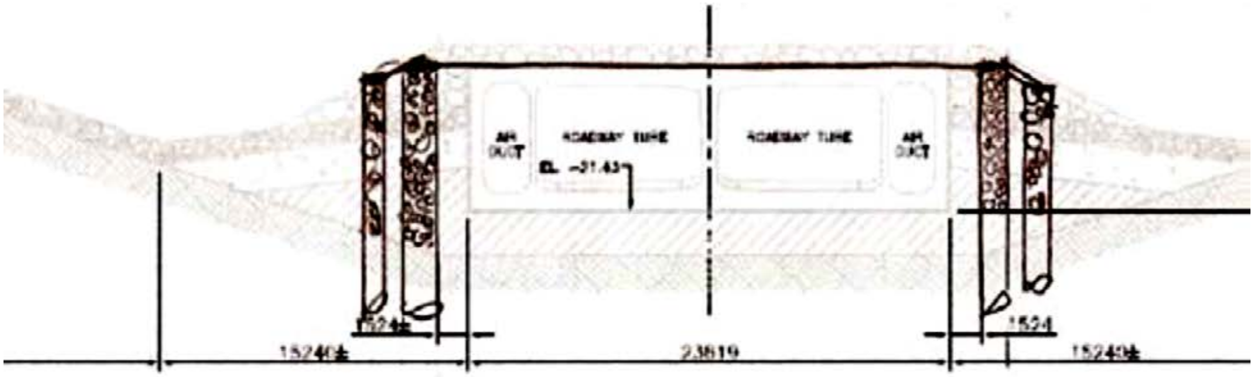

Figure AF-2 2007 VE Proposal 4, Anchor Tunnel with Large Diameter Piles[7].

The retrofit concept would work by preventing seismic displacement of the Tunnel as follows:

- The GI would create a barrier to reduce the volume of liquefied soil available to move towards the Tunnel, reducing the seismic heave as well as lateral forces.
- The rock ballast is replaced by a frame structure comprised of steel piles, steel beams/straps, and precast concrete ballast which would be designed to hold the Tunnel down in the event of net upward forces caused by seismic induced heave associated with liquefied soil.
- The concrete ballast would be attached to the steel cross beams rather than being fully supported on the tunnel roof. Therefore, after a small amount of post-seismic settlement, the tunnel roof would begin to lose contact with the concrete ballast effectively increasing the tunnel buoyancy. As the sand below the tunnel continues to settle, the tunnel would remain "floating" above the settled sand, held down by the piles and the cross beams. Voids under the tunnels floor could be later repaired by means of pressure grouting or jetted sand (as was done for the initial installation of the tunnel).
- The scour rock will keep the slopes flat on each side of the Tunnel, reducing the risk of lateral displacement.

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