Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 2, 2024
A Regional Conference of the Society for Industrial and Systems Engineering

Design of the Next Chesapeake Bay Crossing: An Opportunity for Energy Efficiency, Transportation Equity, and Carbon Reduction

Carolyn Vaseghi, Jose Zorrilla, Richard Collie, Fatima Alarcon, and Naif Al-Harbi

Department of Systems Engineering and Operations Research,
George Mason University,
Fairfax, VA 22030

Corresponding Author's Email: cvasegh@gmu.edu

Author Note: This work was conducted on behalf of the Anne Arundel Transportation Commission.

Abstract: The Chesapeake Bay Bridge is a vital crossing connecting Maryland's eastern and western shores. The bridge faces multiple challenges including traffic congestion and rising maintenance costs. These challenges provide an opportunity to design a better crossing to address issues of transportation equity, energy efficiency, and carbon reduction. Seven design alternatives were evaluated with estimated life-cycle costs ranging from $3.8B for a do-nothing alternative to $9.1B for a High-Speed Group Rapid Transit alternative. A multi-attribute utility function was developed to evaluate each design alternative by driving Level of Service (LOS), mass transit LOS, equity, energy efficiency, and CO2 production. A mode selection and Monte Carlo traffic simulation were developed to generate data for each design alternative's performance. The HSGRT alternative has the highest utility of 0.624 and costs $9.1B. An 8-lane tunnel has a utility of 0.403 and costs $6.6B. The 8-lane tunnel is recommended to balance cost with utility.

Keywords: Anne Arundel County Transportation Commission (AACTC), Bus Rapid Transit (BRT), High-Speed Group Rapid Transit (HSGRT), Maryland Transportation Authority (MDTA), Monte Carlo Simulation, Multi-Attribute Utility Analysis, National Environmental Policy Act (NEPA), Public Information Act (PIA)

1. Introduction

The Chesapeake Bay Bridge is a 5-lane, dual bridge span in corridor #7 of the Chesapeake Bay. It is a vital crossing connecting Maryland's eastern and western shores via US Route 50/301. This 4.3-mile-long bridge is located between two smaller bridges: Severn River Bridge to the west and Kent Narrows Bridge to the east.

But the current bridge faces several challenges. First, traffic demand, increasing at a rate of 1.3% annually (MDTA, 2015), has already exceeded bridge capacity, resulting in severe congestion. Vehicle traffic on the bridge alone produces 125,000 tons of CO2 per year. In addition, both bridge spans are over 50 years old and require major restorative maintenance to keep them safely operational. This will triple cumulative maintenance costs through 2065 (MDTA, 2023a). Finally, the current crossing does not incorporate fast, cost-effective mass transit for Maryland residents without access to a car. The average cost gap between driving from Washington DC to Ocean City, MD (a popular vacation destination on the eastern shore) and taking mass transit is $100. The average time gap is almost 4 hours.

Because of these problems with the current system, the Maryland Transportation Authority (MDTA) is funding a series of National Environmental Policy Act (NEPA) studies to evaluate design alternatives for a new crossing. In response, the Anne Arundel County Transportation Commission (AACTC) is sponsoring an independent study by George Mason University to corroborate the MDTA's results. The results of this study are summarized in this report.

2. Context Analysis

Many factors impact the Chesapeake Bay crossing context. The first is population. The DMV population is currently at 5.49 million and has been growing at a rate of 1.1% per year since 2019 (MacroTrends, 2023). On summer weekends, traffic demand across the Bay Bridge increases by 72% (MDTA, 2018). Traffic demand across the board is growing at a rate of 1.3% annually (MDTA, 2015) which aligns with the DMV population growth rate.

Environmental policy is another major factor in the bay crossing context. The Maryland Department of Energy (MDE) recently released a plan to cut state CO2 emissions in half by 2030 and reach net zero by 2045 (MDE, n.d.). According to the Environmental Protection Agency, an average passenger vehicle emits 4.7 metric tons per year (EPA, n.d.). Since CO2 composes 95-99% of all vehicle emissions (EPA, n.d.), including an electric mass transit system in the new Chesapeake Bay crossing system could help Maryland meet these ambitious emissions goal.

Transportation equity is another factor affecting the crossing system context. Current mass transit systems are limited to shuttles and buses. These bus routes are almost 4 hours slower than driving, because there is no dedicated bus lane. This means that low-income residents of Baltimore and Washington DC without access to a car are unable to reach the eastern shore for day trips. This inequitable access to the shore is becoming a concern among Maryland residents. At a Maryland Transit Administration (MTA) listening session on June 27, 2022, it was found that 89% of those in attendance wanted a new Chesapeake Bay crossing to provide a transit system (Donohue, et. al., 2023a).

Advances in electric mass transit and tunnel boring technology make a mass transit option more feasible. High-Speed Group Rapid Transit (HSGRT) is an emerging technology concept of fully automated, on-demand, rail transit. Individual pods are built on a Chevy Silverado base with a 10-passenger capacity. The battery-powered cars have a 400-mile range and an average speed exceeding 70mph (Donohue, G. et., al., 2023a). The proposed 140-mile route from the Washington DC metro to Ocean City includes 10 stops, achieving a travel time of approximately 120 minutes, as designed by the SYST 699 graduate design team (McCrum, et. al., 2022).

Improving tunnel boring technology makes tunnels faster and cheaper to construct than before. A 4.5-mi long, 60-ft diameter tunnel is estimated to cost $3.3B compared to the $5.4B the current suspension bridge cost (Donohue, et. al., 2023a). These technological advancements may influence the choice of design alternatives as life-cycle costs are compared. In light of the Francis Scott Key Bridge disaster, a tunnel design may also be a safer crossing alternative.

3. Stakeholder Analysis

Key Chesapeake Bay crossing stakeholders and their tensions are listed in Table 1. The primary stakeholder in the Chesapeake Bay crossing system is the MDTA which oversees the funding, construction, operation, and maintenance of critical Maryland infrastructure including the Chesapeake Bay crossing. The AACTC is a volunteer commission of Anne Arundel County residents that provides expertise on county transportation projects to the MDTA. The results of this project's analysis will be shared with the sponsor AACTC and then sent to MDTA for their review.

Table 1. Key Stakeholders and Stakeholder Tensions

Stakeholder	Description	Priorities	Tensions	Influence/Interest
MDTA	MD agency that oversees construction, operation, funding, and management of MD transportation systems	Revenue-neutrality, transit equity, congestion, safety	**EPA** - environmental regulations	High/High
AACTC	Volunteer transportation commission providing expertise to MDTA	Transit equity, congestion, bicycle/pedestrian access	**MDTA** - crossing design	Medium/High
Drivers	MD, VA, and DE commuters and vacationers	Congestion, toll price, reliability	**MDTA** - toll price	High/Medium
Commercial Shipping	Shipping companies that navigate through the Chesapeake Bay	Tunnel design	**Drive-Over Services** - bridge vs tunnel design	High/High
EPA	Federally appointed national agency developing and enforcing human health and environmental regulation	Environmental protection	**Construction/Contracting** - environmental regulations	High/High
Drive-Over Services	Driving service for people afraid to cross the Bay Bridge	Bridge design	**Commercial Shipping** - bridge vs tunnel design	High/Low
Bus/Shuttle Services	Local driving transit services that use the crossing system on transit routes	No new mass transit	**MDTA** - transit equity	High/Low
Construction/ Contracting	Construction companies contracted to build/maintain the crossing system	Maintainability	**MDTA** - funding	Medium/Low

4. As-Is Process & Performance Gaps

The as-is use cases for the Chesapeake Bay Bridge are shown in Table 2. The primary use cases include driving or taking mass transit over the crossing as well as emergency services, vehicle failure, and law enforcement scenarios. Each use case was evaluated based on time, cost, and quality to find performance gaps with the current crossing.

Multiple performance gaps were identified in this analysis. In the primary use case of driving across the bridge, the Level of Service (LOS) consistently falls below the desired threshold of C. LOS is a qualitative measure of congestion based on the number of vehicles/lane/hour. LOS is represented by a letter grade ranging from A to F. The worst LOS on the Bay Bridge occurs during peak-season weekends, resulting in a capacity gap of 1553 vehicles/lane/hour (Donohue, et. al., 2023b). For the transit use case, there is a cost gap of $100 and a time gap of 4 hours between taking mass transit and driving from

ISBN: 97819384962-4-0

Washington DC to Ocean City, MD (Donohue, et. al., 2023b). There are also safety performance gaps in the as-is process because there are no shoulders on the bridge. If a vehicle fails, if there is an accident, or if a policeman needs to pull a vehicle over, there is no safe place to get to the side of the road.

Table 2. As-Is Use Cases

ID	Use Case	Type	ID	Use Case	Type
1	Driving	Primary	7	Maintenance	Ancillary
2	Taking Transit	Primary	8	Safety Inspection	Ancillary
3	Emergency Response	Primary	9	Weather Safety Response	Ancillary
4	Vehicle Failure	Primary	10	Shipping Passage	Ancillary
5	Law Enforcement	Primary	11	Contraflow	Nested
6	Toll Collection	Nested	12	Public Event	Ancillary

Other use cases like maintenance and safety inspections suffer from the absence of maintenance access paths (MDTA, 2023a). The narrow lanes on the bridge also fail current FHWA lane width regulations (FHWA, 2023). Weather safety concerns arise due to the lack of protection on the bridge against high winds (MDTA, 2023d). Bicyclists and pedestrians also lack a dedicated lane to cross the bridge. Finally, there is a cost gap of $1.3 billion between current toll revenue and projected bridge maintenance costs from 2023 to 2065 (Donohue, et. al., 2023b).

5. Need Statement

There is a need for a redesigned Chesapeake Bay crossing system to address these performance gaps. Expanding crossing capacity by 1553 vehicles/lane/hour is necessary to maintain acceptable Levels of Service (LOS) during peak traffic scenarios. There is also a need for mass transit across the bay that is comparable in average cost and time to driving. The system needs to prioritize emergency response efficiency by incorporating dedicated shoulders (Donohue, et. al., 2023b). Infrastructure upgrades including wider lanes to meet current safety standards and protection against adverse weather conditions, are needed to provide a safe Chesapeake Bay crossing (MDTA, 2023a; FWHA, n.d.; MDTA, 2023d). Inclusion of biking/walking paths would improve crossing appeal to local and visiting bicyclists and pedestrians. Finally, to achieve revenue neutrality by 2065, toll revenues must increase, or maintenance costs must decrease by $1.3 billion (MDTA, 2023a; MDTA 2023b).

6. Concept of Operations & Mission Requirements

All use cases for the new crossing are the same as the as-is process use cases for the current crossing with the addition of two new use cases: biking and walking. Although all other use cases carry forward to the CONOPS, the implementation of each use case will change to address the performance gaps. Based on the performance gaps and stakeholder input, five mission requirements for a new crossing system were distilled.

MR.1: The crossing system shall achieve a driving LOS of C or higher at all times and in both travel directions.
MR.2: The crossing system shall achieve a transit LOS of B or higher at all times and in both travel directions.
MR.3: The crossing system shall achieve a proportional equity rating of 0.1 (10% of travelers switch to mass transit).
MR.4: The crossing system shall produce annual CO_2 emissions of no more than 113,000 tons/year.
MR.5: The crossing system shall achieve an energy efficiency of 1.3 kW/passenger-mile.

7. System Design

7.1 Utility Function

The system mission requirements are translated into the utility function shown below in (1) where $x_1 =$ driving LOS (vehicles/lane/hour), $x_2 =$ mass transit LOS (passengers/lane/hour), $x_3 =$ crossing equity (percent of drivers that switch to mass

ISBN: 97819384962-4-0

transit), $x_4 =$ energy efficiency (kW/passenger-mile), and $x_5 =$ CO2 production (tons/year). This function will be used to evaluate the utility of each crossing design alternative. The weights for each utility function parameter were elicited using Analytical Hierarchy Process (AHP) on input from Virginia and Maryland drivers.

$$u(x) = 0.26\,x_1 + 0.12\,x_2 + 0.17\,x_3 + 0.20\,(1 - x_1) + 0.26\,(1 - x_5) \tag{1}$$

7.2 Design Alternatives

Seven crossing alternatives were selected for evaluation in this study based on the as-is performance gaps and stakeholder input. The description and estimated cost of each are outlined in Table 3. Option 1, keeping the current, 5-lane dual bridge structure, is the baseline to compare other alternatives against. Option 2 and 3 are both 8-lane, drive-only alternatives. Option 4 and 5 are both Bus Rapid Transit (BRT) mass transit alternatives with 6 driving lanes. Option 6 is a 7-lane drive-only alternative which would keep the original westbound bridge span operational and expand crossing capacity with an additional 4-lane tunnel. Option 7 is the same as Option 6 but with the addition of HSGRT mass transit. Each design alternative will be evaluated through a traffic simulation against the mission requirements via a utility function.

Table 3. Design Alternatives

Option	Build Type	New Driving Lanes	Existing Driving Lanes	Total Driving Lanes	Mass Transit	LC Cost (2023$)
1	Bridge	0	5	5	None	$3.8B
2	Bridge	8	0	8	None	$7.7B
3	Tunnel	8	0	8	None	$6.6B
4	Bridge	6	0	6	BRT	$9.7B
5	Tunnel	6	0	6	BRT	$8.6B
6	Tunnel	4	3	7	None	$5.6B
7	Tunnel	4	3	7	HSGRT	$9.1B

7.3 Traffic Simulation Design

High-level simulation design is illustrated in Figure 1. The input is hourly traffic demand. Traffic demand is based on MDTA traffic data collected from a Public Information Act (PIA) request. The hourly traffic demand data was sampled from a random peak-season (summer) weekend and an off-season (non-summer) weekday from 2018-2023. This demand is fed into the mode-switching model which divides it into driving demand and mass transit demand. These two sets of hourly traffic demand are inputs of the traffic simulation. This simulation outputs traffic demand satisfied.

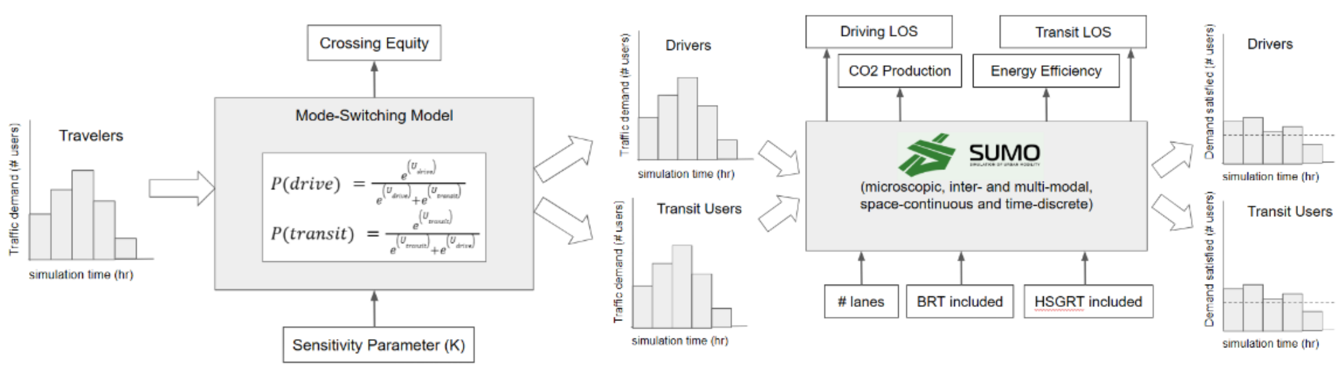

Figure 1. High-Level Simulation Design

The mode-switching model is two multinomial logit models based on a similar model in a peer-reviewed paper by Forinash and Koppelman (1993). One model simulates choices between driving and taking BRT. The other simulates choices between driving and taking HSGRT. The implemented model begins by generating a trip purpose according to probabilities based on historical vehicle crossing data (MDTA, 2023b). If the purpose of the trip is commercial, the user will drive. If the trip is commercial, the user will drive. Otherwise, the utility of each transportation alternative is calculated for that user. These utilities are used to generate the probabilities by which the user will choose either driving or taking mass transit. This mode choice process is run for each instance of traffic demand generated from the hourly traffic data to sort those instances into driving and transit traffic demand.

The driving and mass transit demand are the inputs to the traffic simulation, which is built in SUMO (Simulation of Urban Mobility). SUMO is a python-based, open-source simulation tool. The simulation scope included the Bay Bridge and the 12 interchanges spanning 15.2 miles from Severn River Bridge to Kent Narrows bridge.

The traffic simulation was run as a Monte Carlo simulation. Each design alternative was simulated under both traffic scenarios (peak weekend and off-season weekday) for three reps (six reps total). Each simulation rep was 24 simulation hours long. All design alternatives were simulated with expected 2040 traffic demand including the 5-lane bridge baseline. However, design alternatives 2 and 3 are equivalent from a traffic perspective, so they were simulated as one alternative. The same is true for alternatives 4 and 5 whose mode-switching proportions were set to 0.01 (1% of travelers use BRT). The proportion for Option 7 was set to 0.04 (4% of travelers use HSGRT) according to the mode-switching model output.

7.4 Verification

The mode switching model was verified by running it with expected 2040 levels of traffic demand. The model output (proportion of users driving vs. taking mass transit) was then compared to the analytical mode-switching calculations. The simulation output exactly matched the expected outcome. The traffic simulation was tested with 2023 traffic demand data for 10am, 2pm, 6pm, and 10pm. The number of vehicles generated was compared to the input data range. All outputs were within one sigma of the expected range.

7.5 Results

All utility function values are derived from normalized simulation output for each alternative. The HSGRT alternative (Option 7) has the highest utility of 0.624 because it ranks highest in equity, energy efficiency, and carbon reduction. Both BRT alternatives (Options 4 and 5) have the next highest utility of 0.426 also due to equity, energy efficiency, and carbon reduction. However, both 8-lane alternatives (Options 2 and 3) have a very similar utility to the BRT alternatives at 0.403 because they have the best driving LOS of any design alternative. The 7-lane alternative (Option 6) is far below all other alternatives at 0.215 because it does not improve equity, energy efficiency, or carbon emissions and it has poor driving LOS. The do-nothing alternative has a baseline utility of 0. The utility of each design option is plotted over its estimated life-cycle cost in Figure 2.

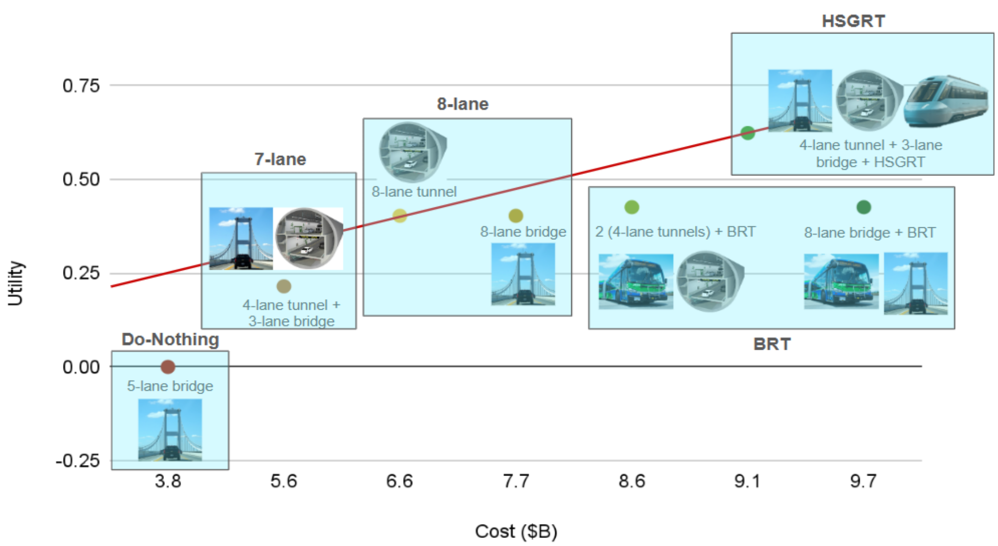

Figure 2. Utility vs. Cost Results for Design Alternatives

ISBN: 97819384962-4-0

Alternatives on the red line are optimal. All other alternatives are dominated. The Option 7 (HSGRT) has the highest utility, but also one of the highest costs. Option 3 (8-lane tunnel) has lower utility but is almost $3 billion cheaper. This represents a marginal utility of 0.09 meaning that little utility is gained from the additional cost of HSGRT. Since marginal utility is so low and since Option 3 is compatible with future HSGRT implementation, Option 3 (an 8-lane tunnel design) is recommended.

8. Conclusion

Based on the utility and cost analysis, Option 7 (2 lanes of HSGRT and 7 lanes of driving traffic) and Option 3 (8-lane tunnel) are the best alternatives to the current 5-lane bridge. However, since Option 3 is still compatible with more advanced mass transit and is significantly less expensive than Option 7, it is the recommended alternative from this study.

According to a sensitivity analysis, if the utility function attributes relating to equity, energy efficiency, and carbon emissions were weighted lower, the 8-lane design alternative would be the clear best solution. If those same attributes are weighted higher, then Option 7 would become the recommended alternative.

Project next steps include sharing these findings with the AACTC. Upon receiving approval from AACTC, these findings will be shared with MDTA and finally to the Maryland governor to help inform the final design decision.

9. References

Donohue, G., et. al. (2023a). *Ultra-Light Rail Transport (ULRT) from WDC Metro to Atlantic Ocean Cities via a New Chesapeake Bay Tunnel.* [Unpublished TRB Review Committee Proposal]. George Mason University.

Donohue, G., et. al. (2023b) *Bay Crossing Study PDR EXECUTIVE Summary.* [Unpublished executive summary]. George Mason University.

Environmental Protection Agency. (n.d.) *What is the National Environmental Policy Act?* Retrieved November 23, 2023, from EPA: https://www.epa.gov/nepa/what-national-environmental-policy-act

Federal Highway Administration (n.d.) *Lane Width.* Retrieved November 25, 2023, from U.S. Department of Transportation: https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_lanewidth.cfm.

Forinash, C. V, & Koppelman, F. S. (1993). Application and Interpretation of Nested Logit Models of Intercity Mode Choice. *Transportation Research Record*, 1413, 98-106.

MacroTrends (1950-2024). *Washington DC Metro Area Population.* Retrieved 2023, from Macro Trends: https://www.macrotrends.net/cities/23174/washington-dc/population.

Maryland Department of Environment. (n.d.). *Maryland releases bold new plan to achieve climate goals.* Retrieved November 22, 2023, from maryland.gov: https://news.maryland.gov/mde/2021/02/19/maryland-releases-bold-new-plan-to-achieve-climate-goals/

Maryland Transportation Authority (2015). *US 50/301 PRESTON LANE JR. MEMORIAL (BAY) BRIDGE, LIFE CYCLE COST ANALYSIS.* Retrieved 2023, from maryland.gov: https://mdta.maryland.gov/sites/default/files/Files/blogs/Bay_Bridge_LCCA_Report_12-2015.pdf

Maryland Transportation Authority (2018). *Traffic Volumes*. Retrieved 2023, from Chesapeake Bay Crossing Study Tier 1 NEPA: https://www.baycrossingstudy.com/images/public_meetings/2018-05/displays/BCS_Spring_2018_Displays_-_11_Traffic_Volumes.pdf

Maryland Transportation Authority (2023a). *Chesapeake Bay Crossing Study Tier 2 NEPA.* Retrieved 2023, from maryland.gov: https://mdta.maryland.gov/sites/default/files/Files/BayCrossingStudies/BCS%20Boards%202023_rd25.pdf

Maryland Transportation Authority (2023b). *Emergency Closures.* Retrieved November 27, 2023, from maryland.gov: https://baybridge.maryland.gov/emergency-closures.

McCrum K., et. al. (2022). *The Next Chesapeake Bay Crossing: An Opportunity for Energy Efficiency, Transportation Equity, and Carbon Reduction.* [Unpublished master's thesis]. George Mason University.