BL OR SV **Capacity and Reliability Study**

Alternatives Evaluation Report

January 2021

WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY

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EXECUTIVE SUMMARY

The Washington Metropolitan Area Transit Authority (Metro) launched the Blue, Orange, and Silver Corridor Capacity and Reliability Study (BOS Study, The Study) in 2019 to identify and evaluate potential solutions to several serious and long-standing challenges impacting transit service in the shared corridor, including:

- Passenger crowding,
- Capacity limitations,
- Issues with reliability and on-time performance,
- Lack of operational flexibility, and
- Furthering Metro's sustainability and equity goals.

Study Process

As shown in

Figure ES-1 below, the study process actively engages stakeholders and the public to identify the study's Purpose and Need, develop and evaluate alternatives to improve transit services in the corridor, and recommend a preferred alternative for review and approval by the WMATA Board of Directors. The report summarizes the results of the cost-benefit analysis (CBA) which will be used as a basis for identifying a Locally Preferred Alternative (LPA) for the BOS corridor.

Figure ES-1: BOS study process.

Alternatives Considered

Input from stakeholders, policymakers, and the public helped develop potential alternatives to address issues and six alternatives were selected for more detailed study. **Figure ES-2** shows the alternatives evaluated and **Table ES-1** briefly describes them. Full descriptions and more detailed maps of these alternatives are shown in section 2.0 Alternatives Evaluated.

Figure ES-2: Alternative maps.

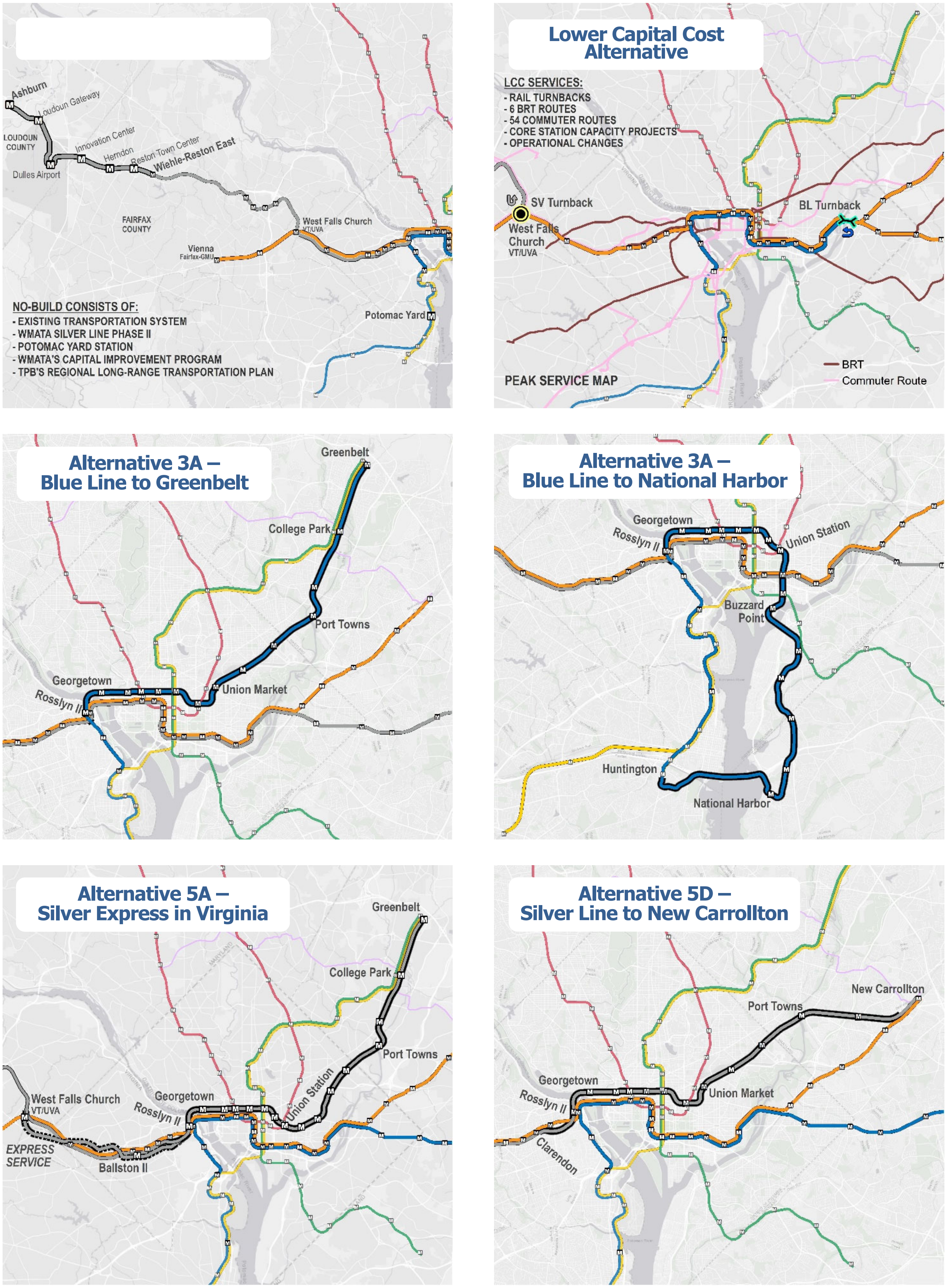


Table ES-1: Alternative descriptions.

Alternative	Description
No-Build Alternative	The baseline for comparison of all other alternatives. Includes all transportation investments planned and programmed to be funded by the region, as listed in the *Visualize 2045 Regional Long-Range Transportation Plan* and Metro's FY 2021-2026 Capital Improvement Program (CIP).
Lower Capital Cost Alternative	A lower cost option—compared to the four rail build alternatives below—including bus rapid transit (BRT) and commuter bus services, targeted rail capital investments, and operational strategies.
Alternative 3A – Blue Line to Greenbelt	A realignment of the Blue Line to serve new stations in downtown before heading northeast to Greenbelt.
Alternative 3C – Blue Line to National Harbor	A realignment of the Blue Line to serve new stations in downtown before heading south to Navy Yard and National Harbor before crossing over the Potomac River to Alexandria.
Alternative 5A – Silver Line Express in Virginia	The addition of a Silver Express line from West Falls Church to Rosslyn plus new stations in downtown. This alignment then heads northeast to Greenbelt.
Alternative 5D – Silver Line to New Carrollton	A realignment of the Silver Line to serve new stations in downtown before heading east to New Carrollton.

Ridership, Revenue, and Cost

Table ES-2 shows the forecast increase in ridership, revenue, net new operating cost, and total capital cost compared to the No-Build Alternative. Net new operating costs equal the new operating costs required for that alternative minus the fare revenue generated by it. While Alternative 3C – Blue Line to National Harbor includes the second highest capital costs, it performs better than the other alternatives in terms of maximizing increases in annual ridership and revenue and minimizes the increase in net operating costs.

Table ES-2: Forecast ridership, revenue, and costs compared to the No-Build Alternative.

Alternative	Annual New Ridership (2040 Linked Trips)	Annual New Revenue (2020 $)	Net New Annual Operating Cost (2020 $)	Total Capital Cost (2020 $)
Lower Capital Cost	4.6 M	$34.0 M	$44.1 M	$2.6 B
3A – BL to Greenbelt	26.4 M	$79.2 M	$27.4 M	$16.5 B
3C – BL to National Harbor	51.5 M	$154.2 M	$22.2 M	$22.2 B
5A – SV Express in Virginia	39.9 M	$119.4 M	$45.9 M	$23.8 B
5D – SV to New Carrollton	26.9 M	$80.4 M	$35.2 M	$18.6 B

Colors indicate lower performance → higher

Cost Benefit Analysis Results

The six alternatives were subjected to a performance assessment and CBA. The purpose of the evaluation was to assess the relative benefits and cost-effectiveness of each alternative compared to the baseline future outcomes represented by the No-Build Alternative. The CBA was structured around 14 performance measures (see section 3.0) that are directly linked to the four BOS corridor goals established by the study's Purpose and Need Statement developed with public and stakeholder input:

Key findings of the CBA are described below. These findings are based on the results of detailed analyses presented in sections 4.0 through 8.0.

Capacity and Crowding

Alternatives 3A – Blue Line to Greenbelt, 3C – Blue Line to National Harbor, and the Lower Capital Cost Alternative perform best at providing the optimal capacity necessary to efficiently meet the projected peak-hour passenger demand by the year 2040. All of the build alternatives provide an improvement over the No-Build Alternative, and each of the rail build alternatives would provide additional new capacity that would accommodate continuing ridership growth for the Metrorail System beyond 2040.

Reliability

Alternative 5D – Silver Line to New Carrollton generally performs best in terms of headway adherence and minimizing passenger travel times. However, Alternatives 3A – Blue Line to Greenbelt and 3C – Blue Line to National Harbor perform the best in terms of minimizing average delay experienced on trips.

Flexibility and Efficiency

Alternative 3C – Blue Line to National Harbor performs best in terms of minimizing annual operating costs on a per mile basis. Alternative 5D – Silver Line to New Carrollton performs best in terms of providing redundancy in the system so that passengers may choose an alternative route to avoid delays due to incidents and scheduled maintenance activities that require single-tracking. The Lower Capital Cost Alternative, with its emphasis on the addition of pocket tracks on the existing system, maximizes the potential to short-turn trains to better match service levels and demand at the ends of the Metrorail lines.

Sustainability and Equity

Alternative 3C – Blue Line to National Harbor performs the best in terms of providing new access to high-capacity transit for the greatest number of people living in Equity Emphasis Areas (EEAs). This alternative also provides access to the greatest number of jobs within a 45-minute travel time for EEA residents. Alternative 3C – Blue Line to National Harbor also provides the greatest potential increase in percentage of peak-hour work trips using transit.

Overall Results

Overall results of the CBA are shown in **Figure ES-3** and **Figure ES-3**: Performance of alternatives.

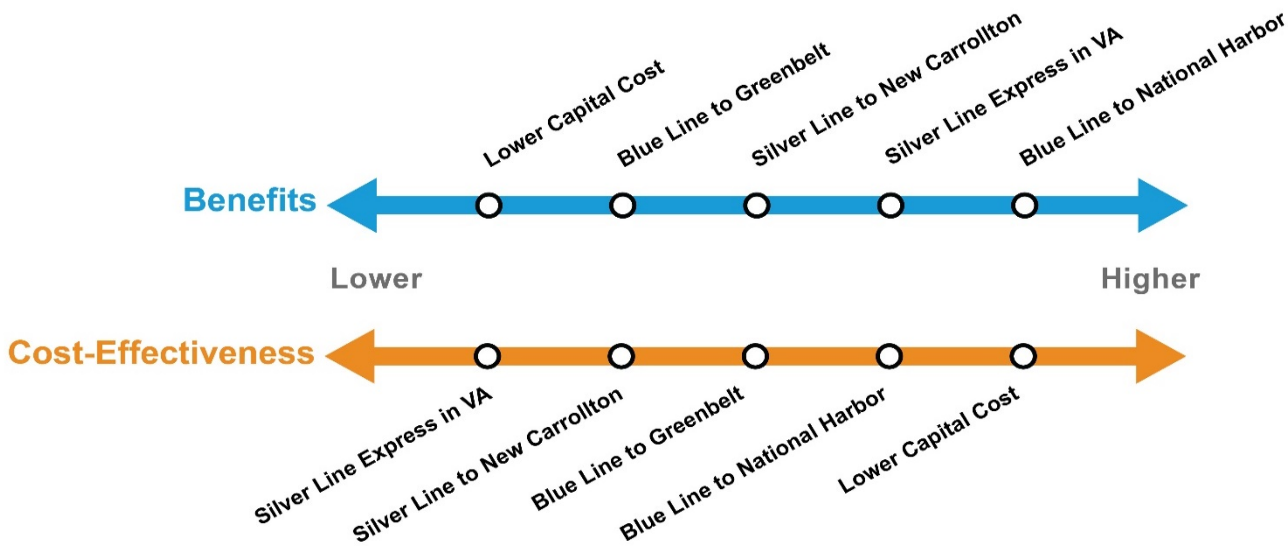


Table ES-3. These results are those stemming from the stakeholder weighting exercise described in section 4.3 Stakeholder Weighting Process. Benefits scores indicate how much improvement an alternative will likely produce regardless of cost, while Cost-Effectiveness scores indicate the magnitude of benefits produced per dollar spent. Alternative 3C – Blue Line to National Harbor would deliver the highest level of benefits above and beyond the No-Build Alternative, while the Lower Capital Cost Alternative would provide the lowest level of benefits. However, when costs are factored in, the Lower Capital Cost Alternative emerges as the most cost-effective, while Alternative 3C – Blue Line to National Harbor is the second most cost-effective option. However, the Lower Capital Cost Alternative's success depends on thousands of peak hour riders shifting from rail to bus service to relieve crowding on Metrorail.

Full results from the CBA are available in section 4.0 Evaluation of Benefits and Cost-Effectiveness, and are further categorized and described by goal in sections 5.0 through 8.0.

Figure ES-3: Performance of alternatives.

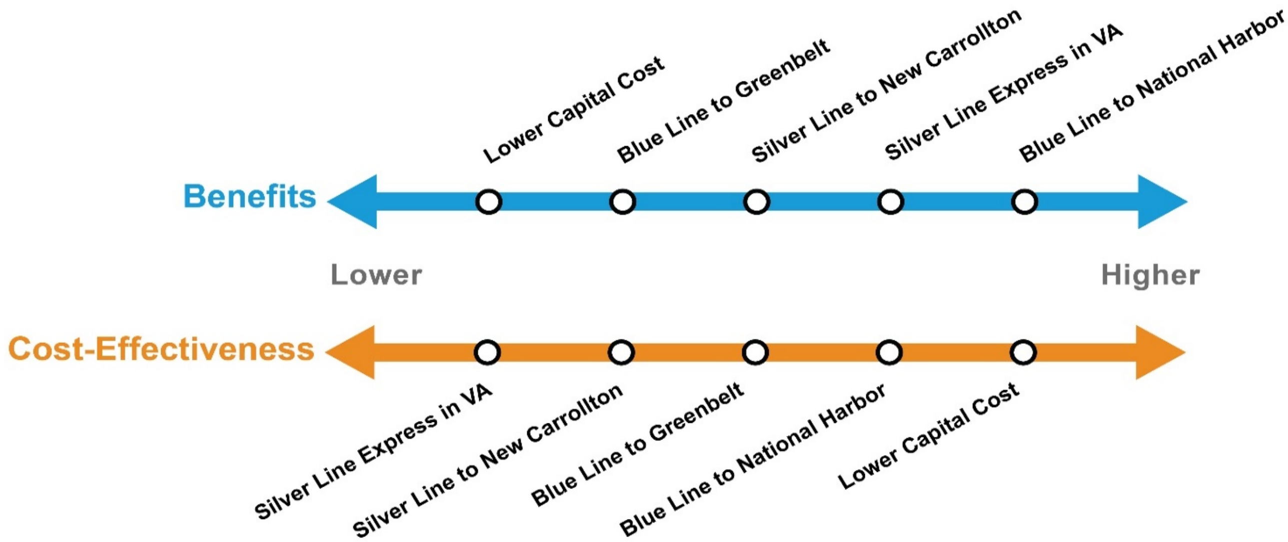


Table ES-3: Weighted benefits and cost-effectiveness scores and ranks (ordered from most to least benefits).

Alternative	Benefits score	Rank	CE score	CE rank
Alternative 3C – BL to National Harbor	43	1	75	2
Alternative 5A – SV Express in Virginia	37	2	59	5
Alternative 5D – SV to New Carrollton	34	3	65	4
Alternative 3A – BL to Greenbelt	29	4	68	3
Lower Capital Cost Alternative	13	5	87	1

Colors indicate lower performance ☐→ higher ☐

Next Steps

Following a third round of public and stakeholder engagement in early 2022, the results of this CBA will support Metro's Board of Directors in selecting a Locally Preferred Alternative (LPA) to advance into environmental planning and project development.

1.0 INTRODUCTION

The Washington Metropolitan Area Transit Authority (Metro) launched the Blue, Orange, and Silver Corridor Capacity and Reliability Study (BOS Study, The Study) in 2019 to identify and evaluate potential solutions to several serious and long-standing challenges impacting transit service in the shared corridor, including:

- Passenger crowding,
- Capacity limitations,
- Issues with reliability and on-time performance,
- Lack of operational flexibility, and
- Need to further Metro's sustainability and equity goals.

Six alternatives were selected for more detailed study (see section 2.0 Alternatives Evaluated) and a full cost-benefit analysis (CBA). Metro combined intensive data analysis and needs identification with robust stakeholder and public input to first identify a full 'universe' of over 275 potential options, then applied a screening process to further narrow those options to the six alternatives described in this report. The identification of initial options and the alternatives screening process are detailed in the separate report titled: *BOS Alternative Concepts Screening Process*.

The six current alternatives were then subjected to a performance assessment and CBA. The purpose was to assess the relative benefits and cost-effectiveness of each alternative compared to the baseline future outcomes represented by the No-Build Alternative. The CBA was structured around 14 performance measures (see section 3.0) that are directly linked to the four BOS corridor goals established by the study's Purpose and Need Statement developed with public and stakeholder input:

1. Provide sufficient rail capacity to serve ridership demand.
2. Improve reliability and on-time performance.
3. Improve operational flexibility and cost-efficiency.
4. Provide transportation options that support sustainable development and expand access to opportunity.

In addition to alignment with the four goals, the performance measures had to be capable of being forecasted and quantified in the analysis year of 2040 with available data and tools. Therefore, common customer service measures like customer on-time performance could not be used.

Following a third round of public and stakeholder engagement in early 2022, the results of this CBA will support Metro's Board of Directors in selecting a Locally Preferred Alternative (LPA) to advance into environmental planning and project development.

2.0 ALTERNATIVES EVALUATED

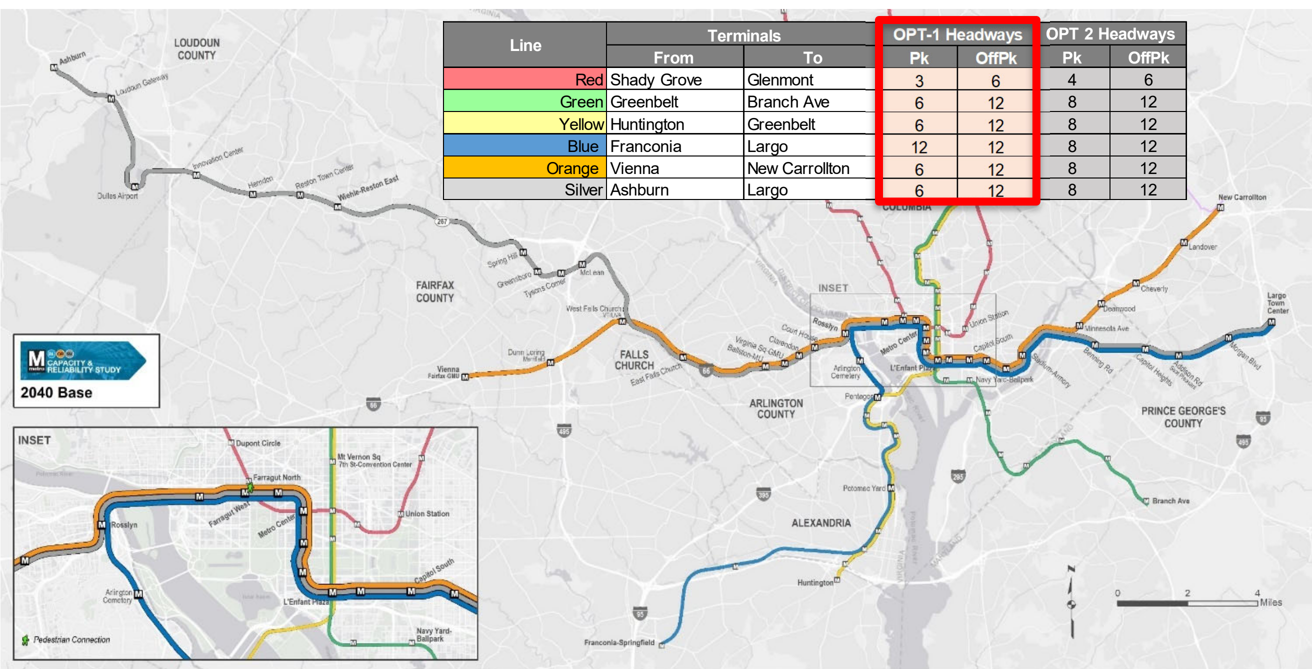
This section reviews the six alternatives evaluated as part of the CBA/performance assessment, starting with a No-Build Alternative that sets a baseline future for comparing and contrasting the other alternatives.

No-Build Alternative

The study considers a No-Build Alternative, which essentially measures whether land use changes and transportation investments that are already planned and funded are sufficient to meet the four goals and identified Purpose and Need for transit in the BOS corridor. This includes the regional land use and population forecasts provided by the region's jurisdictions and approved by the Metropolitan Washington Council of Governments (MWCOG), in this case Cooperative Forecasts Round 9.1. The No-Build Alternative also includes all transportation investments planned and programmed for funding by the region, as listed in the *Visualize 2045 Regional Long-Range Transportation Plan* and Metro's FY 2021-2026 Capital Improvement Program (CIP). The No-Build Alternative includes the existing rail and bus network plus completion of Silver Line Phase 2, the Potomac Yard Metrorail Station, and all of the State-of-Good-Repair and modernization projects included in Metro's CIP. It also includes jurisdictional transit projects such as the State of Maryland's Purple Line light rail and various bus rapid transit (BRT) lines.

While the No-Build Alternative was modeled with two headway options, all results are based on the Option 1 headways shown in **Figure 2-1**. This was considered the most likely scenario for 2040. See Appendix D: Operating Scenarios and Impacts Assessment for details on these two options.

Figure 2-1: No-Build Alternative and assumed headways.



Line	Terminals		OPT-1 Headways		OPT 2 Headways	
	From	To	Pk	OffPk	Pk	OffPk
Red	Shady Grove	Glenmont	3	6	4	6
Green	Greenbelt	Branch Ave	6	12	8	12
Yellow	Huntington	Greenbelt	6	12	8	12
Blue	Franconia	Largo	12	12	8	12
Orange	Vienna	New Carrollton	6	12	8	12
Silver	Ashburn	Largo	6	12	8	12

Because it represents the future transportation network as it is planned and funded today, the No-Build Alternative was used as the baseline from which to compare the potential benefits and costs of the other alternatives. Those other alternatives include the Lower Capital Cost (LCC) Alternative and four potential realignments and extensions of Metrorail lines.

Lower Capital Cost Alternative

The Lower Capital Cost Alternative attempts to attain the four BOS corridor goals at a lower cost than the rail build alternatives. It includes a network of enhanced commuter and BRT services, targeted rail capital investments, and operational strategies. The Lower Capital Cost Alternative includes the following components, which are described in detail in a separate report titled *BOS Study: Lower Capital Cost Alternative*:

- Enhanced bus service (6 bus rapid transit lines and 54 commuter routes – see **Figure 2-2**)
- Rail operations strategies: these include scheduling service to more accurately reflect varying run times during the day and to reduce conflicts at junctions, which will reduce delay and increase schedule/headway adherence.
- New or improved rail junction infrastructure (crossovers and pocket tracks) at West Falls Church and the D&G Junction – see **Figure 2-3**): this infrastructure will allow operational flexibility for short turns and other service options that focus capacity where it is most needed. Pocket tracks can be used to deploy variable service patterns; to reduce the geographic extent and customer impacts of single-tracking events; to remove malfunctioning trains from revenue service tracks; and to insert relief trains in order to recover scheduled service during disruptions.
- Potential railcar passenger carrying capacity enhancements: changes—such as open gangways or flip-up seats—to railcars to increase standing area so more passengers can be carried at peak load times.
- Core station capacity improvements: improvements to increase station capacity at Ballston, Farragut West, Metro Center, and L'Enfant Plaza.
- Customer convenience-focused enhancements: improved real-time messaging related to delays and alternative routing to allow passengers to avoid delays.

The enhanced bus network was designed to be capable of attaining the corridor's capacity goal by reducing peak-period crowding on the BOS rail lines. It could do so by providing adequate bus capacity for the number of peak-hour customers that would need to be diverted from the BOS lines, by providing an attractive transit alternative that offers direct connections between major BOS origin-destination points with bus prioritization strategies. This alternative is designed to meet the minimum BOS capacity and crowding needs in 2040, but would create no new rail capacity; requires substantial jurisdictional investments in bus prioritization infrastructure; and would rely on thousands of peak-period rail customers voluntarily shifting to competitive bus services.

Figure 2-2: Bus routes included in the Lower Capital Cost Alternative.

BRT routes originating in Virginia

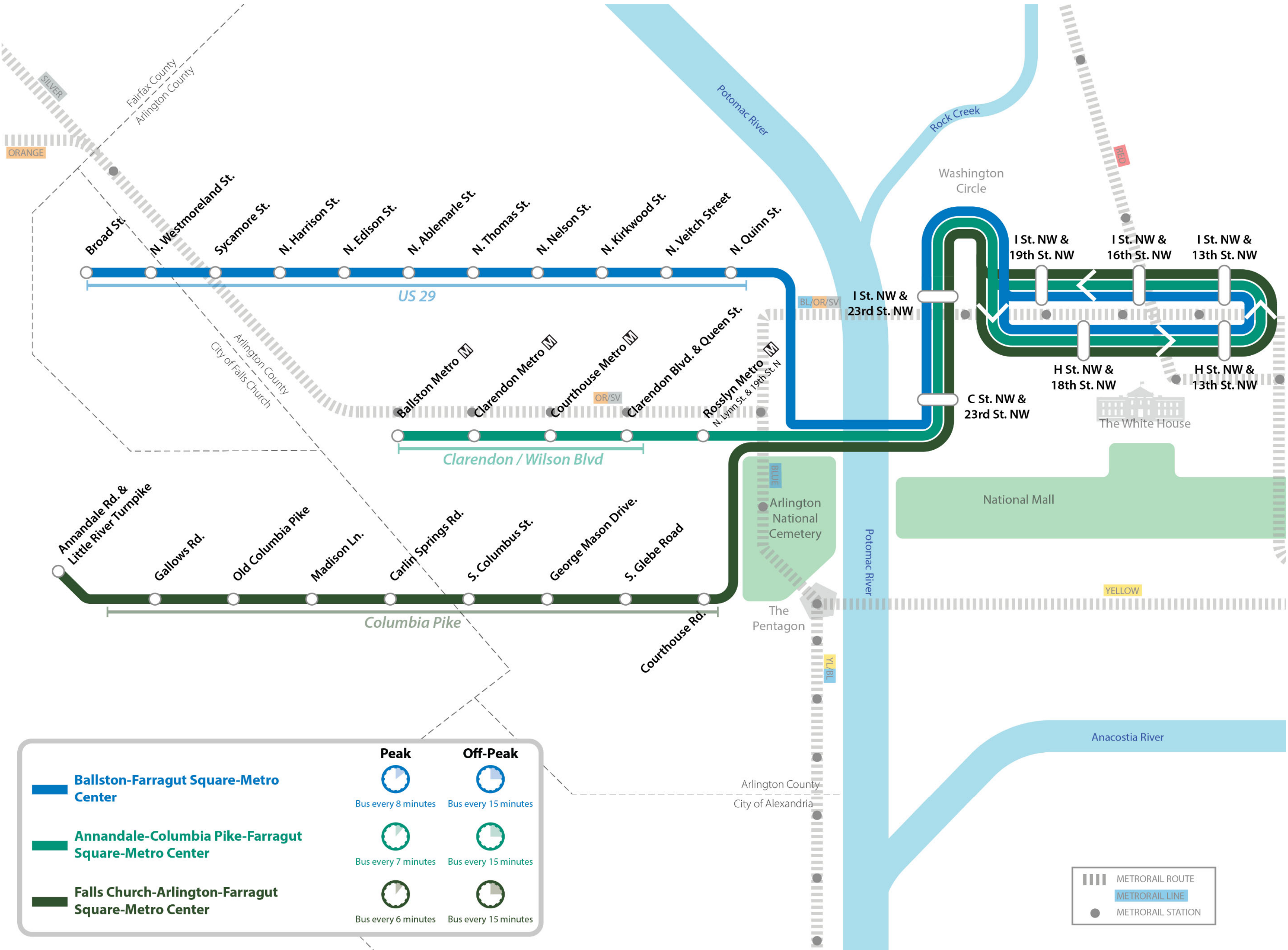


Figure: Bus routes included in the Lower Capital Cost Alternative (cont.) – BRT routes originating in Maryland

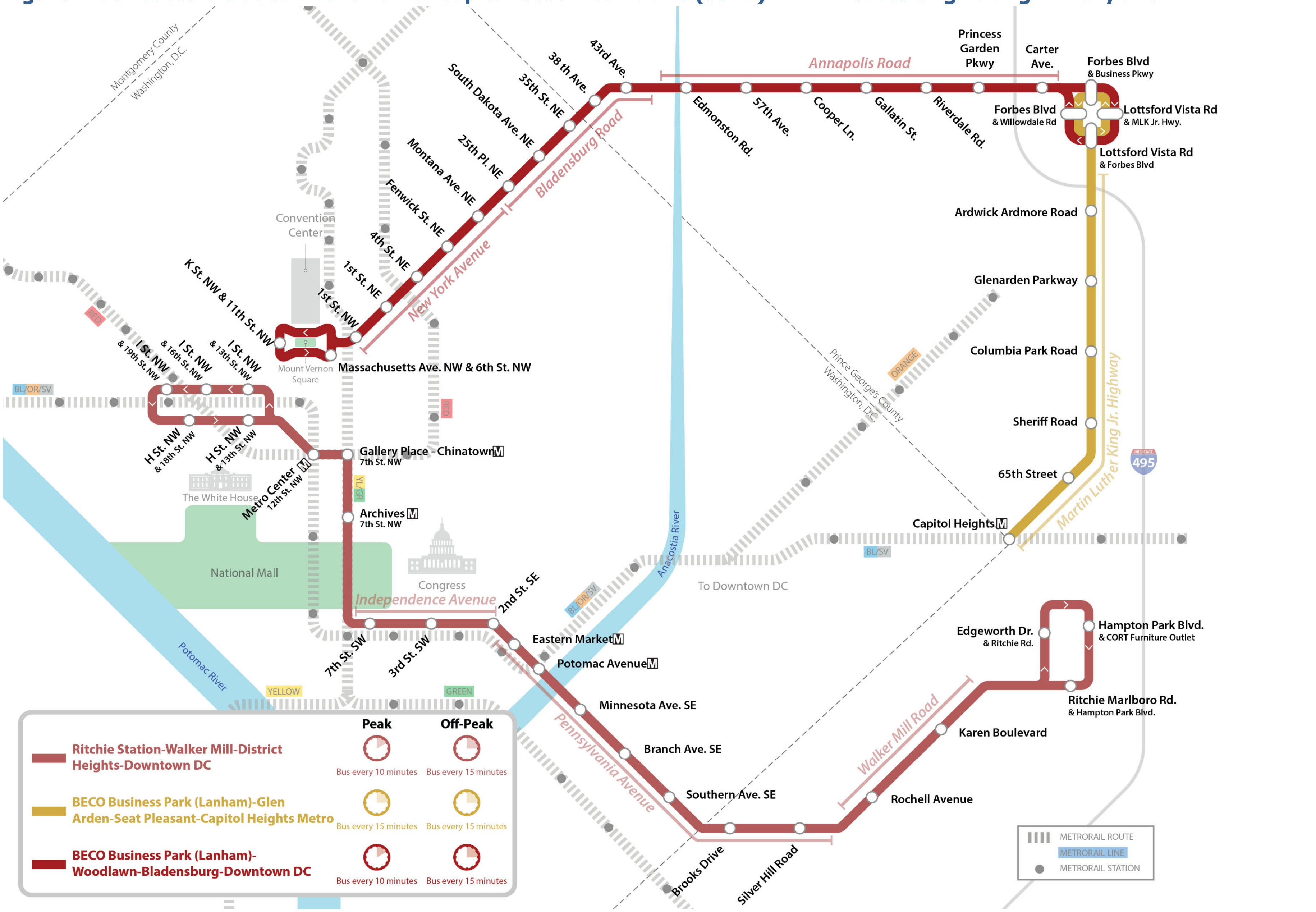


Figure: Bus routes included in the Lower Capital Cost Alternative (cont.) – commuter bus routes originating in Fairfax and Loudon Counties

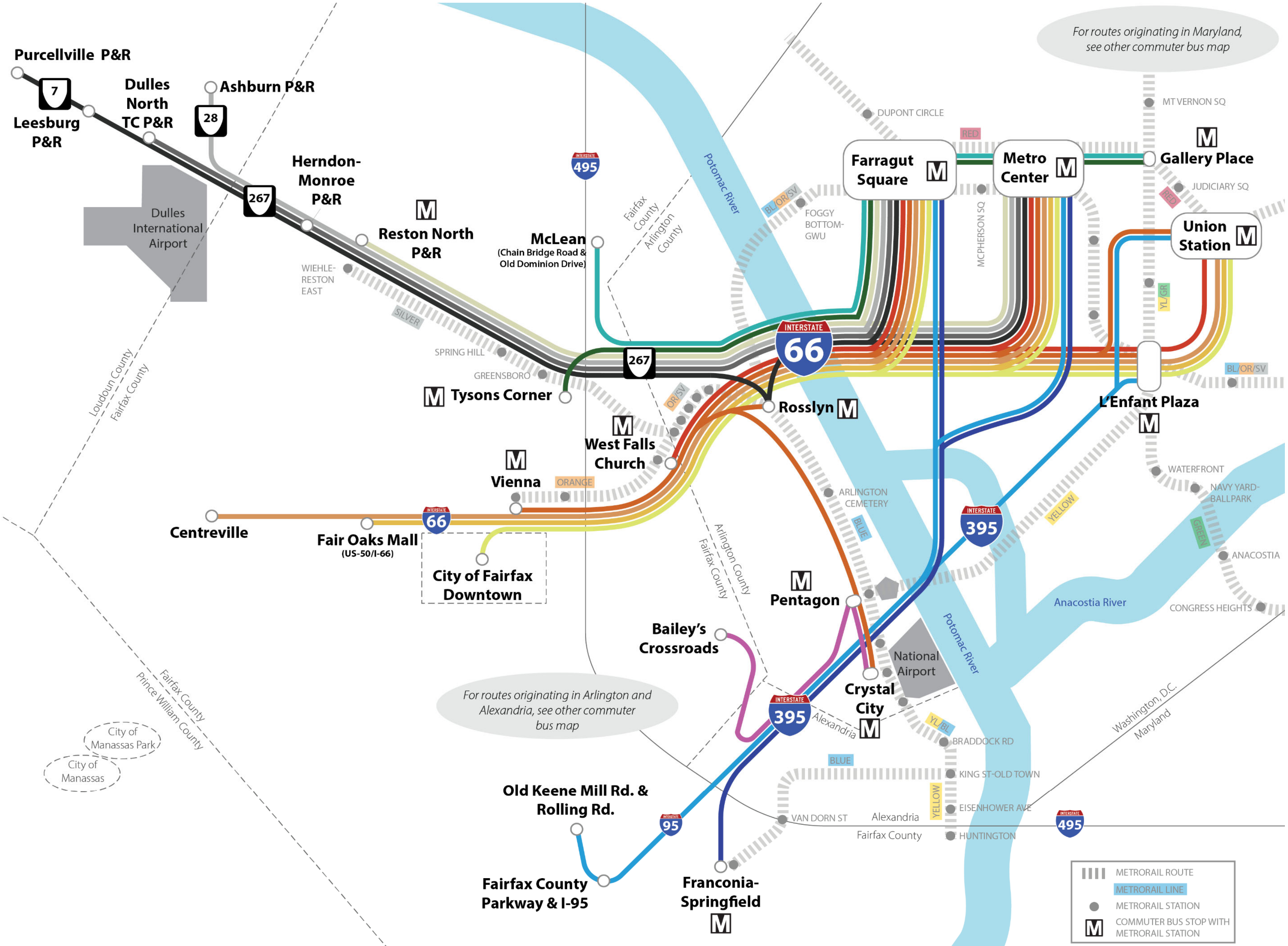


Figure: Bus routes included in the Lower Capital Cost Alternative (cont.) – commuter bus routes originating in Arlington, Alexandria, and Maryland

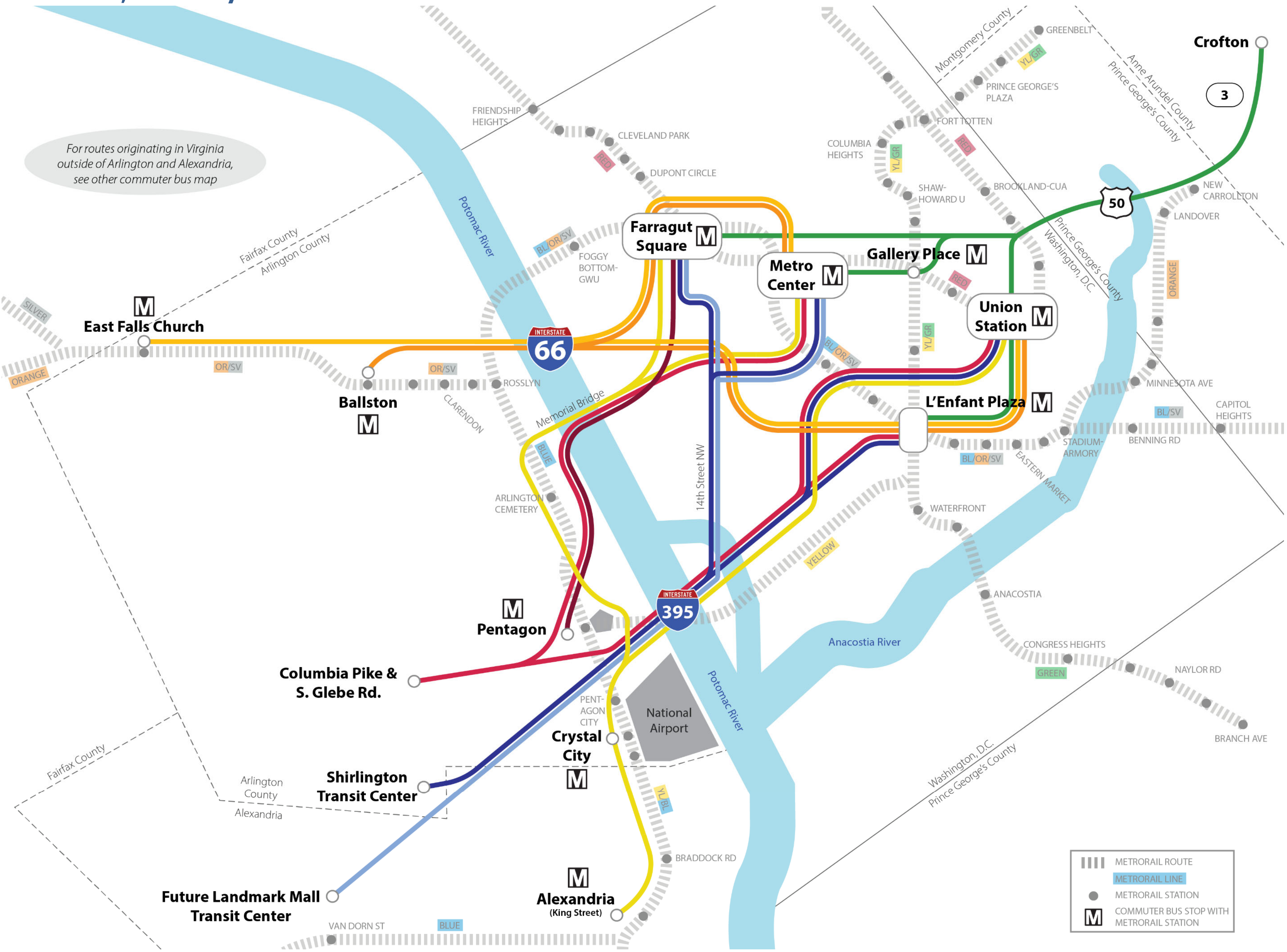
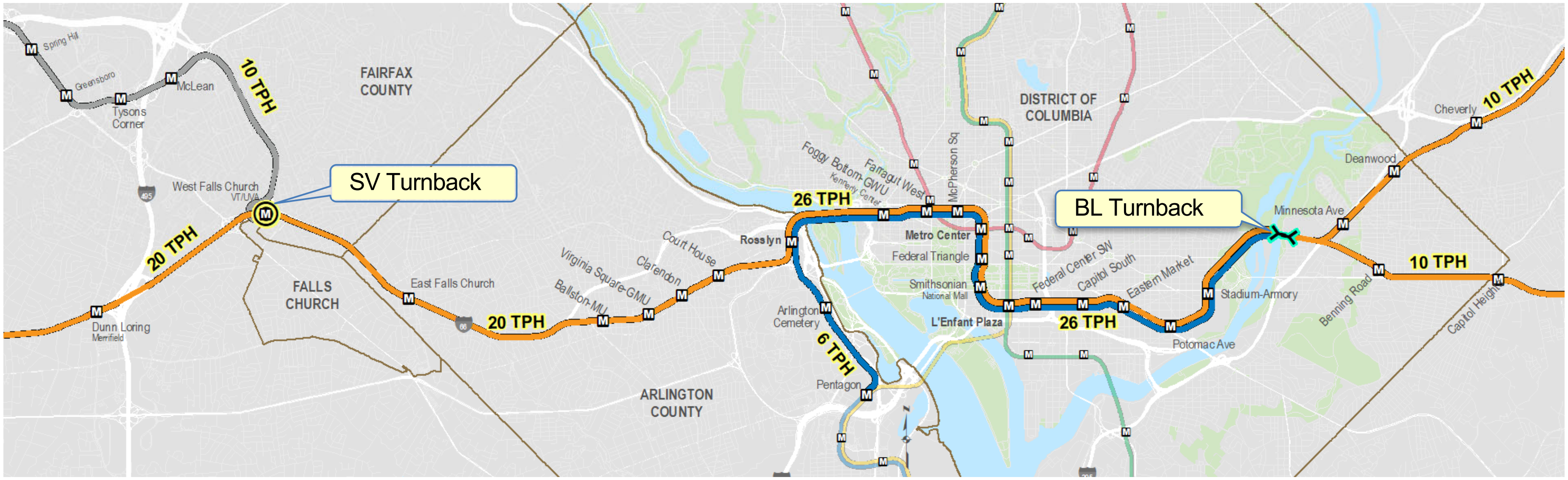


Figure 2-3: Turnback infrastructure included in the Lower Capital Cost Alternative.

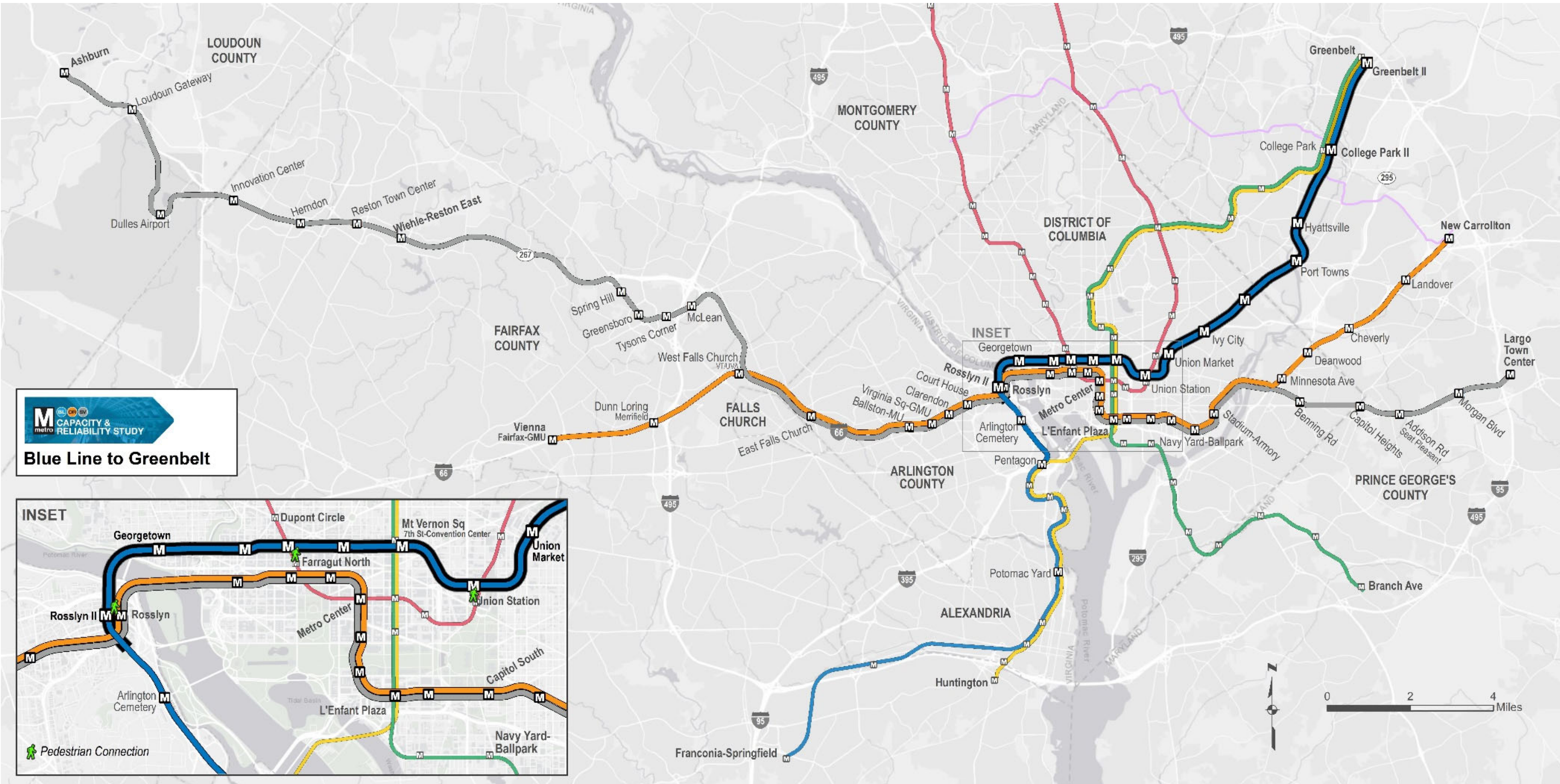


Metrorail Build Alternatives

The four Metrorail build alternatives selected for more detailed analysis are described in the following pages.

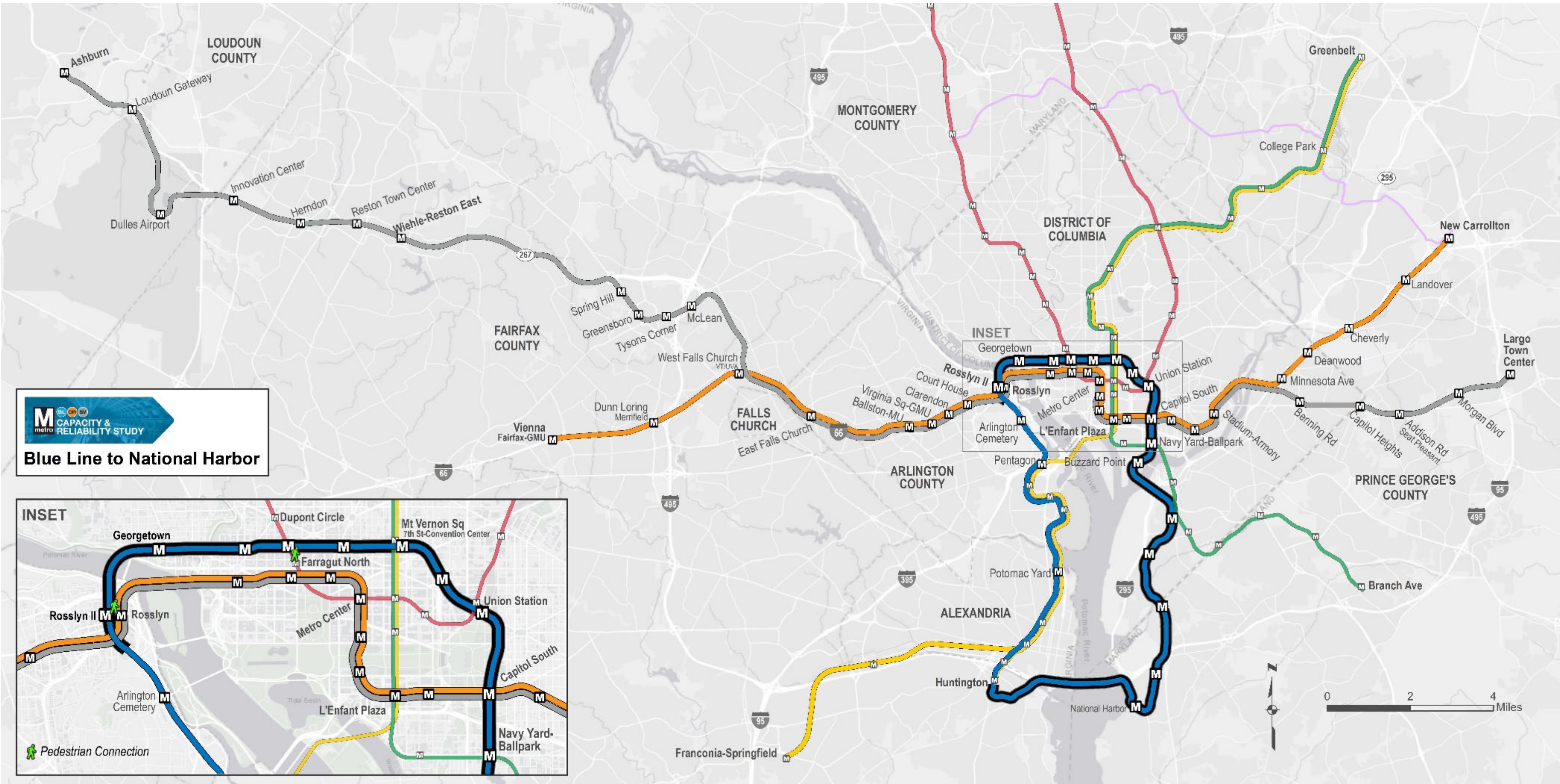
Metrorail Build Alternative 3A - Blue Line to Greenbelt: This alternative would realign the existing Blue Line from the Arlington Cemetery Station to a new Rosslyn II station, which would offer a direct pedestrian connection to the existing Rosslyn Station. From there it would run through a separate tunnel into Georgetown, along M Street, through the District's downtown to Union Station, then northeast through Union Market, Ivy City, Port Towns, Hyattsville, and College Park to Greenbelt. It would operate on separate tracks from the existing Green and Yellow Lines in order to avoid re-interlining. This alternative would create net new rail capacity of 16 TPH per direction.

Figure 2-4: Alternative 3A - Blue Line to Greenbelt



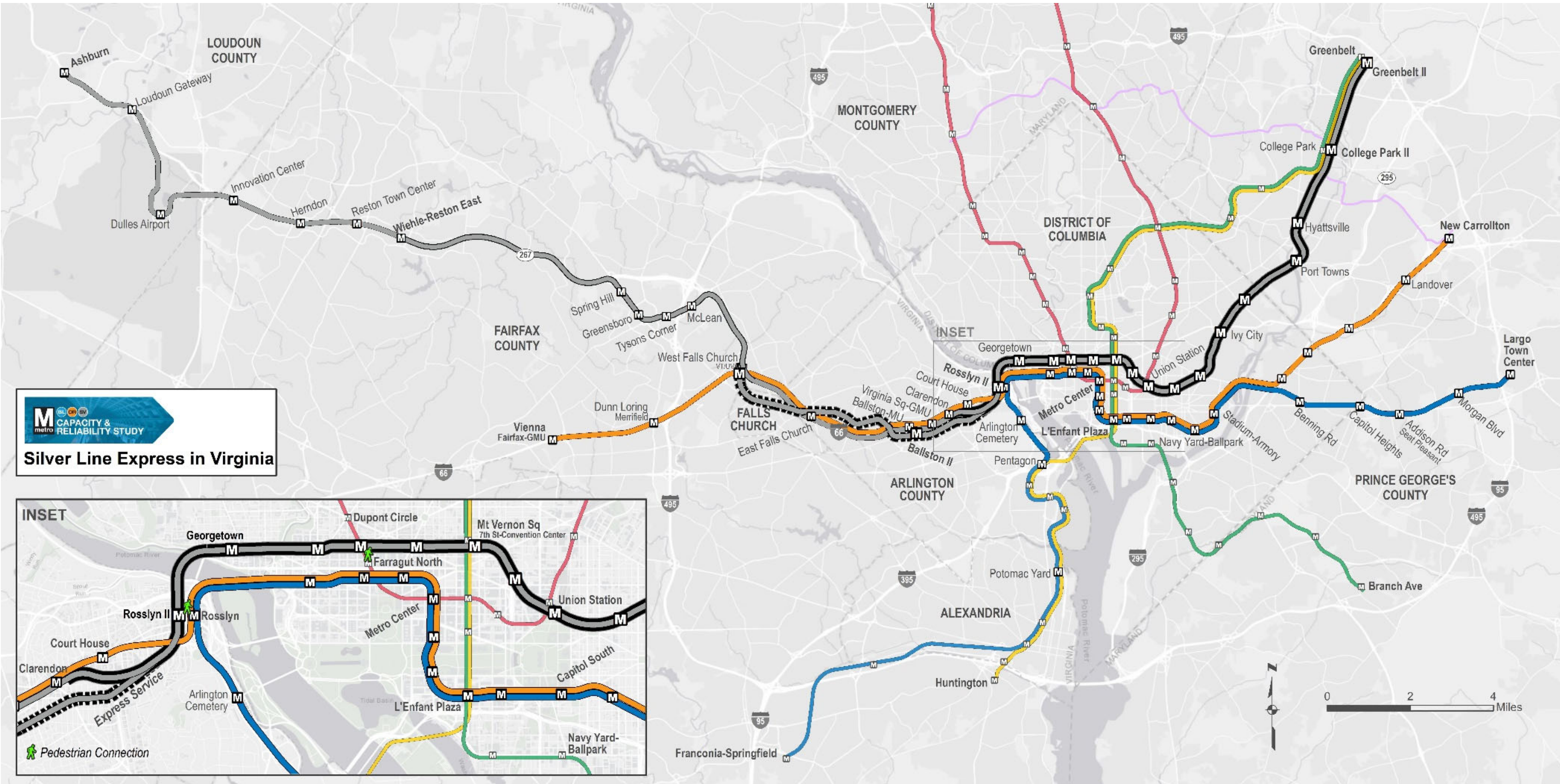
Metrorail Build Alternative 3C - Blue Line to National Harbor: This alternative would also realign the existing Blue Line from Arlington Cemetery Station to a new Rosslyn II station, continuing through Georgetown and along M Street to Union Station. From Union Station it would turn south, providing new north-south service in Waterfront and Navy Yard and creating new rail access in areas targeted for development, such as Buzzard Point, St. Elizabeths, and National Harbor, before crossing the Potomac River to Alexandria. This alternative would create net new rail capacity of 16 TPH per direction.

Figure 2-5: Alternative 3C - Blue Line to National Harbor



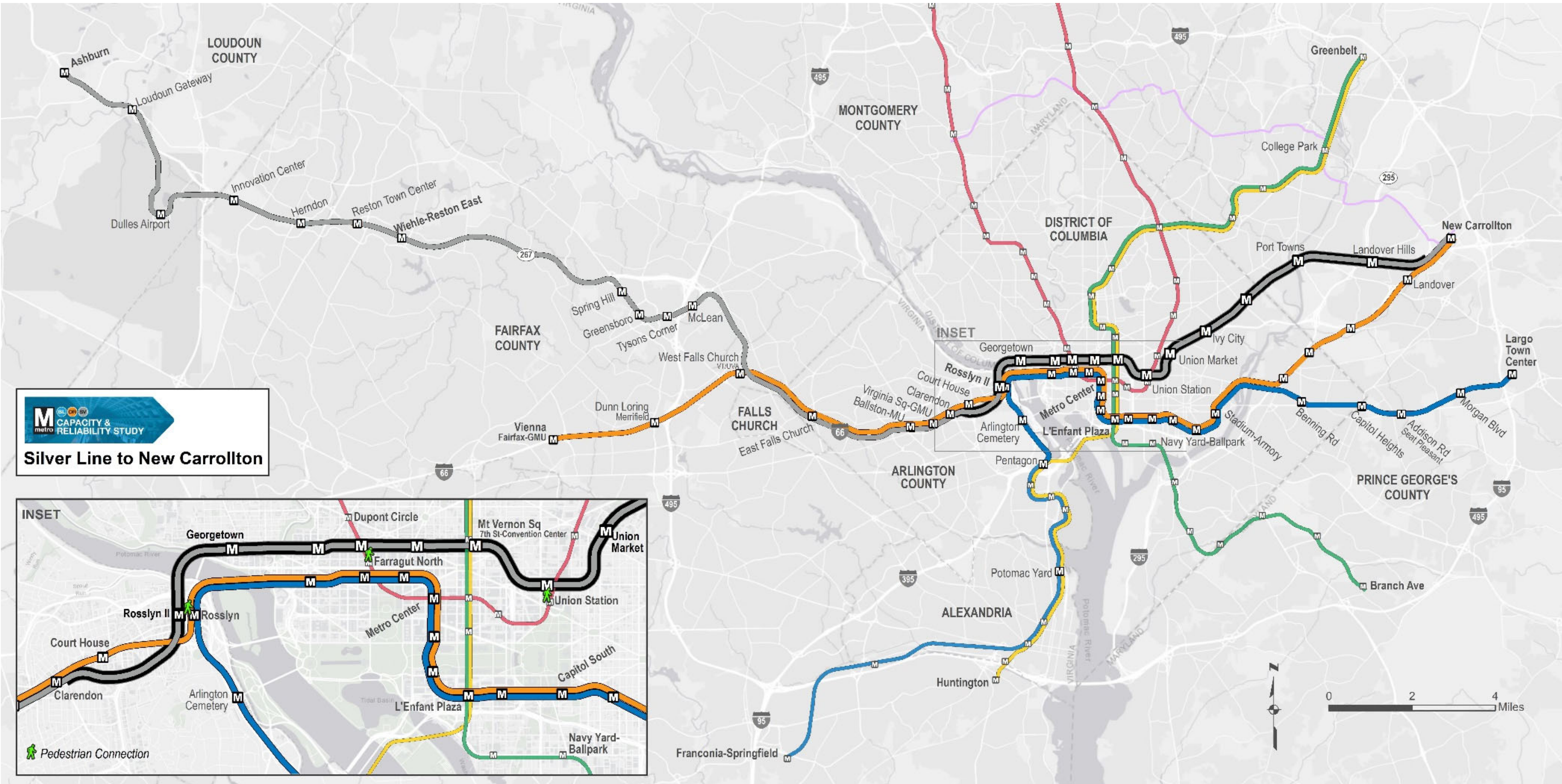
Metrorail Build Alternative 5A - Silver Line Express in Virginia: This alternative would create a separate tunnel and tracks for the Silver Line, starting at West Falls Church Station. From WFC to the new Rosslyn II station, the new tunnel could support express service, local service, or a mix of express and local service. From the new Rosslyn II station, the Silver Line would travel through Georgetown along M Street to Union Station, then through Capitol Hill, Ivy City, Port Towns, Hyattsville, and College Park to Greenbelt. This alternative would create net new rail capacity of 26 TPH per direction.

Figure 2-6: Alternative 5A - Silver Line Express in Virginia



Metrorail Build Alternative 5D - Silver Line to New Carrollton: This alternative would separate the Silver Line from the Orange Line at Clarendon Station, creating a new connection at a new Rosslyn II station before continuing through Georgetown to Union Station. From Union Station, the new tunnel would turn north and east to serve Ivy City and Port Towns, then run along the Annapolis Road/MD 450 corridor to New Carrollton Station. This alternative would create net new rail capacity of 16 TPH per direction.

Figure 2-7: Alternative 5D - Silver Line to New Carrollton.



Throughout the report, alternatives will be referred to by shortened names as shown in **Table 2-1**.

Table 2-1: Full and shortened names of alternatives.

Full Name	Shortened Name
No-Build Alternative	No-Build
Lower Capital Cost Alternative	LCC Alt
Alternative 3A – Blue Line to Greenbelt	Alt 3A (Greenbelt)
Alternative 3C – Blue Line to National Harbor	Alt 3C (National Harbor)
Alternative 5A – Silver Line Express in Virginia	Alt 5A (SV Express)
Alternative 5D – Silver Line to New Carrollton	Alt 5D (New Carrollton)

3.0 EVALUATION PERFORMANCE MEASURES

The CBA is structured around 14 performance measures, each of which is directly related to the established BOS corridor goals and objectives (**Table 3-1**). These measures were developed with public and stakeholder input. For more information on those goals and objectives, see the report titled *BOS Study: Purpose & Need Statement.* Measures were used to evaluate alternatives and compare performance and cost as part of the CBA, with results indicating which alternative produces the most benefits per dollar spent. The CBA process is described in section 4.1 CBA Scoring and Evaluation Method and full detail is in Appendix B: CBA Scoring and Evaluation Method Details. CBA results are shown in section 4.2 Summary of Results.

Following the CBA method and results in section 4.0 Evaluation of Benefits and Cost-Effectiveness, the remainder of the report documents the CBA results organized by goal (sections 5.0 through 8.0). Detailed explanations of the data, methods, and assumptions used in the CBA are provided in the Appendices. Results, combined with additional feedback from stakeholders, elected officials, and the public, will assist Metro's Board of Directors in identifying an LPA.

Table 3-1: Goals, objectives, and performance measures.

Goals	Objectives	Performance Measures	Results in	Method in
1. Provide sufficient rail capacity to serve ridership demand.	1.1 Deliver optimal railcar passenger loads at 100 passengers per car (PPC).	Passengers per car at maximum load points	5.1 Passengers per Car	Appendix C: Ridership Estimates and Capacity
	1.2 Safely and efficiently accommodate passenger and transfer demand.	Vertical circulation V/C ratio at Rosslyn, Metro Center, L'Enfant Plaza, Union Station (% change)	5.2 Vertical Circulation Ratio	Appendix C: Ridership Estimates and Capacity
	1.3 Increase capacity, flexibility, and resiliency to serve ridership demand and east-west travel.	Percent of select O/D pairs served by multiple routes	5.3 Percent of O/D Pairs Served by Multiple Routes	Appendix C: Ridership Estimates and Capacity
2. Improve reliability and on-time performance.	2.1 Maintain or increase percentage of trains arriving on time.	Train headway adherence from Rosslyn to Stadium-Armory	6.1 Train Headway Adherence	Appendix D: Operating Scenarios and Impacts Assessment
	2.2 Maintain or increase the percentage of customers completing their trips on time.	Total minutes saved (AM peak rail trips for select O/D pairs)	6.2 Travel Time Savings	Appendix D: Operating Scenarios and Impacts Assessment
	2.3 Minimize the number of significant trip delays.	Delay percent on BOS central corridor	6.3 Train Delay Percent	Appendix D: Operating Scenarios and Impacts Assessment

Goals	Objectives	Performance Measures	Results in	Method in
3. Improve operational flexibility and cost-efficiency.	3.1 Minimize the travel time impacts of work zones and disruptions.	AM peak-hour BOS passengers able to avoid single tracking at maximum load points	7.1 BOS Passengers Able to Avoid Single Tracking	Appendix E: Flexibility Method
	3.2 Meet ridership demand cost-effectively.	O&M costs per revenue mile	7.2 O&M Costs per Revenue Mile	Appendix E: Flexibility Method
	3.3 Provide flexibility to match service levels to changes in ridership.	Percent change in train miles traveled to nearest pocket track after PPC falls below 50	7.3 Percent Change in Train Miles Traveled to Nearest Pocket Track	Appendix E: Flexibility Method
4. Provide transportation options that support sustainable development and expand access to opportunity.	4.1 Increase corridor transit mode share.	Transit mode share	8.1 Transit Mode Share	Appendix C: Ridership Estimates and Capacity
	4.2 Enhance passenger safety and convenience.	Within half-mile station walkshed: a. Household density b. Employment density	8.2 Household and Employment Density	Appendix F: Land Use and Development Impacts
	4.3 Support transit-oriented development (TOD) and improved transit access.	a. People in EEAs with new access to HCT w/in half-mile station walkshed b. Avg total jobs accessible w/in 45 minutes from stations in EEAs	a. 8.3 People in EEAs with New Access to Transit b. 8.4 Average Total Job Accessibility	Appendix F: Land Use and Development Impacts

4.0 EVALUATION OF BENEFITS AND COST-EFFECTIVENESS

4.1 CBA Scoring and Evaluation Method

The CBA is based on 14 performance measures, each linked to an objective which in turn is linked to one of the four goals. These linkages directly connect the study's Purpose and Need to the evaluation of alternatives in order to help identify an LPA that will address the corridor's goals and needs.

The alternatives received a score for each performance measure, as well as overall composite scores for Benefits and Cost-Effectiveness. Those results were calculated and recorded in an Alternatives Evaluation Matrix that includes the metrics, data, scoring calculations, and results. This section of the report explains the CBA method and summarizes results. For more detailed results, see Appendix A: BOS Alternatives Evaluation Matrix and for a more comprehensive explanation of the CBA method see Appendix B: CBA Scoring and Evaluation Method Details.

Each performance measure required the use of specific models and other data analysis tools. The results were entered into the Alternatives Evaluation Matrix according to the following process:

1. Alternatives received a score from one to four points on each measure, with a four representing the best performance and a one the lowest performance.
2. Scores were totaled for each goal, using equal weights.
3. Goal scores were summed into a total benefits score.
4. Total benefits scores minus the No-Build benefits score produced Benefits scores. This made the alternatives more comparable to each other, by using the No-Build's performance as a baseline.
5. Benefits scores were then divided by annualized cost (capital costs + operating costs – passenger revenue) to obtain the Cost-Effectiveness score.

For example, the No-Build received an overall Benefits score of 42 out of 100. The LCC Alt received a Benefits score of 52, or 10 once the No-Build results were subtracted. This provides a better view of the marginal benefits each build alternative would deliver above and beyond the No-Build, while still allowing the build alternatives to be comparatively ranked and assessed against each other. The Benefits score shows whether each alternative (including the No-Build) could attain the four corridor goals, and how successful each would be in doing so. In other words, it shows the scale of benefits and impacts each alternative offers compared to each other and the likely future.

However, benefits and impacts also need to be placed in context with the likely costs of providing those benefits. To assess each alternative's performance in this regard, the CBA also calculated a Cost-Effectiveness score, which is an alternative's Benefits score divided by a total, annualized improvement cost. The total annualized improvement costs were determined by adding an alternative's capital costs and estimated annual operating and maintenance (O&M) costs, then subtracting projected annual passenger fare revenue. These Cost-Effectiveness scores can be directly compared, with the largest value indicating the alternative that might offer the greatest benefits or impact per dollar spent.

For the initial CBA evaluation all performance measures and goals were equally weighted. An additional CBA scoring was performed using variable weights based on feedback from the study's stakeholder committees. See Section 4.3 Stakeholder Weighting Process for more detail on the weighting exercise.

The Alternatives Evaluation Matrix in Appendix A includes all scores and rankings.

4.2 Summary of Results

With each measure given equal weight, **Table 4-1** and **Figure 4-2** show the Benefits and Cost-Effectiveness scores and ranks for each alternative. The alternatives are ordered from highest to lowest performance by Benefits score. Alt 3C (National Harbor) provides the most benefits and is the second most cost-effective of the five build alternatives considered. The LCC Alt provides relatively few benefits above the No-Build, but is the most cost-effective. This is largely due to an estimated capital cost orders of magnitude lower than the rail build alternatives (approximately $2.5 billion vs. $20-$25 billion). However, it must be noted that the LCC's ability to attain the four corridor goals and meet the Purpose and Need Statement entirely depends upon substantial jurisdictional investments in bus prioritization treatments and the willingness of thousands of peak-hour BOS commutes to switch from rail to competitive bus alternatives.

Figure 4-1: Performance of alternatives.

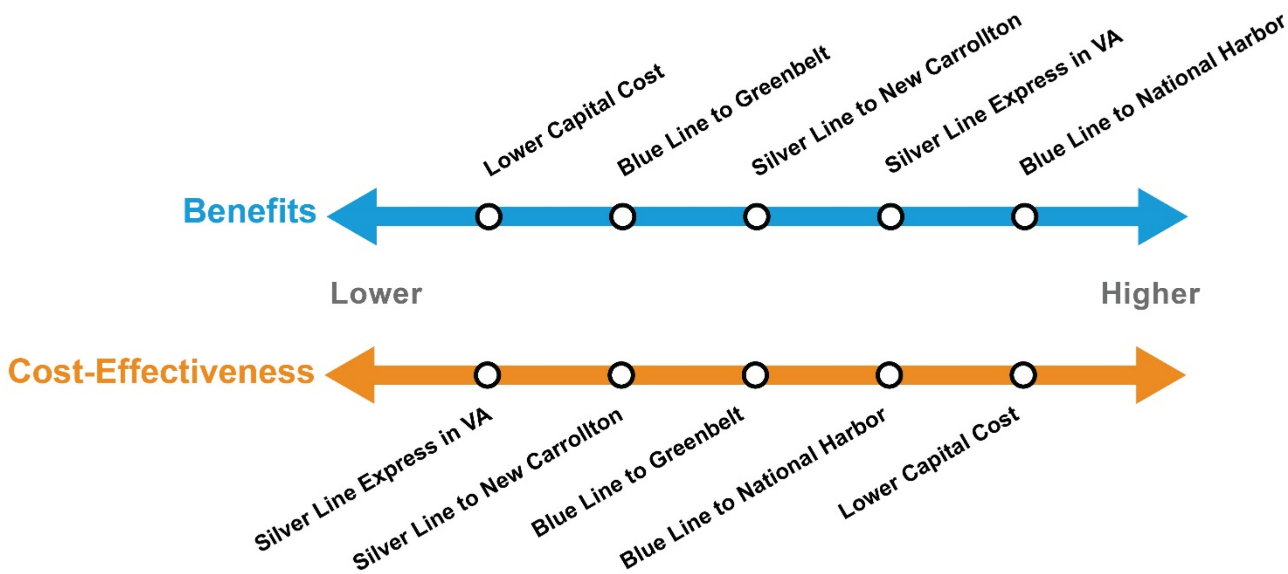
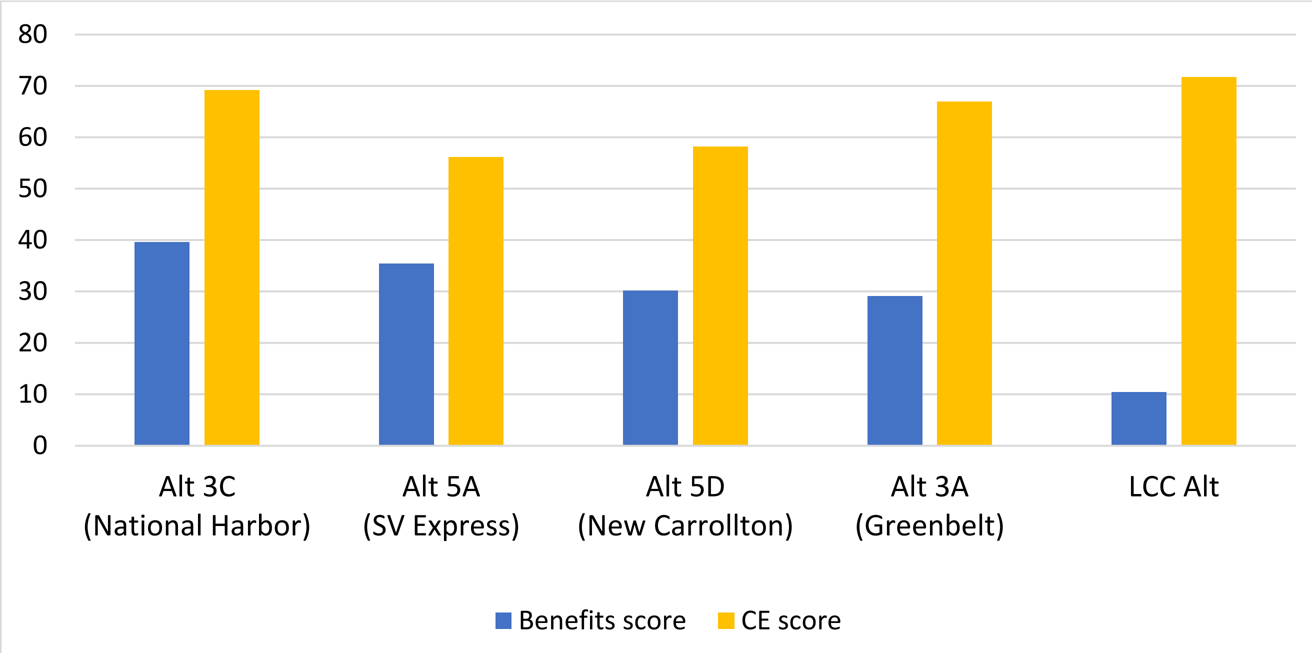


Table 4-1: Equal weight benefits and cost-effectiveness scores and ranks (ordered from most to least benefits).

Alternative	Benefits score	Benefits Rank	CE score	CE rank
3C – BL to National Harbor	40	1	69	2
5A – SV Express in Virginia	35	2	56	5
5D – SV to New Carrollton	30	3	58	4
3A – BL to Greenbelt	29	4	67	3
Lower Capital Cost	10	5	72	1

Colors indicate lower performance ☐→ higher ☐

Figure 4-2: Equal weight benefits and cost-effectiveness scores (ordered from most to least benefits).



4.3 Stakeholder Weighting Process

Once the initial CBA evaluation was completed, Metro undertook a weighting process to provide an opportunity for stakeholder partners to provide additional input. Stakeholders were engaged during the development and selection of goals and performance measures and it was important to gather input again to ensure performance measures were weighted to reflect regional priorities and understand if and how results changed when analysis focused on those regional priorities. Therefore, the study's four stakeholder committees were invited to indicate their preferred weighting framework by either selecting one of four pre-formulated weighting scenarios that prioritize specific outcomes, or submitting their own custom weights for each measure. The four provided weighting scenarios are shown below and in **Table 4-2**, and were designed to allow stakeholders to prioritize certain measures over others:

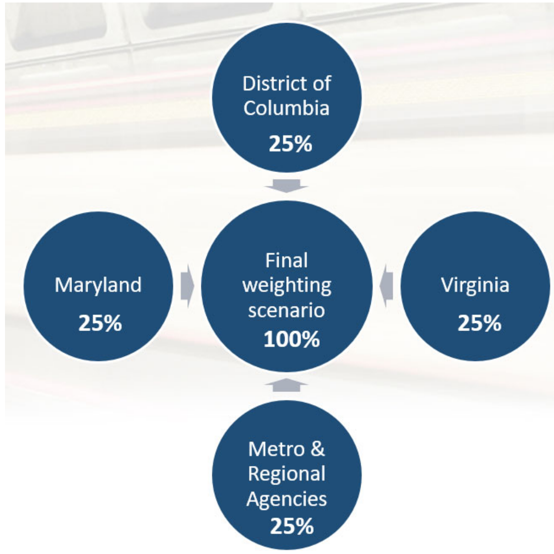
- Scenario 1: Equal Weights (as used in the initial CBA)
- Scenario 2: Capacity and the Customer Experience
- Scenario 3: Equity and Regional Benefits
- Scenario 4: Operational Flexibility and Cost-Efficiency

As mentioned above, stakeholders were also allowed to submit custom weights for each measure. Responses were grouped by jurisdiction and averaged, then weighted by geography (25 percent weight each for the District of Columbia, Maryland, Virginia, and Metro and other regional agencies). The resulting weighting framework is shown in **Table 4-2** and **Figure 4-3**.

Table 4-2: Weighting scenarios provided to stakeholders and the final weights used for evaluation.

Goal	Objective	Measure	Proposed weighting scenarios: Equal weights for all objectives	Proposed weighting scenarios: Capacity & passenger experience	Proposed weighting scenarios: Equity & regional benefits	Proposed weighting scenarios: Operational flexibility & efficiency	Weights used for Evaluation
1. Capacity	Deliver optimal railcar passenger loads at 100 passengers per car (PPC).	Passengers per car (PPC) at maximum load points	8.3%	12.0%	12.0%	6.0%	**8.7%**
	Safely and efficiently accommodate passenger and transfer demand.	Vertical circulation V/C ratio at key transfer stations	8.3%	12.0%	6.5%	6.0%	**8.3%**
	Increase capacity, flexibility, and resiliency to serve ridership demand & east-west travel.	Percent of select OD pairs served by additional routes	8.3%	12.0%	6.5%	12.0%	**9.0%**
		Overall Goal 1. Capacity Weight	*25%*	*36%*	*25%*	*24%*	
2. Reliability	Maintain or increase percentage of trains arriving on-time.	Train headway adherence from Rosslyn to Stadium-Armory	8.3%	12.0%	6.5%	6.0%	**7.7%**
	Maintain or increase percentage of customers completing their trips on time.	Daily AM peak travel time savings for select OD pairs	8.3%	12.0%	6.5%	6.0%	**9.0%**
	Minimize the number of significant trip delays.	Delay percent on BOS corridor (AM peak)	8.3%	12.0%	6.5%	12.0%	**9.3%**
		Overall Goal 2. Reliability Weight	*25%*	*36%*	*20%*	*24%*	
3. Flexibility	Minimize the travel-time impacts of work zones and disruptions.	AM peak hour BOS passengers able to avoid single tracking	8.3%	4.5%	6.5%	12.0%	**6.6%**
	Meet ridership demand cost-effectively.	Operating and maintenance costs per revenue vehicle mile	8.3%	4.5%	6.5%	12.0%	**5.9%**
	Provide flexibility to match service levels to changes in ridership.	Change in train-miles traveled to nearest pocket track after PPC falls below 50	8.3%	4.5%	6.5%	12.0%	**5.9%**
		Overall Goal 3. Flexibility Weight	*25%*	*14%*	*20%*	*36%*	
4. Sustainability	Increase corridor transit mode share.	Transit mode share	8.3%	4.5%	12.0%	6.0%	**10.0%**
	Support Transit-Oriented Development (TOD).	Household density within one half mile station/stop walksheds	4.3%	2.5%	6.0%	2.5%	**4.4%**
		Employment density within one half mile station/stop walksheds	4.3%	2.5%	6.0%	2.5%	**4.6%**
	Expand access to opportunity for equity populations.	People in EEAs with new access to HCT within one half mile station/stop walksheds	4.3%	2.5%	6.0%	2.5%	**5.6%**
		Average jobs accessible within 45 min from stations/stops in EEAs	4.3%	2.5%	6.0%	2.5%	**5.0%**
		Overall Goal 4. Sustainability Weight	*25%*	*15%*	*36%*	*16%*	

Figure 4-3: Jurisdictional weighting for measure weights.



4.4 Stakeholder Weighted Results

The weighted Benefits and Cost-Effectiveness scores and ranks are shown in **Table 4-3** and **Figure 4-4**. Alternatives are ordered from highest to lowest performance according to Benefits score.

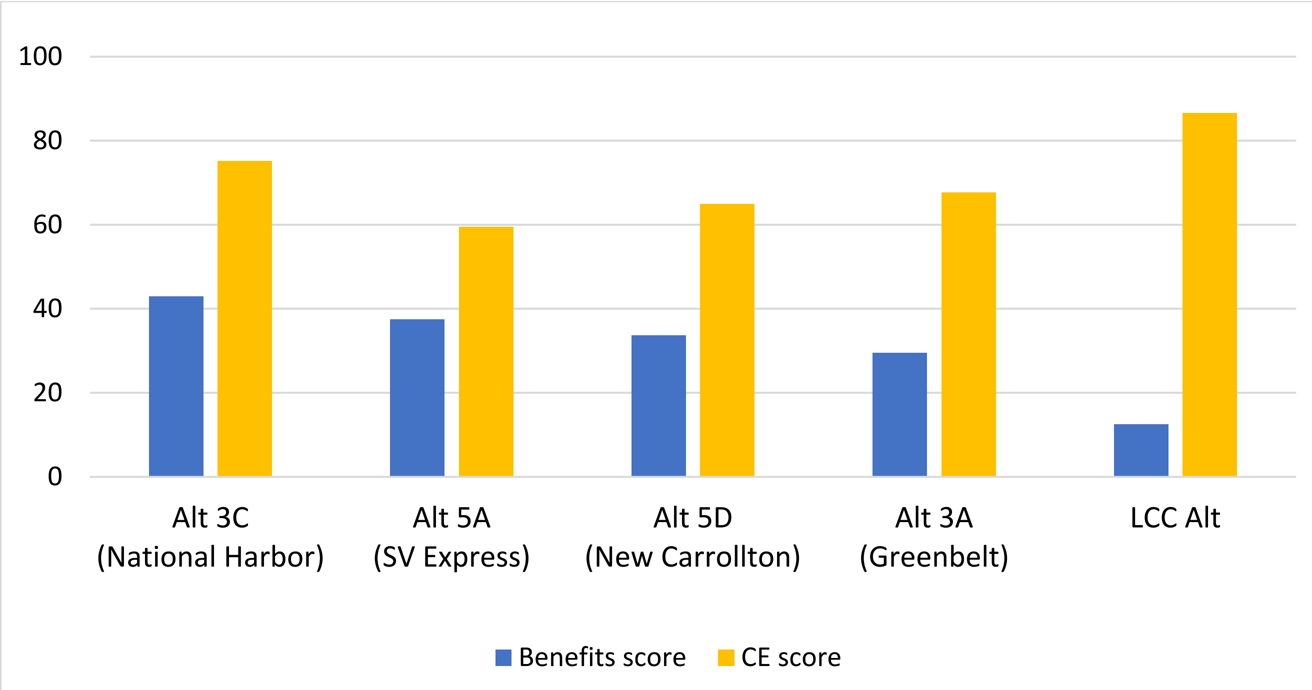
The overall rankings under the weighted scenario did not change from the initial, unweighted results; therefore, Alt 3C (National Harbor) remains the top-ranked alternative for Benefits, though by a greater margin because its Benefits score increased. Benefits scores also increased for Alternatives 5A and 5D, but not enough to impact the overall rankings. Cost-Effectiveness scores increased for all alternatives, and the LCC Alt remains the most cost-effective but by a larger margin.

Table 4-3: Benefits and cost-effectiveness scores and ranks (ordered from most to least benefits).

Alternative	Benefits score	Rank	CE score	CE rank
3C – BL to National Harbor	43	1	75	2
5A – SV Express in Virginia	37	2	59	5
5D – SV to New Carrollton	34	3	65	4
3A – BL to Greenbelt	29	4	68	3
Lower Capital Cost	13	5	87	1

Colors indicate lower performance → higher

Figure 4-4: Benefits and cost-effectiveness scores (ordered from most to least benefits).



4.5 Key CBA Findings

This section presents key results and findings from the CBA. Detailed results by goal are located in the following sections.

Figure 4-5 and **Table 4-4** show projected ridership, passenger revenue, and cost estimates for each alternative relative to the No-Build; in other words, the net increases in ridership, revenue, and costs to the Metro System each alternative would deliver over the 2040 baseline future (No-Build).

In **Figure 4-5**, the blue line indicates the annualized improvement cost (capital + operating costs – revenue) over the No-Build, which combines the other elements of the chart into a single value of total additional cost of the alternative for a single year.

Figure 4-5: Annualized revenue and costs relative to the No-Build (NB) Alternative.

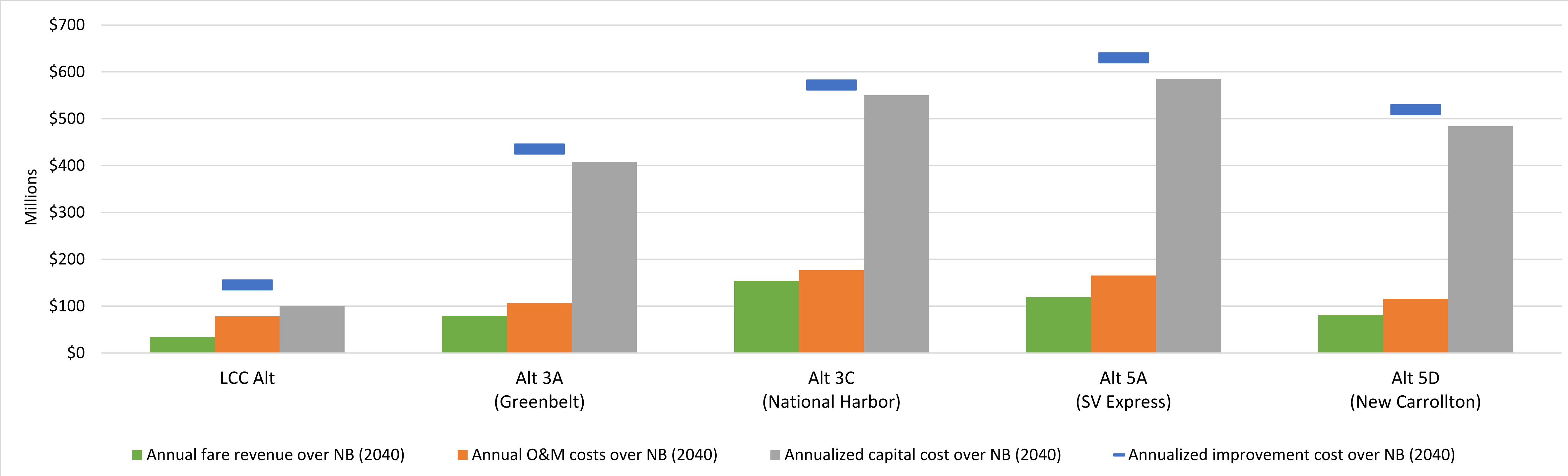


Table 4-4: Revenue and costs.

	No-Build	Lower Capital Cost		Alt 3A (Greenbelt)		Alt 3C (National Harbor)		Alt 5A (SV Express)		Alt 5D (New Carrollton)	
	Value	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change
Weekday linked trips over NB (2040)	0	16,000	2%	92,000	11%	180,000	21%	139,000	16%	94,000	11%
Annual linked trips over NB (2040)	0	4,556,000	2%	26,440,000	11%	51,490,000	21%	39,856,000	16%	26,861,000	11%
Annual fare revenue over NB (2040)	$0	$33,969,000	5%	$79,175,000	11%	$154,191,000	21%	$119,352,000	16%	$80,437,000	11%
Annual O&M costs over NB (2040)	$0	$78,091,000	2%	$106,529,000	3%	$176,375,000	6%	$165,207,000	5%	$115,654,000	4%
Annualized capital cost over NB (2040)	$0	$101,058,000		$407,763,000		$549,742,000		$584,002,000		$484,079,000	
Annualized improvement cost over NB (2040)	$0	$145,179,000		$435,117,000		$571,927,000		$629,857,000		$519,296,000	
Total capital cost (includes 25% contingency)	$0	$2.56 B		$16.51 B		$22.15 B		$23.76 B		$18.57 B	

Equity

Recognizing the importance regional stakeholders placed on equity outcomes by assigning higher weights to the two equity-related performance measures, **Figure 4-6** and **Figure 4-7** show the results across alternatives on those measures. Alt 3C (National Harbor) is expected to provide an additional 35,000 individuals living in EEAs with new access to high-capacity transit within a half-mile walking distance. This is 8,000 more individuals than the next best alternatives, the LCC Alt and Alt 5A (SV Express).

Alt 3C (National Harbor) again performs best on job accessibility from equity areas (**Figure 4-7**). Alt 3C (National Harbor) provides access to 19,000 more jobs within 45 minutes than does Alt 5D (New Carrollton), the next best performer. For more information on these outcomes, see section 8.4.

Figure 4-6: Number of people in EEAs with new access to high-capacity transit within half mile station walksheds.

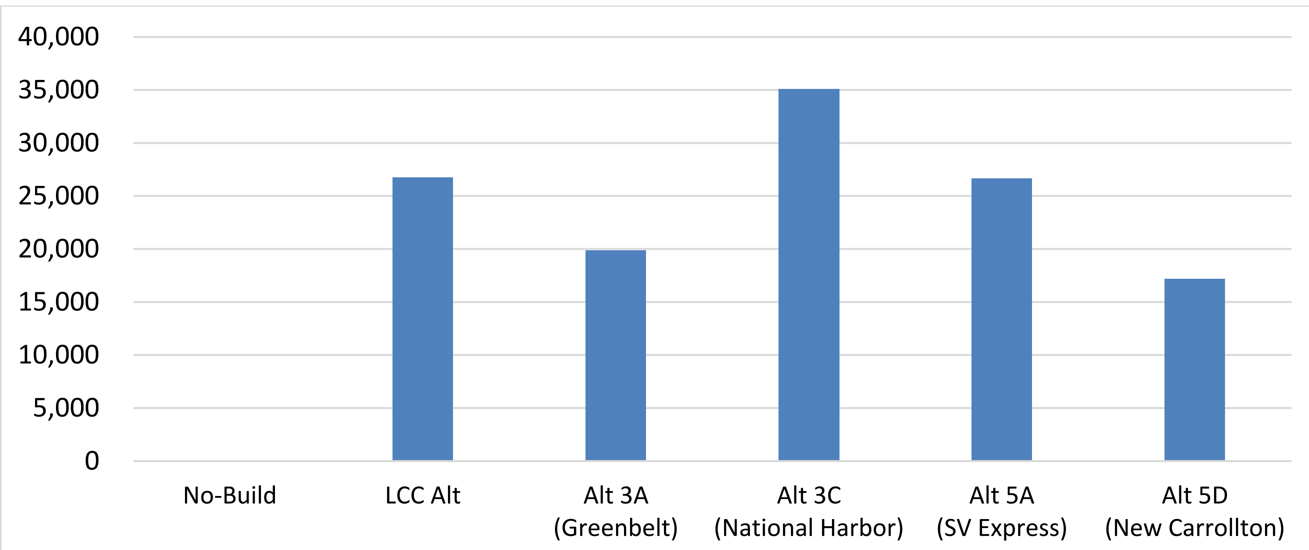
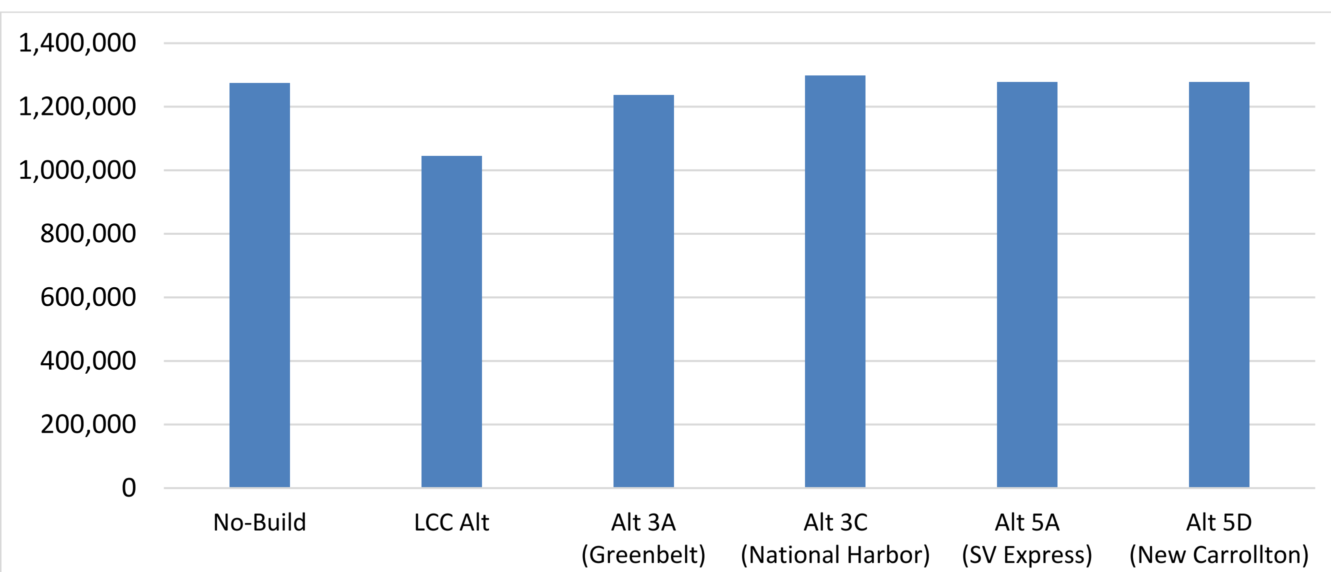


Figure 4-7: Average number of jobs accessible within 45 minutes from stations in EEAs.



Capacity and Crowding

One of the goals established with public and stakeholder input for this study is providing sufficient capacity to reduce peak-period passenger crowding and to meet future ridership demand. **Figure 4-8** shows results for the performance measure most directly related to capacity and crowding, passengers per rail car (PPC) at the line's maximum load point. Metro's adopted service standards target 100 PPC as the optimal passenger load. 80 PPC and below at a maximum load point indicates potential service productivity issues, and 120 PPC indicates severe and potentially dangerous crowding that violates service standards. The target of 100 PPC is represented by a horizontal black line in the chart.

Note that the PPC figures for each alternative are driven largely by two factors:

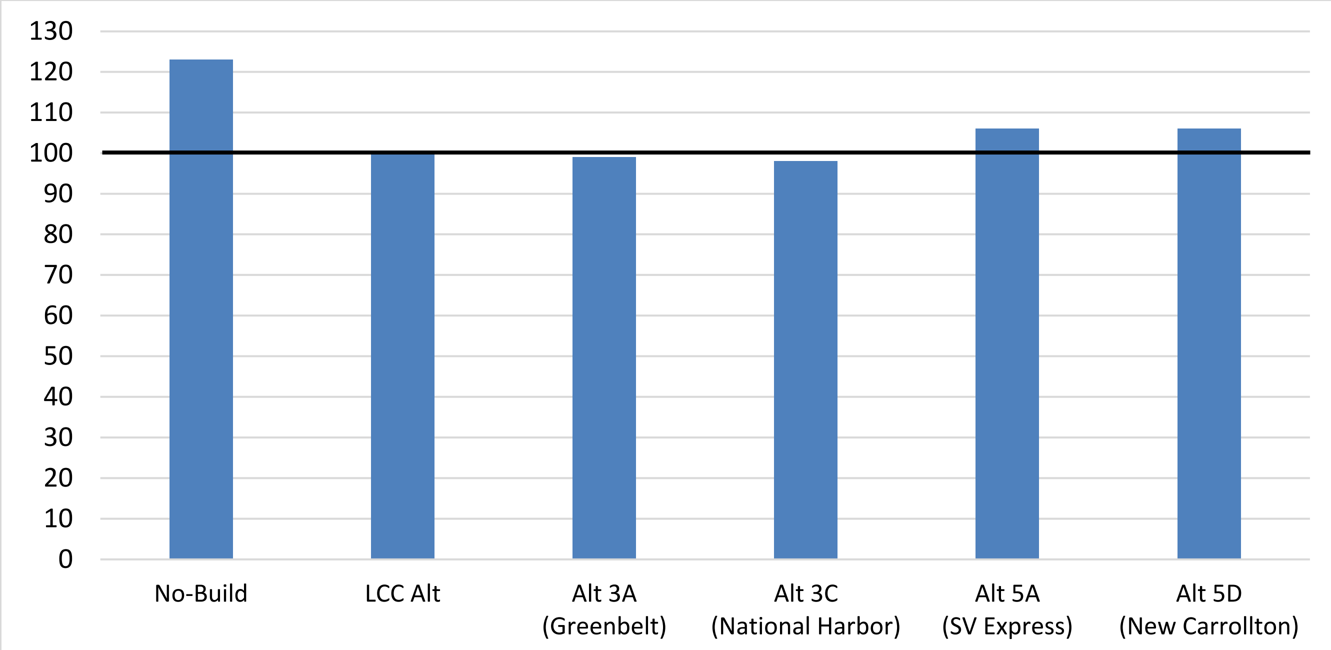
1) the new train throughput capacity each alternative would offer, plus

2) the assumed service plan that establishes peak-period headways on each line.

In order to provide a direct comparison between the alternatives and the No-Build baseline, the CBA assumed a six-minute peak schedule. In the case of the No-Build, this means six-minute headways on the Orange and Silver Lines (10-11 trains per hour on each), but only 12 minutes on the Blue Line (five trains per hour). This is due to the existing capacity constraint of 26 trains per hour in the shared BOS corridor and the lack of new capacity in the No-Build. The LCC Alt—like the No-Build—does not add new rail capacity and therefore shares 26 trains per hour capacity constraint. However, the LCC Alt seeks to relieve crowding in railcars by encouraging customers to switch to bus service. The LCC Alt service plan also incorporates the potential to vary service patterns in response to ridership demand by offering train turnback opportunities at the West Falls Church station and the D&G Junction near the Stadium-Armory station. Each of the rail build alternatives provides new train throughput capacity that would allow all three lines to achieve six-minute headways. Each of the rail build alternatives would also provide excess capacity that could support higher service levels than the assumed six-minute schedule, which would in turn further reduce PPC through maximum load points. The service plans used for the CBA and additional detail are available in Appendix D: Operating Scenarios and Impacts Assessment.

The No-Build would not meet Metro's capacity needs and passenger load targets. Alternatives 3A, 3C, and the LCC Alt perform best on this measure, hitting or nearly hitting the optimal target of 100 PPC. Alternatives 5A and 5D would not perform as well, at least not under the assumed six-minute schedule, delivering passenger loads between 100 and 110 PPC at the max load point. All build alternatives provide an improvement over the No-Build, and each of the rail build alternatives would provide additional new capacity that would help future-proof the Metrorail System.

Figure 4-8: Passengers per car (PPC) at maximum load points.



Comparing Benefits and Costs (Tradeoffs)

In terms of overall benefits, Alt 3C (National Harbor) emerged as the highest performer among the six alternatives. It would extend Metrorail service into new markets and areas targeted for growth and development, such as Waterfront, Buzzard Point, St. Elizabeths, and National Harbor. In the core area, Alt 3C (National Harbor) would also provide two new transfer stations at Capitol South and Navy Yard, which would reduce crowding at existing transfer stations, increase system resiliency, and improve riders' ability to move around a mostly radial network. Alt 3C (National Harbor) also performs best on the equity measures (expanding access to transit and economic opportunities in Equity Emphasis Areas).

Looking primarily at cost-effectiveness, the LCC Alt performs best by imposing the lowest new capital and O&M costs. However, this alternative would offer marginal net benefits above the No-Build (lowest Benefits score of the five build alternatives). And though it was designed to be capable of attaining the four corridor goals, its ability to do so depends on thousands of peak-hour riders voluntarily switching from rail to bus to relieve rail crowding, as well as substantial jurisdictional investments in bus prioritization strategies. Finally, unlike the rail build alternatives, the LCC Alt would not provide excess capacity to accommodate future growth beyond 2040.

Table 4-5 summarizes performance in terms of the CBA Benefits and Cost-Effectiveness rankings as well as additional metrics. The green and orange color-coding indicate the highest- and lowest-performing alternative in each category, to allow quick visualization of overall performance.

Table 4-5: Summary of performance for selected measures.

Outcomes	Lower Capital Cost	Alt 3A (Greenbelt)	Alt 3C (National Harbor)	Alt 5A (SV Express)	Alt 5D (New Carrollton)
Benefits rank	5	4	1	2	3
Cost-effectiveness rank	1	3	2	5	4
Net new rail capacity (TPH)	0	16	16	26	16
Net new ridership	4.6 M	26.4 M	51.5 M	39.8 M	26.9 M
Net new revenue	$33.9 M	$79.1 M	$154.2 M	$119.4 M	$80.4 M
Capital costs	$2.55 B	$16.51 B	$22.15 B	$23.76 B	$18.57 B
O&M costs per revenue mile	$22.55	$20.12	$19.50	$19.81	$20.01
Equity access	Medium	Low	High	Medium	Low

Colors indicate lowest performance and highest performance for each measure.

5.0 GOAL 1: CAPACITY RESULTS

This section presents results for the performance measures under Goal 1: Capacity as shown in **Table 5-1**. For more detail on datasets and analytical methods see Appendix C: Ridership Estimates and Capacity.

Table 5-1: Goal 1 objectives and performance measures.

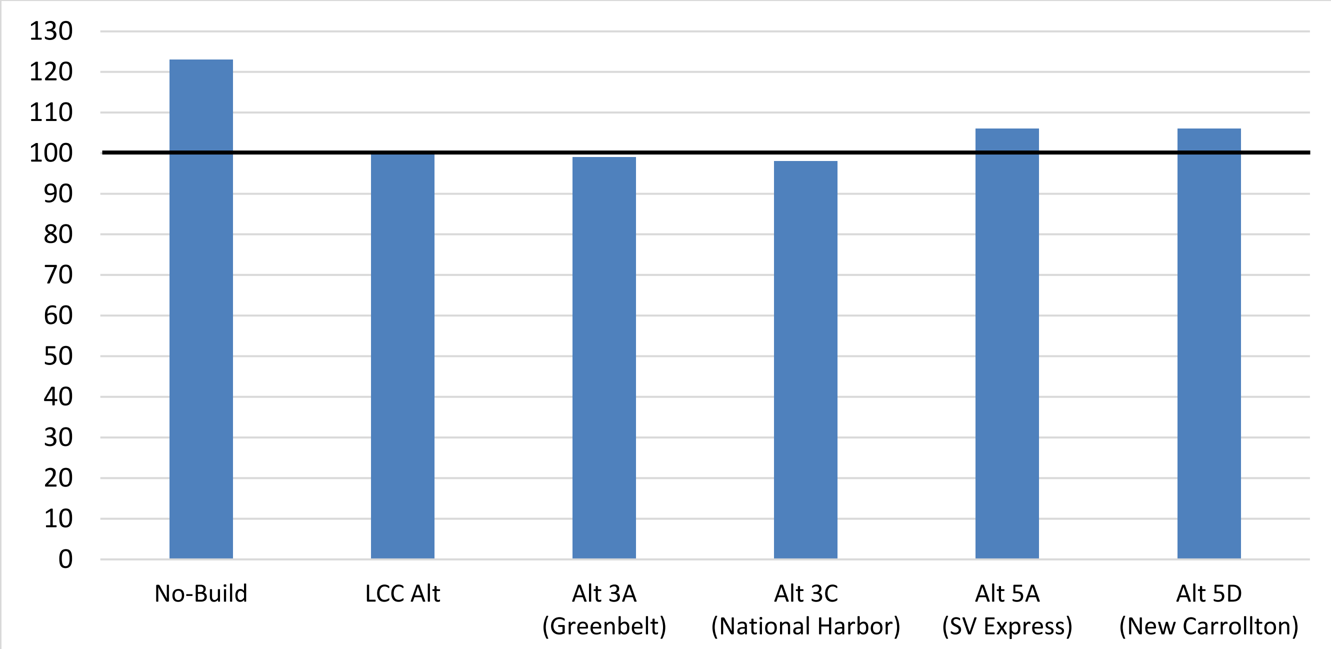
Goals	Objectives	Performance Measures
1. Provide sufficient rail capacity to serve ridership demand. Capacity & Crowding	1.1 Deliver optimal railcar passenger loads at 100 passengers per car (PPC).	Passengers per car at maximum load points
	1.2 Safely and efficiently accommodate passenger and transfer demand.	Vertical circulation V/C ratio at Rosslyn, Metro Center, L'Enfant Plaza, Union Station (% change)
	1.3 Increase capacity, flexibility, and resiliency to serve ridership demand and east-west travel.	Percent of select O/D pairs served by multiple routes

5.1 Passengers per Car

A key goal for this study is to provide the capacity needed to address current (pre-COVID-19) passenger crowding and future ridership demand in the corridor. **Figure 5-1** shows results for the performance measure of passengers per car (PPC) at maximum load points. 100 PPC is considered optimal passenger loading under Metro's adopted service standards; that target is represented by a horizontal black line in the chart. Alternatives 3A, Alt 3C (National Harbor), and the LCC Alt perform the best on this measure. Alternatives 5A and 5D result in PPC slightly above that target, though still below 110 PPC. Because it does not include any capacity expansion components, the No-Build does not reduce projected crowding and would not attain the Capacity goal.

Note that these modeled results are determined in part by the assumed 2040 service plan of a return to six-minute peak schedules. That service plan provides a direct comparison to the assumed operating plan for the No-Build's likely future conditions. However, this means none of the rail build alternatives are maximizing the use of net increases in train throughput capacity, which could support more frequent service than the six-minute schedule and further reduce passenger loads per railcar. This also has the effect of future-proofing Metrorail capacity in this corridor. More detail on the operating and service plans underlying the CBA is available in Appendix D: Operating Scenarios and Impacts Assessment.

Figure 5-1: Passengers per car (PPC) at maximum load points.



5.2 Vertical Circulation Ratio

The vertical circulation volume-to-capacity ratio measures the utilization of, and crowding on, rail station vertical circulation elements, meaning escalators and stairs. It divides the maximum number of passengers using each asset by that asset's safe carrying capacity. This is an important capacity measure because it indicates whether passengers have adequate time to clear platforms before the next train arrives. When the volume-to-capacity ratio rises above 0.50, it indicates the likelihood of heavy queuing at escalators, which in turn leads to crowding on platforms. It also indicates potential customer safety concerns. When assessing average vertical circulation at major transfer stations (Rosslyn, Metro Center, Union Station, and L'Enfant Plaza), all alternatives showed an improvement over the No-Build, with the greatest improvement associated with Alt 3C (National Harbor) (**Table 5-2**). This alternative's alignment includes stations at Capitol South and Navy Yard; while these stations are not included in this measure, those additional transfer opportunities and travel path options result in improvements in crowding at the major downtown transfer stations that are included in this measure.

Table 5-2: Vertical circulation volume to capacity ratio and percent change from the No-Build.

	Peak hour volume/capacity	Percent change from No-Build
No-Build	0.57	-
LCC Alt	0.56	-2%
Alt 3A (Greenbelt)	0.51	-12%
Alt 3C (National Harbor)	0.41	-29%
Alt 5A (SV Express)	0.45	-21%
Alt 5D (New Carrollton)	0.44	-23%

5.3 Percent of O/D Pairs Served by Multiple Routes

The capacity goal includes an objective to increase the capacity, flexibility, and resiliency of east-west transit service. To assess whether and how alternatives provide riders with multiple pathways between major origins and destinations, and to build resiliency for construction activities and single-tracking events, the CBA measured the percentage of major O/D pairs that would be connected by additional routes/options, compared to the No-Build. Origin and destination locations are existing Metrorail stations and were chosen to include trips throughout the BOS corridor and trips to major transfer stations (see **Figure C-1** in Appendix C: Ridership Estimates and Capacity). **Table 5-3** shows the results. Because Alt 5A (SV Express) would build a new rail line between West Falls Church and Rosslyn, and support a mix of local and express service, it would provide travel alternatives for the greatest number of O/D pairs. The other rail alternatives perform similarly well, better than the No-Build but substantially less impactful than Alt 5A (SV Express). The LCC Alt would provide the lowest number of OD pairs with additional route choices, though still more than the No-Build. This is partly because most of the BRT routes in the LCC Alt do not parallel existing Metrorail corridors or serve those particular stations selected as origins/destinations for this measure. Therefore, the LCC Alt does provide service to new locations in the region, but does not provide additional route choices as measured here.

Table 5-3: Percent of selected origin-destination pairs with additional route choices relative to the No-Build.

	Percent of OD pairs
No-Build	-
LCC Alt	16%
Alt 3A (Greenbelt)	31%
Alt 3C (National Harbor)	28%
Alt 5A (SV Express)	74%
Alt 5D (New Carrollton)	27%

6.0 GOAL 2: RELIABILITY RESULTS

This section presents results for performance measures under Goal 2: Reliability, as shown in **Table 6-1**.

Table 6-1: Goal 2 objectives and performance measures.

Goals	Objectives	Performance Measures
2. Improve reliability and on-time performance. Reliability & OTP	2.1 Maintain or increase percentage of trains arriving on time.	Train headway adherence from Rosslyn to Stadium-Armory
	2.2 Maintain or increase the percentage of customers completing their trips on time.	Total minutes saved (AM peak rail trips for select O/D pairs)
	2.3 Minimize the number of significant trip delays.	Delay percent on BOS central corridor

6.1 Train Headway Adherence

For the purposes of projecting performance out to 2040, one of the on-time performance (OTP) measures is train adherence to headways. This analysis modeled train OTP results by using three thresholds for defining headway adherence:

- Threshold 1: Trains are late when more than ten minutes late
- Threshold 2: Trains are late when more than five minutes late
- Threshold 3: Trains are late when more than one minute late

The percentage of trains arriving on time decreases the closer the performance threshold gets to zero (perfect headway adherence). Threshold 3 is therefore the most stringent; any train more than one minute late contributes to reducing overall OTP. Performance was modeled for each alternative on the BOS corridor from McLean, Vienna, and Pentagon to Minnesota Ave and Benning Road in the east. When the OTP threshold is 10 minutes, all alternatives achieved OTP above 90%, and performed within 0.8 percentage points of each other. The highest performer was the No-Build, and the lowest was the LCC Alt. At Threshold 2 (five minutes), all alternatives again scored above 90% and within 2.5 percentage points of each other, again except for the LCC Alt. But the results change significantly using Threshold 3 (one minute), the most stringent definition. The headway adherence spread widened to 20 percentage points between alternatives, and the best-performing alternatives, Alt 5D (New Carrollton) and the LCC Alt, fell below 90% OTP. The other alternatives, including the No-Build, demonstrated 70-75% OTP.

Table 6-2 summarizes results for all thresholds, but the CBA uses only Threshold 3 values. Note that the headway adherence results shown here differ from those in Appendix A: BOS Alternatives Evaluation Matrix, because the Alternatives Evaluation Matrix considers only stations between Rosslyn and Stadium-Armory, inclusive. This focuses the evaluation on the interlined portion of the BOS corridor.

For method details for this measure, see Appendix D: Operating Scenarios and Impacts Assessment.

Table 6-2: All alternatives ranked by headway adherence.

Alternative	10-Min	Rank	5-Min	Rank	1-Min	Rank
No-Build	99.09%	1	97.63%	3	71.19%	5
LCC Alt	90.46%	6	90.46%	6	87.02%	1
Alt 3A (Greenbelt)	98.39%	4	95.84%	4	75.18%	3
Alt 3C (National Harbor)	98.39%	4	95.84%	4	75.18%	3
Alt 5A (SV Express)	99.05%	3	97.66%	2	70.59%	6
Alt 5D (New Carrollton)	99.06%	2	98.00%	1	86.76%	2

Colors indicate lower performance → higher

The No-Build performed best in terms of headway adherence at 99.09 percent at 10 minutes and 97.63 percent at 5 minutes. In both cases this alternative was within one percentage point of the top ranked alternative, 5D. However, the No-Build performs second worst at the one-minute threshold behind Alt 5A (SV Express) which experiences conflicts stemming from normal and express service.

The rail component of the LCC Alt performed best at 87 percent headway adherence at the one-minute threshold, but performed worst at both the five- and ten-minute thresholds. To keep headways equitable on the Orange Line, trains were scheduled three minutes apart, and in the interest of keeping Blue Line trains at equitable ten-minute headways, trains were scheduled evenly. If all rotations started on the top of the hour, every tenth train slot would overlap. In order to avoid this, Blue Line trains were shifted by 30 seconds. This slotting causes the headways to fall below the three-minute ideal minimum threshold. BRT OTP is expected to be 83.2% based on a peer review synthesis of comparable operating systems; however, to compare alternatives accurately, only rail OTP values were used in the evaluation.

Alt 3A (Greenbelt) and Alt 3C (National Harbor) are statistically the same, and the same model was used for both alternatives. This result is because in both alternatives, the Blue Line breaks away from the core simulated network before Rosslyn and runs through a second tunnel downtown. The complete separation of the Blue Line in this alternative prevented cascading delays from affecting the core. Alt 3A (Greenbelt) performed fourth and fifth at five- and ten-minute thresholds, respectively.

Alt 5A (SV Express) performed second best with 99.1 percent headway adherence at 10 minutes and best with 98 percent headway adherence at the five-minute threshold. It performs second worst at the one-minute threshold due to conflicts stemming from normal and express service.

Alt 5D (New Carrollton) performed best with 99.1 percent headway adherence at the 10-minute threshold, best with 98 percent headway adherence at five minutes, and second best with 86.8 percent headway adherence at one minute. Alt 5D (New Carrollton) had fewer conflicting moves than 5A due to the lack of an express track, improving its performance relative to Alt 5A (SV Express).

6.2 Travel Time Savings

Rail travel time savings were assessed for the AM peak period, in terms of total minutes saved across trips between selected OD pairs. The results are shown in **Table 6-3**. All alternatives provide rail travel time savings except for the LCC Alt. Because this alternative incorporates turnback movements, some passengers would need to transfer, which adds time to these trips. For example, a passenger traveling from Wiehle-Reston East to Foggy Bottom would need to transfer from the Silver Line to the Orange Line at West Falls Church. Alt 5A (SV Express) produces large travel time savings due to the assumed express service, while Alt 5D (New Carrollton) produces large travel time savings for trips to/from New Carrollton.

For method details for this measure, see Appendix C: Ridership Estimates and Capacity.

Table 6-3: Total minutes saved in the AM peak.

Alternative	Total minutes saved in AM peak
No-Build	-
LCC Alt	-5
Alt 3A (Greenbelt)	5
Alt 3C (National Harbor)	5
Alt 5A (SV Express)	42
Alt 5D (New Carrollton)	78

6.3 Train Delay Percent

Another reliability measure used was train delay percent. This measures the delay experienced, on average, compared to an ideal trip. In other words, the amount of delay compared to the scheduled trip. Additional measures shown in **Table 6-4** are shown for interest but are not included in the CBA.

The No-Build showed much more delay in the core at the one-minute threshold. The scheduling decision was made to provide equitable headways on all lines; however, with 6/6/12 headways in the core, this service pattern would cause every fourth train of the Orange/Silver lines to overlap with the Blue Line trains at 12-minute increments. This scenario was adjusted by shifting away from a three-minute core headway to a 3:00/3:00/2:30/0:30 headway which caused cascading delays at the junctions.

The LCC performed worst in delay percent. See Section 6.1 Train Headway Adherence above for more detail on the LCC schedule assumptions Alternatives 3A and 3C, statistically identical as discussed above, performed best overall in delay percent.

For method details for this measure, see Appendix D: Operating Scenarios and Impacts Assessment.

Table 6-4: All alternatives ranked by other operations performance metrics.

Alternative	Ave. Speed w/o Dwell	Rank	Ave. Speed w/ Dwell	Rank	Total Elapsed Time	Rank	Delay %	Rank	Delay per 100-Train Miles	Rank
No-Build	26.4	2	25.8	2	0:29:56	2	0.56%	5	1.43	5
LCC Alt	22.6	6	22.2	6	0:40:50	4	0.70%	6	2.18	6
Alt 3A (Greenbelt)	23.9	4	23.5	4	0:44:22	5	0.24%	1	0.64	1
Alt 3C (National Harbor)	23.9	4	23.5	4	0:44:22	5	0.24%	1	0.64	1
Alt 5A (SV Express)	29.6	1	28.1	1	0:27:59	1	0.40%	3	1.08	3
Alt 5D (New Carrollton)	26.4	2	25.8	2	0:29:56	2	0.52%	4	1.36	4

Colors indicate lower performance → higher

7.0 GOAL 3: FLEXIBILITY RESULTS

This section presents results for the performance measures under Goal 3: Flexibility as shown in **Table 7-1**. For method details for this measure, see Appendix E: Flexibility Method.

Table 7-1: Goal 3 objectives and performance measures.

Goals	Objectives	Performance Measures
3. Improve operational flexibility and cost-efficiency. Flexibility & Cost-Efficiency	3.1 Minimize the travel time impacts of work zones and disruptions.	AM peak-hour BOS passengers able to avoid single tracking at maximum load points
	3.2 Meet ridership demand cost-effectively.	O&M costs per revenue mile
	3.3 Provide flexibility to match service levels to changes in ridership.	Percent change in train miles traveled to nearest pocket track after PPC falls below 50

7.1 BOS Passengers Able to Avoid Single Tracking

To understand the potential improvement the alternatives would offer in reducing impacts to passengers due to work zones or incidents, the CBA compared the total number of passengers traveling through maximum load points. This serves as an indication of whether the alternatives provide additional routing options for passengers—system redundancy—to avoid single-tracking when it occurs. The percent change from the No-Build was calculated to quantify the reduction in passengers impacted under each build alternative.

All alternatives reduced the potential impacts of single-tracking, with Alternatives 5A and 5D providing the largest reduction by providing parallel track on a high-ridership segment in Northern Virginia that allows passengers to take either the Silver or Orange to avoid single tracking on the other line (**Table 7-2**). While Alt 5A (SV Express) provides a longer parallel express track than Alt 5D (New Carrollton), the reductions in other segments of the alignment for Alt 5D (New Carrollton) result in a higher overall reduction in passengers impacted by single tracking.

Table 7-2: BOS passengers able to avoid single tracking.

	Percent change from No-Build
No-Build	-
LCC Alt	-7.2%
Alt 3A (Greenbelt)	-13.2%
Alt 3C (National Harbor)	-14.5%
Alt 5A (SV Express)	-32.1%
Alt 5D (New Carrollton)	-34.3%

7.2 O&M Costs per Revenue Mile

Net annual operating and maintenance (O&M) costs per revenue mile were calculated to understand the impact of new service on Metro's budget. Estimated fare revenue was subtracted from O&M costs and the resulting value was divided by revenue miles. All rail build alternatives reduce O&M costs per revenue mile compared to the No-Build, while the LCC Alt increases those costs due to the need to deploy a large number of buses and operators vs. trains to attain the modeled service levels (**Table 7-3**). Outside of this increase, differences between alternatives are not large. Detail on O&M costs can be found in section 9.2 Operating and Maintenance Costs.

Table 7-3: O&M costs per revenue mile.

	O&M costs per revenue mile
No-Build	$20.58
LCC Alt	$22.55
Alt 3A (Greenbelt)	$20.12
Alt 3C (National Harbor)	$19.50
Alt 5A (SV Express)	$19.81
Alt 5D (New Carrollton)	$20.01

7.3 Percent Change in Train Miles Traveled to Nearest Pocket Track

Pocket tracks allow trains to short turn, or turn around, before the end of the line. For example, a Yellow Line train to Greenbelt could short turn at Mt. Vernon Square during rush hour to provide additional capacity in the core during peak periods. This reduces the cost of trains operating to Greenbelt if additional train capacity is not needed on outer portions of the line. This ability to match service to ridership is measured among the alternatives by determining how far a train would need to travel to reach a pocket track where it could turn around after ridership falls below 50 PPC. Results for each build alternative were compared to the No-Build.

Table 7-4 shows that two alternatives, 3C and 5D, increase the distance to pocket tracks after PPC falls below 50 while three alternatives (LCC, 3A, and 5A) reduce that distance. The largest reduction is provided by the LCC Alt because it specifically includes additional pocket track infrastructure as a key component. The largest increase in distance is provided by Alt 5D (New Carrollton); most of the new portion of track—between Mt. Vernon Square and New Carrollton—shows ridership below 50 PPC, adding a considerable distance to reach the pocket track at New Carrollton.

Table 7-4: Percent change in train miles traveled to nearest pocket track.

	Percent change in train miles traveled to nearest pocket track
No-Build	-
LCC Alt	-46%
Alt 3A (Greenbelt)	-7%
Alt 3C (National Harbor)	3%
Alt 5A (SV Express)	-4%
Alt 5D (New Carrollton)	36%

8.0 GOAL 4: SUSTAINABILITY RESULTS

This section presents results for the performance measures under Goal 4: Sustainability as shown in **Table 8-1**. For all measures in this section except for transit mode share, method details are in Appendix F: Land Use and Development Impacts. Transit mode share method details are in Appendix C: Ridership Estimates and Capacity.

Table 8-1: Goal 4 objectives and performance measures.

Goals	Objectives	Performance Measures
4. Provide transportation options that support sustainable development and expand access to opportunity. Sustainability & Equity	4.1 Increase corridor transit mode share.	Transit mode share
	4.2 Support transit-oriented development (TOD).	Within half-mile station walkshed: a. Household density b. Employment density
	4.3 Expand access to economic opportunity for equity populations.	a. People in EEAs with new access to HCT w/in half-mile station walkshed b. Avg total jobs accessible w/in 45 minutes from stations in EEAs

8.1 Transit Mode Share

Transit mode share is a key measure for assessing the benefits of a transit investment as it indicates the attractiveness of a transit project compared to other modes of travel. Alt 3C (National Harbor) produces the highest transit mode share for AM peak work trips, 39%, with the remaining alternatives performing within a narrow range between 35 and 36 percent (**Table 8-2**).

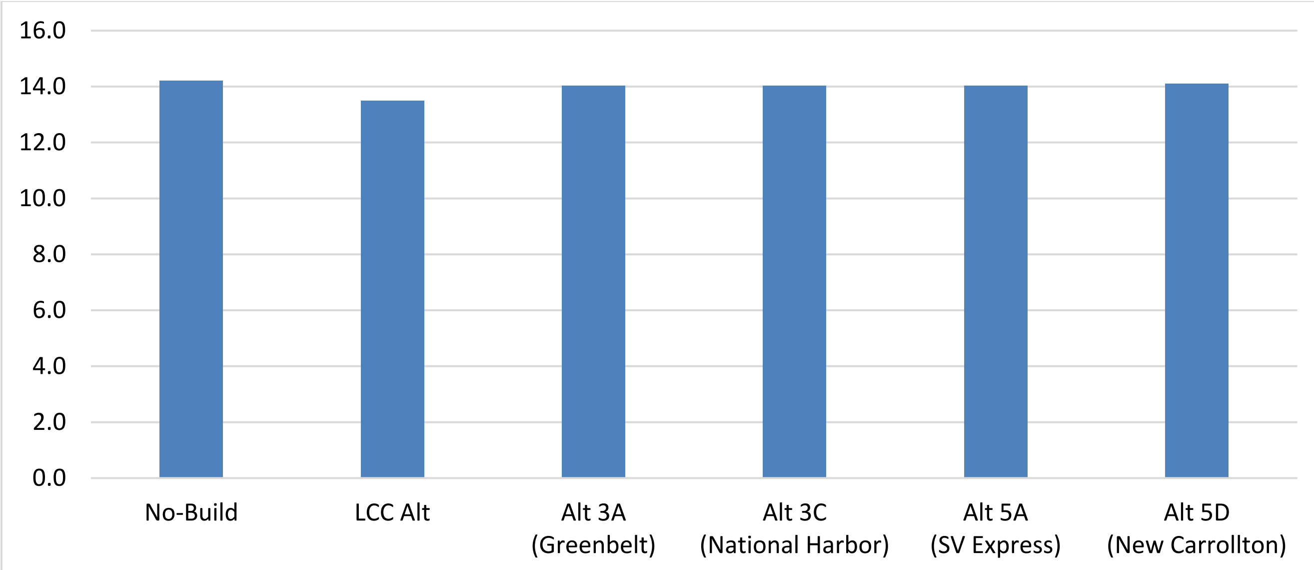
Table 8-2: Transit mode share.

	Transit mode share
No-Build	35%
LCC Alt	36%
Alt 3A (Greenbelt)	36%
Alt 3C (National Harbor)	39%
Alt 5A (SV Express)	36%
Alt 5D (New Carrollton)	36%

8.2 Household and Employment Density

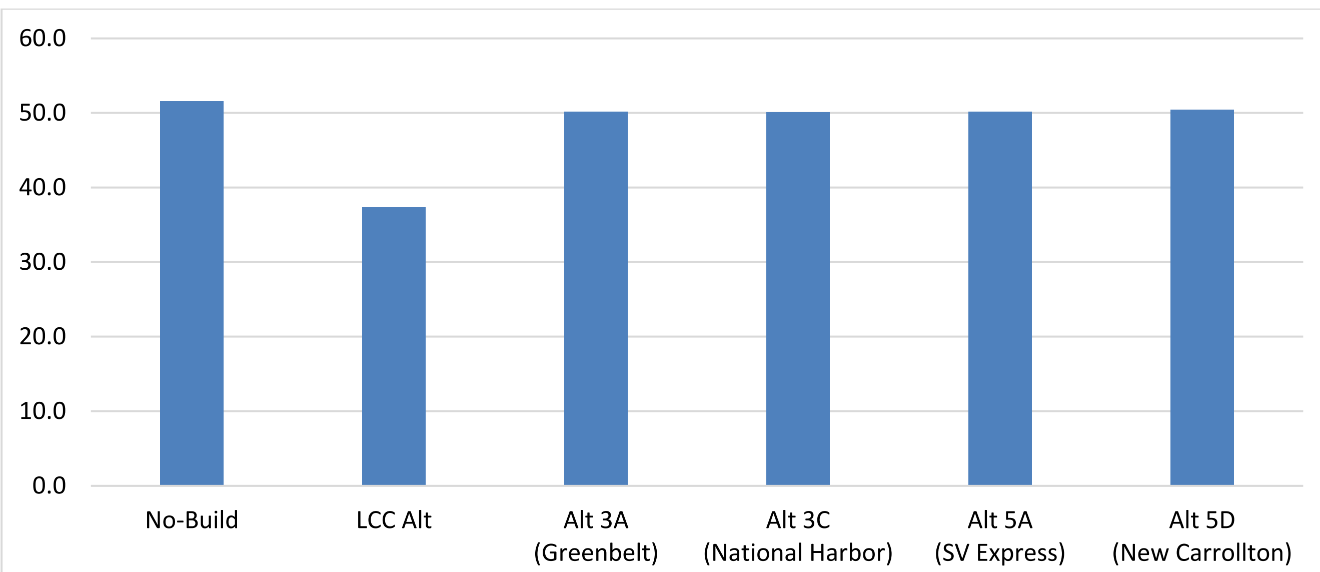
Household and employment density indicate to some degree how well land use and transit investments are linked. Higher densities around transit stations mean that more people will benefit from transit investments by having high-capacity service within walking distance of home or work. It also means the transit service is more likely to carry financially sustainable levels of ridership, as densities of people, jobs, and activity combined with ease of access to transit largely determine ridership demand. **Figure 8-1** and **Figure 8-2** below identify the household and employment density, respectively, that fall within station walksheds.

Figure 8-1: Household density within half mile walkshed.



Based on **Figure 8-1**, it appears that average household density across alternatives will be comparable in 2040. The difference between the highest serving alternative (No-Build) and least-highest serving alternative (LCC Alt) is only 0.7 households per acre.

Figure 8-2: Employment density within half mile walkshed.



Based on the results shown in **Figure 8-2**, it appears that most alternatives will serve a roughly similar density of jobs in 2040. The one exception is the LCC Alt, which includes new bus and BRT routes that serve a number of lower-density areas compared to the No-Build and the rail build alternatives.

Similar to results for household density, alternatives serve comparable densities. However, the difference between the highest serving alternative (No-Build) and least-highest serving alternative (LCC Alt) is 14.3 jobs per acre, a larger difference than seen for household density.

The No-Build serves slightly higher densities than build alternatives in these results because many of the areas to be served by the build alternatives are either already built-up (for example, new stations in Rosslyn or downtown DC) or forecasts of population and employment already considers growth in those station areas (for example, new stations at St. Elizabeths for Alt 3C (National Harbor)). While these results are used in the CBA, a separate investigation of induced demand stemming from Metrorail expansion was completed to understand the potential impacts of transit investment on land use in station areas. Details are in section F.4 Induced Demand.

8.3 People in EEAs with New Access to Transit

Figure 8-3 below identifies the cumulative number of individuals living within Equity Emphasis Areas (EEAs) that would also be located within station walksheds. This analysis was used to identify how each alternative performed in terms of extending new access to high-capacity transit (HCT) to people living in EEAs who currently do not have ready access to HCT.

Figure 8-4 shows the number of individuals gaining access to HCT under each alternative, *relative to the No-Build*. This is an easy way to see how many more people in EEAs are served by HCT. Alt 3C (National Harbor) would offer the greatest expansion of new access to HCT in EEAs relative to the No-Build, expanding station walksheds to an additional 35,000 residents of EEAs. This alignment travels through southeast DC and to National Harbor, most of which is designated as EEAs with high-population station areas in 2040.

Figure 8-3: EEA populations within half mile walkshed.

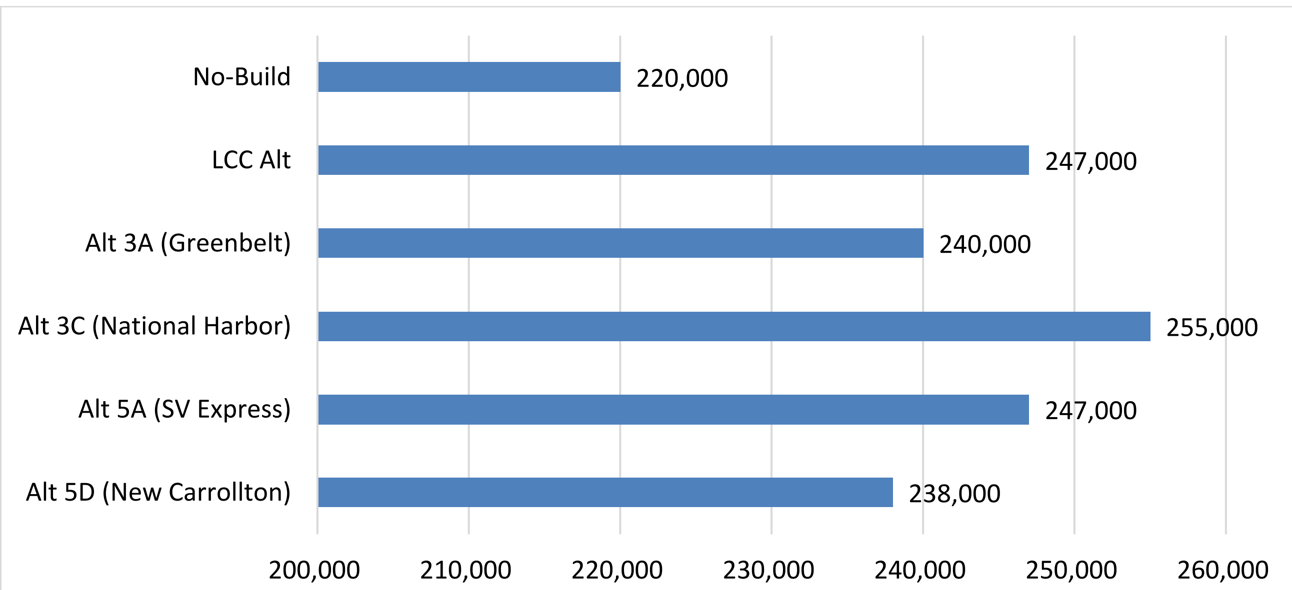
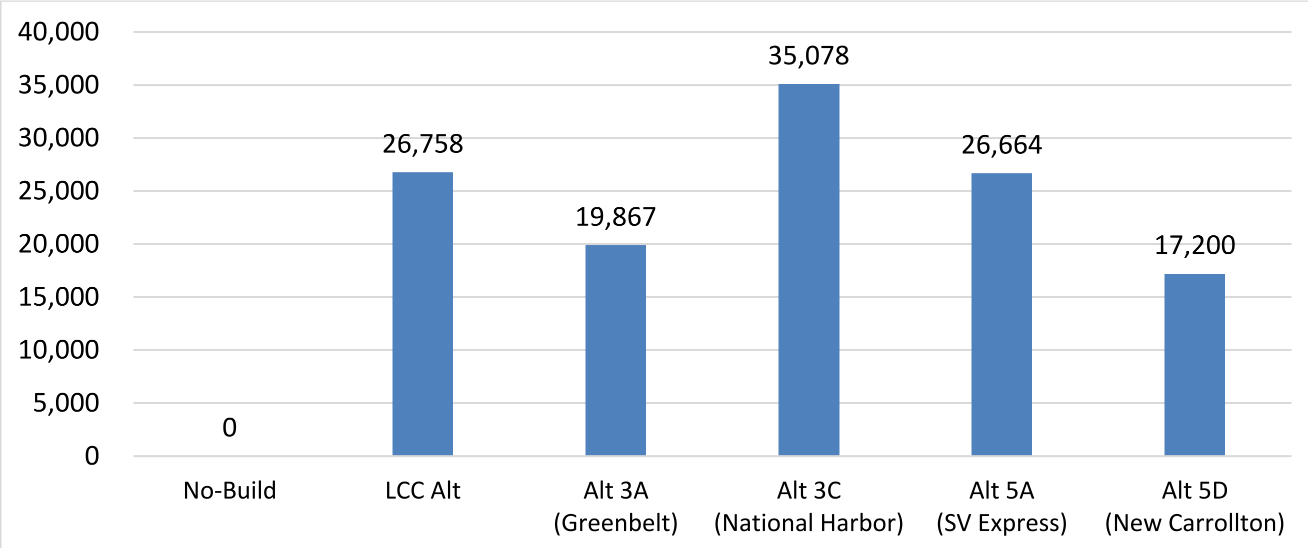


Figure 8-4: Number of people in EEAs with new access to high-capacity transit within half mile station walksheds, vs. No-Build



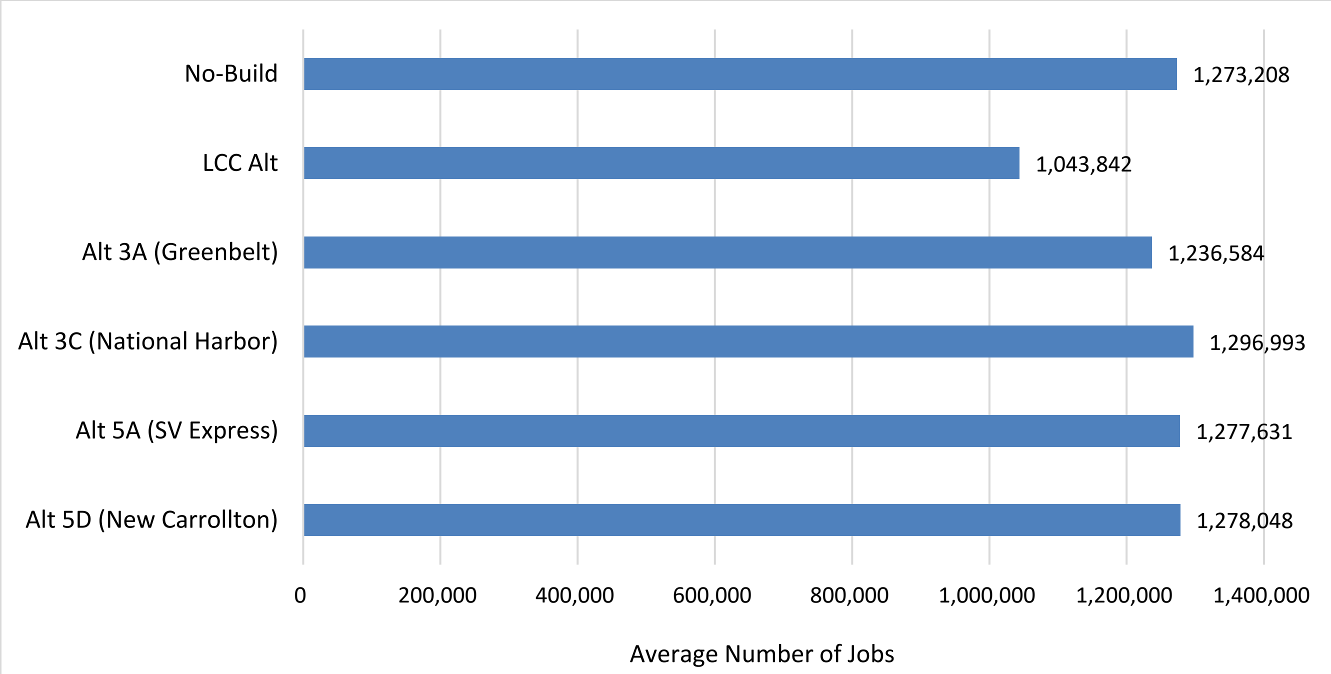
8.4 Average Total Job Accessibility

Figure 8-5 below identifies the total number of jobs accessible within 45 minutes of stations located in EEAs for each alternative. The measure quantifies how well new transit would connect individuals to employment opportunities in the region by counting the number of jobs reachable within 45 minutes using transit from the origin station.

Based on the results provided in **Figure 8-5**, Alt 3C (National Harbor) will provide access to the largest number of jobs within 45 minutes from 67 EEA stations, followed by Alt 5A (SV Express) and 5D with 17,000 fewer accessible jobs. Only three of the five build alternatives increase the number of jobs accessible compared to the No-Build. The LCC Alt's lower performance is likely due to the large number of EEA stations served that have lower levels of employment and therefore bring down the overall average of accessible jobs. Its lower performance may also be due to lower speeds of buses compared to rail, though all bus routes were designed with considerable priority so this may not be a large impact.

Alt 3A (Greenbelt) shows lower performance because it serves less employment-rich areas in the eastern portion of the study area compared to Alt 5D (New Carrollton). While Alt 5A (SV Express) has a similar eastern alignment as Alt 3A (Greenbelt), Alt 5A (SV Express) has two additional stations in the core where high numbers of jobs are located.

Figure 8-5: Average number of jobs accessible within 45 minutes of EEA stations.



9.0 ESTIMATES OF CAPITAL COSTS, OPERATING COSTS, RIDERSHIP, AND FARE REVENUE

The following sub-sections summarize the methods, assumptions, and outcomes of estimating each alternative's capital costs, operating and maintenance (O&M) costs, and passenger fare revenue.

9.1 Capital Costs

Planning-level conceptual capital costs for the alternatives were developed using the Federal Transit Administration's (FTA) Standard Cost Category (SCC) structure and format as noted in **Table 9-1**. This is common practice for alternatives analysis studies and aligns with FTA guidance.

Table 9-1: Capital cost elements included in estimate.

SCC Element	Details
10	Guideway, Track, and Structures (including Special Trackwork) (LCC Alt also includes the planned D&G Pocket Track expansion). Per Linear Feet (LF) unit costs were used for all horizontal infrastructure elements.
20	Stations including entrances and vertical circulation (LCC Alt also includes the Ballston and Farragut West Station improvements). Per station unit costs varied depending on the station type (i.e., at-grade, elevated, mined tunnel).
30	Yard and Facilities improvements to accommodate storage and maintenance of the additional fleet (assumed expansion build-out at the Silver Line Phase 2 Yard). Estimates of capital cost for Silver Line Phase 2 Maintenance Yard Expansion were developed as a conceptual or representative cost for the expansion within the footprint of the Silver Line Phase 2 Yard set to open in 2021. This expansion of this facility is not necessarily intended to be the location for maintenance and storage of additional fleet subject to a more detailed fleet management analysis that should indicate the optimal yard storage and maintenance locations to minimize deadheading.
40	Sitework and Special Conditions including Utility Relocations.
50	Systems including Train Control & Communications, Signals and Traction Power. Per Linear Feet (LF) unit costs were used for all horizontal infrastructure elements.
60	Right-of-Way (ROW) Acquisition. The planning level capital cost estimates estimated ROW or purchase of land related costs by assuming these costs to be approximately two percent of the Construction Cost Subtotal (addition of capital cost estimates for elements under SCC10-50).
70	Revenue vehicles, in the case of this study railcars. Assumed new procurement for purchase of 8000 series+, and per vehicle unit costs were based on historical purchase of 7000 series railcars.
80	Professional Services costs elements including: • Preliminary Engineering/NEPA • Final Design • Project Management for Design and Construction • Construction Administration & Management

SCC Element	Details
	• Professional Liability and other Non-Construction Insurance • Legal; Permits; Review Fees by other agencies, cities, etc. • Surveys, Testing, Investigation, Inspection • Start up These are assumed to be 36.5 percent of the Construction Cost Subtotal. Estimates for different elements under this costs category were based on best practices and guidelines developed by the FTA and Transportation Research Board's (TRB's) Transit Cooperative Research Program (TCRP) including TCRP Report 138
90	An Unallocated Contingency cost was assumed to account for uncertainties and the fact that the costs were estimated based on planning level design and information. Unallocated Contingency cost rate of 25 percent was applied to the subtotal of SCC elements 10-70.* No allocated contingency was included per individual SCC category or line item to account for complexity factors of working in an urban environment with limited access, design allowances, or commodities/market risk.
100	Itemized Finance costs (which could be significant for a program of this size) were not included.

* The 25 percent contingency is at the low end of the range of rates typically used for capital cost estimates developed using planning level information (between 25 and 40 percent). FTA has assigned contingency levels between 20 and 30 percent at the completion of preliminary engineering, which is approximately equivalent to a 30 percent level of design.

The horizontal infrastructure (right-of-way tracks and tunnels) needed for each alternative was quantified and calculated by track structure type (underground, at-grade, or aerial structures) based on concept level designs (**Table 9-2**). The cost of each track structure type varies, with underground segments the most expensive, followed by aerial segments, then at-grade segments. Cost estimates also quantified the number of new stations by station type and the number of new revenue vehicles required (railcars for the rail alternatives, buses for the LCC Alt).

Table 9-2: Proposed corridor right-of-way length and configuration.

Alternatives	No-Build	LCC	3A	3C	5A	5D
Proposed Corridor Length (mi. of guideway)	0.00	2.02	19.68	22.61	27.94	15.56
At-Grade Segment	0.00	1.56	9.28	0.77	9.73	0.53
Aerial Segment	0.00	0.00	0.00	7.18	0.00	0.00
Underground Segment	0.00	0.46	10.39	14.66	18.22	15.03

Unit costs used for estimates were developed using FTA's Capital Cost Database (latest version). The FTA Capital Cost Database is a Microsoft Access database of as-built costs tracked in FTA's SCCs for 54 federally funded projects and is intended for performing historical cost analysis and developing order-of-magnitude cost estimates for conceptual transit projects. The FTA Capital Cost Database data was calibrated using available cost data from previous Metro or regional projects. This included information from Metro's Capital Needs Inventory (CNI), its Connect Greater Washington Study (2014) and Silver Line Junction Feasibility Study (2016), and cost data utilized in the Silver Line Phase I estimates.

Planning-level capital cost estimates for the LCC Alt include:

- Station Capacity and Access Improvement projects (SCC 20) – estimates of capital costs based on information from Metro's previous planning studies, which include:
    1) Second Entrance at Ballston Station
    2) Farragut West Station Improvements
    3) Metro Center Station Improvements
    4) L'Enfant Plaza Station Access Improvements
- Enhanced bus services (SCC 30) – capital cost estimates include vehicle acquisition for both commuter and BRT services, build-out of park-and-ride facilities, jurisdictional bus prioritization measures, stations and passenger amenities, and a storage and maintenance facility.

Based on the planning-level capital cost estimates, Alt 5A (SV Express) has the highest capital cost and the LCC Alt has the lowest capital cost (**Table 9-3**). When placing capital costs within the context of corridor length, or how much it costs to build one mile of each potential project, Alt 5D (New Carrollton) has the highest cost per mile and Alt 3A (Greenbelt) the lowest cost per mile (**Table 9-4**).

Table 9-3: Planning-level capital cost estimate (in millions, 2020 dollars).

Alternatives	Range Low	Range High	Average
No-Build	0	0	0
LCC Alt	2,300	2,810	2,555
Alt 3A (Greenbelt)	14,900	18,200	16,550
Alt 3C (National Harbor)	19,900	24,400	22,150
Alt 5A (SV Express)	21,400	26,100	23,750
Alt 5D (New Carrollton)	16,750	20,450	18,600

Table 9-4: Planning level capital cost per mile of proposed corridor (in millions, 2020 dollars).

Alternative	Range Low	Range High	Average
No-Build	0	0	0
LCC Alt	1,141	1,394	1,267
Alt 3A (Greenbelt)	757	925	841
Alt 3C (National Harbor)	880	1,079	980
Alt 5A (SV Express)	766	934	850
Alt 5D (New Carrollton)	1,078	1,317	1,198

9.2 Operating and Maintenance Costs

Planning-level O&M cost estimates were developed using Metro's O&M Cost Model (2016).

All the assumptions already built into and used by the model were maintained for this study, with the exception of the cost drivers that differed per alternative. These cost drivers included the following factors: revenue hours (bus and train), track-miles, peak vehicles (bus and railcars), revenue miles (bus and railcar), number of elevators and escalators, number of mezzanines, number of stations, and/or unlinked trips (bus and rail). Operations metrics were calculated using a proprietary timetable analysis spreadsheet model. Results are summarized in **Table 9-5**.

Table 9-5: O&M cost inputs for each alternative.

	Train Revenue Hours	Track-Miles	Peak Rail Cars	Revenue Car Miles
No-Build	1,993	247	1,352	416,254
LCC Alt	1,840	249	1,352	386,760
Alt 3A (Greenbelt)	2,018	275	1,408	430,446
Alt 3C (National Harbor)	2,117	284	1,472	443,294
Alt 5A (SV Express)	2,048	291	1,432	440,537
Alt 5D (New Carrollton)	2,025	275	1,416	434,176

Colors indicate values lower → higher

Alt 5A (SV Express) had the highest number of track miles (291 miles) and generated the second-highest number of train revenue hours (2,048 hours), car revenue miles (440,537 miles), and peak railcars (1,432 cars). The LCC Alt had the lowest number of new track miles (249 miles total) and generated the second lowest number of train revenue hours (1,840 hours), car revenue miles (386,760 miles), and peak railcars (1,352 cars, same as the No-Build).

O&M Cost Model outputs were used to compare alternatives and understand the relative difference in O&M cost impacts that one alternative would have relative to the No-Build. More detailed O&M cost estimates will be prepared for the LPA based on additional design in future project development work.

Based on the above method, relatively speaking, Alternatives 3C and 5A are expected to require the greatest increase in Metro's O&M costs relative to the No-Build (**Table 9-6**).

Table 9-6: Summary of O&M cost impact for alternatives relative to the No-Build (in millions, 2020 dollars).

	Relative to No-Build
LCC Alt	$78.1 M
Alt 3A (Greenbelt)	$106.5 M
Alt 3C (National Harbor)	$176.4 M
Alt 5A (SV Express)	$165.2 M
Alt 5D (New Carrollton)	$115.7 M

9.3 Ridership and Revenue

Table 9-7 shows both the total and net change in forecasted annual systemwide linked trips and associated revenue for each alternative. Alt 3C (National Harbor) would attract over 51 million annual linked trips and over $154 million in revenue *in addition to* trips and revenue attracted by the No-Build. The LCC Alt would perform slightly better than the No-Build, and the four rail build alternatives seem to perform consistently better than the LCC Alt by a greater margin.

Table 9-7: Annual systemwide linked trips and revenue.

Alternative	Weekday linked trips	Weekday linked trips increase from No-Build	Annual linked trips	Annual linked trips increase from No-Build	Annual revenue	Annual revenue increase from No-Build
No-Build	867,000	-	247,983,000	-	$742,600,000	-
LCC	883,000	16,000	252,539,000	4,556,000	$756,244,000	$33,969,000
3A	960,000	92,000	274,422,000	26,440,000	$821,775,000	$79,175,000
3C	1,047,000	180,000	299,473,000	51,490,000	$896,791,000	$154,191,000
5A	1,006,000	139,000	287,839,000	39,856,000	$861,953,000	$119,352,000
5D	961,000	94,000	274,844,000	26,861,000	$823,038,000	$80,437,000

APPENDIX A: BOS ALTERNATIVES EVALUATION MATRIX

Colors indicate scores from lowest to highest performance: 1 2 3 4

Goal	Measure	Score ranges (alternative)	No-Build	LCC Alt	Alt 3A (Greenbelt)	Alt 3C (National Harbor)	Alt 5A (SV Express)	Alt 5D (New Carrollton)
1. Capacity	1. Passengers per car (PPC) at maximum load points	1 = above 120 or below 50 2 = 111-120, or 50-80 3 = 106-110, or 81-90 4 = 91-105	123	100	99	98	106	106
	2. Vertical circulation V/C ratio at Rosslyn, Metro Center, L'Enfant Plaza, Union Station (% change)	1 = 0% to -7% 2 = -8 to -15% 3 = -16 to -23% 4 = -24 to -31%	0%	-2%	-12%	-29%	-21%	-23%
	3. Percent of select OD pairs with additional route choices compared to No-Build	1 = 0% 2 = 1-25% 3 = 26-50% 4 = 50% or more	0%	16%	31%	28%	74%	27%
2. Reliability	1. Train headway adherence Rosslyn to Stadium-Armory	1 = 70% and lower 2 = 71-76% 3 = 77-83% 4 = 84-100%	68.80%	81.00%	75.59%	75.59%	69.31%	87.65%
	2. Total minutes saved (AM peak rail trips between select OD pairs)	1 = no saving or increase 2 = 1-29 minutes 3 = 30-59 minutes 4 = 60 minutes or more	0	-5	5	5	42	78
	3. Delay percent of run time on BOS central corridor (AM peak)	1 = 0.75-0.84% 2 = 0.65-0.74% 3 = 0.55-0.64% 4 = 0.45-0.54%	0.70%	0.80%	0.45%	0.45%	0.54%	0.73%
3. Flexibility	1. AM peak hour BOS passengers able to avoid single tracking at max load points (% change)	1 = 0% 2 = -1 to -10% 3 = -11 to -20% 4 = -21% or more	0%	-7.2%	-13.2%	-14.5%	-32.1%	-34.3%
	2. Operating and maintenance costs per revenue vehicle mile	1 = $22.00-22.99 2 = $21.00-21.99 3 = $20.00-20.99 4 = $19.00-19.99	$20.58	$22.55	$20.12	$19.50	$19.81	$20.01
	3. Percent change in train-miles traveled to nearest pocket track after PPC falls below 50	1 = 25-50% 2 = 0 to 24% 3 = -24 to -1% 4 = -50 to -25%	0%	-46%	-7%	3%	-4%	36%
4. Sustainability	1. Transit mode share (AM peak work trips)	1 = 30-32% 2 = 33-35% 3 = 36-38% 4 = 39-41%	35%	36%	36%	39%	36%	36%
	2a. Household density within one half mile station/stop walksheds	1 = 13.0-13.99 2 = 14.0-14.99 3 = 15.0-15.99 4 = 16.0 and above	14.2	13.5	14.0	14.0	14.0	14.1
	2b. Employment density within one half mile station/stop walksheds	1 = 0-49 2 = 50-99 3 = 100-149 4 = 150 and above	51.6	37.3	50.1	50.1	50.1	50.4
	3a. Number of people in EEAs with new access to HCT within one half mile station/stop walksheds	1 = 0-9,999 2 = 10,000-19,999 3 = 20,000-29,999 4 = 30,000-39,999	0	26,758	19,867	35,078	26,664	17,200
	3b. Average number of jobs accessible within 45 min from stations/stops in EEAs	1 = 1,199,999 and below 2 = 1,200,000-1,239,999 3 = 1,240,000-1,279,999 4 = 1,280,000 and above	1,273,208	1,043,842	1,236,584	1,296,993	1,277,631	1,278,048

Ridership, revenue, and costs	No-Build	LCC Alt	Alt 3A (Greenbelt)	Alt 3C (National Harbor)	Alt 5A (SV Express)	Alt 5D (New Carrollton)
Annual total systemwide linked trips	247,982,878	252,538,858	274,422,434	299,473,174	287,839,266	274,843,998
Annual fare revenue over NB (2040)	$0	$33,969,401	$79,174,920	$154,190,942	$119,352,470	$80,437,320
Annual O&M costs over NB (2040)	$0	$78,091,238	$106,529,054	$176,375,217	$165,207,253	$115,654,073
Annualized capital cost over NB (2040)	$0	$101,057,524	$407,762,944	$549,742,433	$584,002,125	$484,079,092
Total capital cost	$0	$2,557,073,082	$16,514,577,820	$22,150,025,328	$23,757,643,224	$18,572,152,501
Total capital cost minus 25% contingency	$0	$2,445,473,559	$13,211,662,256	$17,720,020,262	$19,006,114,579	$14,857,722,001

Annualized improvement cost over NB (2040)	$0	$145,179,361	$435,117,078	$571,926,708	$629,856,908	$519,295,845

Goal	Measure	Score ranges	Scores: No-Build	LCC Alt	Alt 3A (Greenbelt)	Alt 3C (Natl. Harbor)	Alt 5A (SV Express)	Alt 5D (New Carrollton)
1. Capacity	1. Passengers per car (PPC) at maximum load points	1 = above 120 or below 50 2 = 111-120, or 50-80 3 = 106-110, or 81-90 4 = 91-105	1	4	4	4	3	3
1. Capacity	2. Vertical circulation V/C ratio at Rosslyn, Metro Center, L'Enfant Plaza, Union Station (% change)	1 = 0% to -7% 2 = -8 to -15% 3 = -16 to -23% 4 = -24 to -31%	1	1	2	4	3	3
1. Capacity	3. Percent of select OD pairs with additional route choices compared to No-Build	1 = 0% 2 = 1-25% 3 = 26-50% 4 = 50% or more	1	2	3	3	4	3
2. Reliability	1. Train headway adherence Rosslyn to Stadium-Armory	1 = 70% and lower 2 = 71-76% 3 = 77-83% 4 = 84-100%	1	3	2	2	1	4
2. Reliability	2. Total minutes saved (AM peak rail trips between select OD pairs)	1 = no saving or increase 2 = 1-29 minutes 3 = 30-59 minutes 4 = 60 minutes or more	1	1	2	2	3	4
2. Reliability	3. Delay percent of run time on BOS central corridor (AM peak)	1 = 0.75-0.84% 2 = 0.65-0.74% 3 = 0.55-0.64% 4 = 0.45-0.54%	2	1	4	4	4	2
3. Flexibility	1. AM peak hour BOS passengers able to avoid single tracking at max load points (% change)	1 = 0% 2 = -1 to -10% 3 = -11 to -20% 4 = -21% or more	1	2	3	3	4	4
3. Flexibility	2. Operating and maintenance costs per revenue vehicle mile	1 = $22.00-22.99 2 = $21.00-21.99 3 = $20.00-20.99 4 = $19.00-19.99	3	1	3	4	4	3
3. Flexibility	3. Percent change in train-miles traveled to nearest pocket track after PPC falls below 50	1 = 25-50% 2 = 0 to 24% 3 = -24 to -1% 4 = -50 to -25%	2	4	3	2	3	1
4. Sustainability	1. Transit mode share	1 = 30-32% 2 = 33-35% 3 = 36-38% 4 = 39-41%	2	3	3	4	3	3
4. Sustainability	2a. Household density within one half mile station/stop walksheds	1 = 13.0-13.99 2 = 14.0-14.99 3 = 15.0-15.99 4 = 16.0 and above	2	1	2	2	2	2
4. Sustainability	2b. Employment density within one half mile station/stop walksheds	1 = 0-49 2 = 50-99 3 = 100-149 4 = 150 and above	2	1	2	2	2	2
4. Sustainability	3a. Number of people in EEAs with new access to HCT within one half mile station/stop walksheds	1 = 0-9,999 2 = 10,000-19,999 3 = 20,000-29,999 4 = 30,000-39,999	1	3	2	4	3	2
4. Sustainability	3b. Average number of jobs accessible within 45 min from stations/stops in EEAs	1 = 1,199,999 and below 2 = 1,200,000-1,239,999 3 = 1,240,000-1,279,999 4 = 1,280,000 and above	3	1	2	4	3	3
Annualized improvement cost over NB (2040)			$0	$145,179,361	$435,117,078	$571,926,708	$629,856,908	$519,295,845

Goal	Scores summarized by goal and overall: No-Build	LCC Alt	Alt 3A (Greenbelt)	Alt 3C (Natl. Harbor)	Alt 5A (SV Express)	Alt 5D (New Carrollton)
1	26	61	78	95	87	78
2	35	41	71	71	72	85
3	36	43	55	55	68	50
4	59	61	69	100	80	74
Benefits score	40	53	69	83	77	74
Benefits score (over NB)	0	13	29	43	37	34
Benefits rank	-	5	4	1	2	3
CE score	0	87	68	75	59	65
CE rank	-	1	3	2	5	4

APPENDIX B: CBA SCORING AND EVALUATION METHOD DETAILS

The CBA is based on 14 performance measures, each linked to an objective which in turn is linked to one of the four goals. These linkages directly connect the study's Purpose and Need to the evaluation of alternatives in order to help identify an LPA that will address the corridor's goals and needs.

The alternatives received a score for each performance measure, as well as overall composite scores for Benefits and Cost-Effectiveness. Those results were calculated and recorded in an Alternatives Evaluation Matrix which includes the metrics, data, scoring calculations, and results.

Once data were entered into the Alternatives Evaluation Matrix, score categories were determined based on natural breaks in the data. Each performance measure required the use of specific models and other data analysis tools, but all measures were assessed on a common scale of one to four with a four representing the best performance. Those points were determined by value ranges or 'buckets' based on natural breaks in the data. Each measure had a specific set of numerical ranges governing what values received which scores. The examples below illustrate how data breaks were used to set scoring buckets, and how those scoring buckets translated into points:

- Passengers per Railcar at Maximum Load Points
    - 1 = above 120 or below 50
    - 2 = 111-120, or 50-80
    - 3 = 106-110, or 81-90
    - 4 = 91-105
- Number of People in Equity Emphasis Areas with New Access to High-Capacity Transit within Half-Mile Walkshed
    - 1 = 0-9,999
    - 2 = 10,000-19,999
    - 3 = 20,000-29,999
    - 4 = 30,000+

The results were then used to calculate two overall, composite scores for each alternative: Benefits and Cost-Effectiveness. The Benefits score was calculated by combining the scores for individual measures within each goal category (Capacity, Reliability, etc.), to obtain a single score for that goal. Each measure was multiplied by its assigned weight before being added to the others and multiplied by 100 to obtain an easy-to-understand score. The goal scores ranged from 0 to 100, with 100 representing the best possible performance. The formula for this combination of individual measure scores to a single goal score is:

$$(Measure_1 Score * Weight_1 + Measure_2 Score * Weight_2 + Measure_3 Score * Weight_3) * 100 = Goal\ Score$$

The result of the above calculation is four overall goal scores (one for each goal). To combine these four scores into an overall alternative Benefits score, the following formula was used:

$$Goal_1 Score * Weight_1 + Goal_2 Score * Weight_2 + Goal_3 Score * Weight_3 + Goal_4 Score * Weight_4 = Benefits\ Score$$

To quantify the improvement each alternative provides *over and above the No-Build*, the No-Build's Benefits score was subtracted from the Benefits score for each alternative. For example, the No-Build received an overall Benefits score of 42 out of 100. The LCC Alt received a Benefits score of 52, or 10 once the No-Build results were subtracted. This provides a better view of the marginal benefits each build alternative would deliver over and above the No-Build, while still allowing the build alternatives to be comparatively ranked and assessed against each other. Benefits scores for each alternative were then ranked to compare performance between and among alternatives.

$$Benefits\ Score_{LCC} - Benefits\ Score_{No\ Build} = Benefits\ Score_{LCC}$$

The Benefits score shows whether each alternative (including the No-Build) could attain the four corridor goals, and how successful each would be in doing so. In other words, it shows the scale of benefits and impacts each alternative offers compared to each other and the likely future.

However, benefits and impacts also need to be placed in context with the likely costs of providing those benefits. To assess each alternative's performance in this regard, the CBA also calculated a Cost-Effectiveness score, which is an alternative's Benefits score divided by a total, annualized improvement cost. The total annualized improvement costs were determined by adding an alternative's capital costs and estimated annual operating and maintenance (O&M) costs, then subtracting projected annual passenger fare revenue:

$$\begin{aligned} &Annual\ O\&M\ costs - \ Annual\ fare\ revenue + Annualized\ capital\ cost \\ &= Relative\ total\ annualized\ improvement\ cost \end{aligned}$$

Capital costs were annualized by summing the calculated annualized figures for individual line items in the FTA Standard Cost Categories worksheets, using the FTA's recommended annualization factor for each item. For more details on each alternative's estimated capital and operating costs, see Section 9.0: Estimates of Capital Costs, Operating Costs, Ridership, and Fare Revenue.

The total annualized improvement cost for each alternative was then divided by \$1 billion. The Benefits score was then divided by this annualized cost factor to obtain a Cost-Effectiveness score for each alternative. This ensured that alternatives were compared equally and that the resulting Cost-Effectiveness scores are reasonable, understandable, and usable values (rather than small decimals or extremely large numbers, for example).

$$\frac{Benefits\ Score_{3A}}{\left(\frac{Annualized\ improvement\ cost_{3A}}{\$1\ billion}\right)} = Cost\ effectiveness$$

The Cost-Effectiveness score indicates the relative magnitude of benefits per dollar spent for each alternative. These values can be directly compared, with the largest value indicating the alternative that might offer the greatest benefits or impact per dollar spent.

For the initial CBA evaluation all performance measures and goals were equally weighted. An additional CBA scoring was performed using variable weights based on feedback from the study's stakeholder committees. See Section 10.3: Stakeholder Weighting Process for more detail on the weighting exercise.

APPENDIX C: RIDERSHIP ESTIMATES AND CAPACITY

C.1 COG/TPB Model

The BOS Study used the designated metropolitan planning organizations' (MPO) regional travel demand model for ridership and capacity estimates. The Metropolitan Washington Council of Governments' (COG)/National Capital Region Transportation Planning Board's (TPB) model Version 2.3.75 was recently adopted and used in the Air Quality Conformity Determination of the 2018 Financially Constrained Long Rang Transportation Plan (*Visualize 2045*) and FY 2019-2024 Transportation Improvement Program (TIP) and reflects the latest regional planning assumptions.

Two major inputs to the model include: 1) the transportation network developed for the *Visualize 2045* long-range transportation plan and the FY 2019-2024 TIP and 2) the land use forecasts of population and employment by TAZ in the MWCOG Round 9.1 Cooperative Forecasts. For this study, the model's performance was further reviewed and checked for the reasonableness of its application to the BOS Study area. Model estimates for the base year were summarized in terms of system ridership, BOS ridership, and travel patterns. The Metrorail System stations were classified to 22 station groups, and passenger flows were tabulated among the 22 station groups for the base year and 2040. Model estimates of ridership and travel patterns were compared with the observed ridership and forecasts from Metro's LineLoad tool.

The BOS alternatives were coded in the COG/TPB model, reflecting the key service characteristics of the build alternatives such as station locations, transfers, frequency/headways, and run time/speed. The COG/TPB model generates person-trips by mode and assigns the transit trips to the transit network, with the results for two time periods of the day: a combined AM/PM peak period and an off-peak period. These results were tabulated in terms of boardings, alightings, and where applicable, transfers.

C.2 WMATA LineLoad Application

Metro's LineLoad Application is a custom-developed tool that distributes the load of passengers across the Metrorail system based on their points of entry and exit, and allows estimation of passenger loads on the rail system per station link (between Metrorail stations). LineLoad can be used to project those outputs to the planning horizon year of 2040 by applying trip growth factors based on extrapolations from Metro's Short-Term Ridership Forecasts (July 2018). It estimates trips for new Metrorail stations based on station-to-station forecasts generated by the MWCOG regional travel model. The LineLoad tool provides baseline forecasts of passengers by segment, including maximum load points such as the Rosslyn Tunnel.

C.3 Method

The objective of this analysis is to evaluate the selected BOS alternatives in terms of key performance measures in ridership and capacity in the BOS corridor. To serve this purpose, results were integrated from the two modeling tools discussed above, because the COG/TPB model consistently overestimates rail ridership.

The LineLoad Application results serve as the No-Build baseline, which reflects the officially adopted forecasts for Metrorail ridership and travel patterns. The COG model was used to generate forecasts under build alternatives, representing the responses of transit demand to these build alternatives under the officially adopted planning assumptions, including the socioeconomic and land use forecasts and planned transportation networks.

The difference between the No-Build baseline and each build alternative in the COG model results reflect the effects of build alternatives on ridership and travel patterns; the percentage difference was used as a multiplier applied to No-Build LineLoad outputs. This procedure of model output refinements and post-processing is consistent with the recommended practice in the NCHRP Report 765, Analytical Travel Forecasting Approaches for Project-Level Planning and Design (2014) and VDOT's Travel Demand Modeling Policies and Procedures (2020). Model output refinement and post-processing are an established practice to account for the uncertainties and errors of forecasts generated by travel demand models.

A simplified outline of the process for refining the COG/TPB model using LineLoad data is provided below:

1. The 2040 No-Build baseline was established using the WMATA LineLoad Application and Short-Term Ridership Forecasts
2. BOS build alternatives were coded into the 2040 COG/TPB regional model, in terms of service characteristics such as alignments, station locations, frequency/headways, and run time/speed.
3. The 2040 COG/TPB regional model was run for all alternatives.
4. The differences in model results between each build alternative and the No-Build were computed. The percentage difference in these values were then used as a multiplier to No-Build LineLoad values to obtain values for each build alternative.

C.4 Performance Measures

The procedures for developing some of the key performance measures include:

- **AM Peak Ridership:** AM peak-hour boardings were summarized using the LineLoad results. The peak-period boardings from the COG/TPB model runs represent the AM transit boarding patterns and the percentage differences were computed between build alternatives and No-Build baseline and represent the effects of the build alternatives. The LineLoad AM peak hour boardings were used as the base to derive AM peak hour boardings for build alternatives, with incremental changes derived by multiplying the LineLoad AM peak ridership by the percentage differences between build alternatives and No-Build baseline computed from the COG/TPB model runs.
- **Average Weekday Ridership:** Similarly, weekday boardings were computed for build alternatives, using the LineLoad daily boardings as the baseline, with adjustments using the percentage differences in daily boardings between build alternatives and No-Build baseline from the COG/TPB model runs.
- **Daily Passenger Miles:** In the same way, daily passenger miles were calculated for build alternatives. Annual passenger miles were computed using an annualization factor of 286, which reflects the weekday and weekend ridership distribution from recent Metro data.
- **Transfer Station Demand/Activity:** Station activities for key transfer stations in the BOS lines were tabulated, including entries, exits, and transfers. Again, the LineLoad results were used as the baseline, and the COG/TPB model results were used for post-processing and

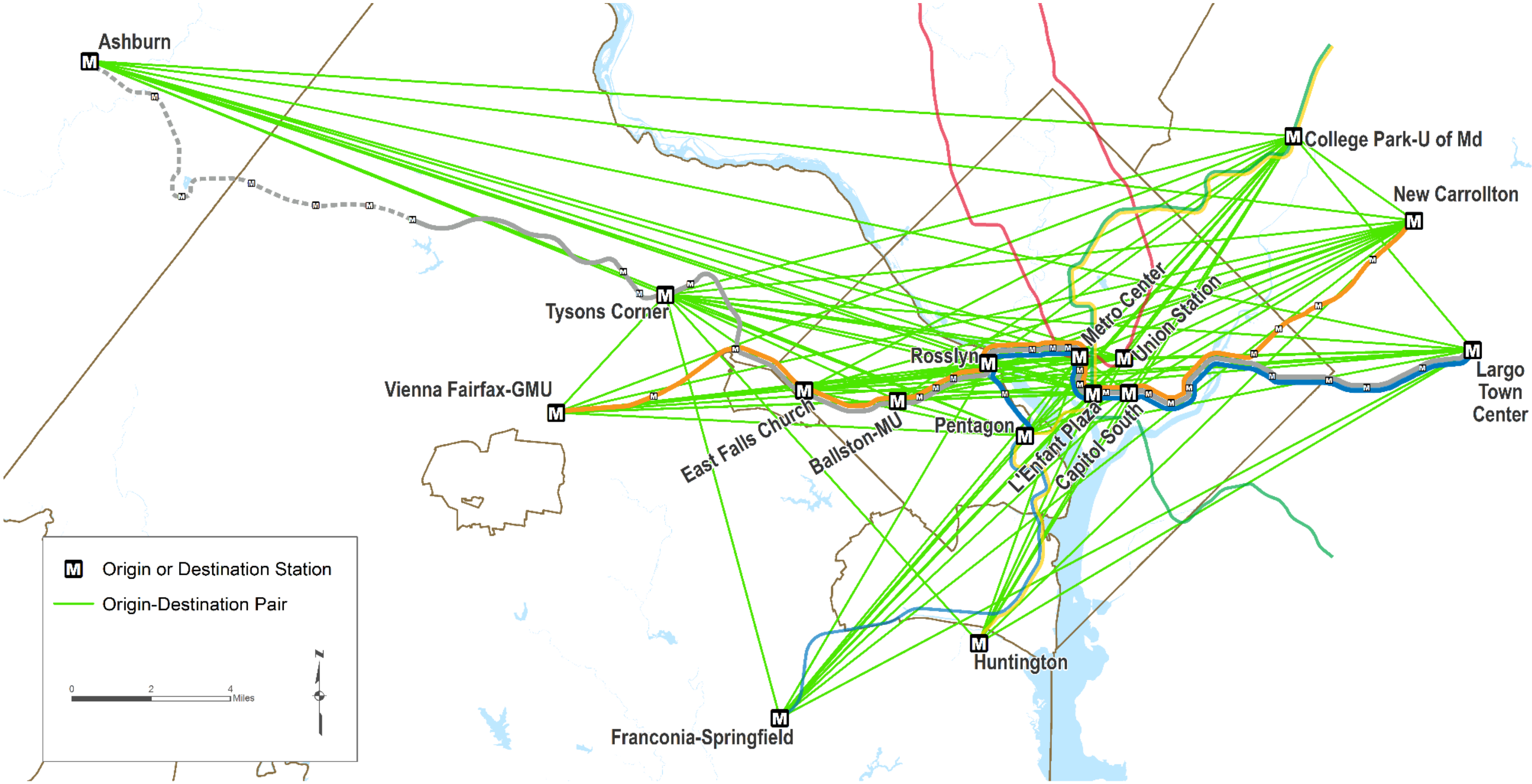
adjustments. Peak hour vertical circulation volume/capacity was calculated by first determining the maximum AM peak hour volume and dividing it by the station's vertical circulation capacity to determine the peak hour volume to capacity ratio. This V/C ratio was then multiplied by the peak hour peak direction volume of passengers at that station. An average value across all four stations (Rosslyn, Metro Center, Union Station, and L'Enfant Plaza) was then calculated to indicate overall alternative performance using a single value for each alternative (**Table C-1**).

- **Peak Passengers Per Car:** AM peak hour loads (passenger volume) for station pairs were computed from the LineLoad and used as the baseline. These were post-processed to reflect the effects of build alternatives, using the COG/TPB model results.
- **Mode share:** Modal shares for AM peak work trips were computed using the COG/TPB mode choice results. A one-mile buffer was used to delineate the TAZs around stations, except for the terminal stations where a five-mile buffer was utilized. Because of the differences in the alignments for build alternatives and No-Build baseline, the areas included in the computation of modal shares were different for different alternatives.
- **Changes to transit travel times:** Metrorail travel times were compiled from the COG/TPB model, including in-vehicle time, initial wait time, and transfer time, for representative station pairs in the BOS corridor. Total minutes saved in the AM peak were calculated for each alternative, reflecting the changes in frequency/headways, transfers, and run time.

Table C-1: Vertical circulation volume to capacity ratio.

Alt.	Data	Rosslyn		Metro Center		Union Station		L'Enfant Plaza		Avg. V/C
		Entries/Exits	Transfers	Entries/Exits	Transfers	Entries/Exits	Transfers	Entries/Exits	Transfers	
No-Build	Max peak hour volume	2,943	1,089	8,333	5,171	6,272	-	6,129	11,890	0.57
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.34	0.13	0.30	0.43	0.48	-	0.24	1.15	
	Weighted V/C	1,002	137	2,511	2,211	3,036	-	1,449	13,636	
LCC	Max peak hour volume	3,030	1,121	8,315	5,380	6,693	-	6,390	11,519	0.56
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.35	0.13	0.30	0.44	0.52	-	0.25	1.11	
	Weighted V/C	1,063	145	2,501	2,393	3,457	-	1,575	12,799	
3A	Max peak hour volume	4,492	743	8,873	3,830	6,753	-	6,396	9,737	0.51
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.52	0.09	0.32	0.32	0.52	-	0.25	0.94	
	Weighted V/C	2,336	64	2,848	1,213	3,518	-	1,578	9,145	
3C	Max peak hour volume	5,615	928	9,174	3,804	4,967	-	6,359	6,069	0.41
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.65	0.11	0.33	0.31	0.38	-	0.25	0.59	
	Weighted V/C	3,649	100	3,044	1,197	1,904	-	1,560	3,553	
5A	Max peak hour volume	5,494	928	8,830	3,107	4,110	-	6,283	8,369	0.45
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.64	0.11	0.32	0.26	0.32	-	0.24	0.81	
	Weighted V/C	3,493	100	2,820	798	1,304	-	1,523	6,755	
5D	Max peak hour volume	3,029	349	8,810	3,216	6,714	-	6,301	8,181	0.44
	Peak hour capacity	8,640	8,640	27,648	12,096	12,960	-	25,920	10,368	
	Peak hour V/C	0.35	0.04	0.32	0.27	0.52	-	0.24	0.79	
	Weighted V/C	1,062	14	2,807	855	3,478	-	1,532	6,455	

Figure C-1: OD pairs used for measure "percent of O/D pairs served by multiple routes."



APPENDIX D: OPERATING SCENARIOS AND IMPACTS ASSESSMENT

This section describes the operations analysis effort, including the rail simulation modeling method and assumptions incorporated into the operations simulation models.

D.1 Rail Data

Method

The analysis was completed using two tools: Berkeley Simulation Software's Rail Traffic Controller® (RTC) simulation software[1], and a proprietary timetable analysis tool.

RTC is an operations simulation package widely used to simulate the operations of rail transit systems to test and evaluate operating plans, proposed capital improvements and infrastructure alternatives, and impacts to existing services at a detailed and realistic level. Each alternative was simulated in RTC for development and comparison to simulation results for operational metrics.

The first step for this analysis was to develop a No-Build RTC simulation model. The model was built for the section of track from Minnesota Ave and Benning Road in the east to McLean, Vienna, and Pentagon in the south/west. All three (Blue/Orange/Silver) lines operate on this section, so it was most important to understand an alternative's impact in this section of track. Because the whole system was not being modeled, the simulation models were set up to allow for dwell time randomization as well as entry delay randomization. The first accounts for varying levels of customers that take more or less time to board, and the second includes proxies for delayed trains due to unforeseen situations, both of which reflect the reality of running a complex rail network.

The No-Build model was calibrated using FY18 train data provided by WMATA. After the No-Build model was developed and calibrated, each of the proposed build alternatives was built into the RTC model. The assumptions for each proposed alternative are described further in the Assumptions section below.

Once the infrastructure was built into the RTC models specific to each proposed alternative, the proposed service plans were then input into each RTC model and calibrated to resolve conflicts and minimize impacts under deterministic conditions.

The RTC software simulates trains operating under 'deterministic' and 'randomized' conditions.

- Under **deterministic** operations, all train equipment initially enters service on-time and follows fixed departure times and dwell times at stations according to the schedules.
- Simulating under **randomized** conditions allows for the introduction of randomized delays to the simulation in order to observe the effects on operations. This is important in order to determine the overall stability of an operation. Random delays happen in real day-to-day operations due to weather conditions, signal or track maintenance, malfunctioning equipment or disabled trains, or conflicts with other operations.

Speed Commands were programmed from the following source material[2]:

[1] http://berkeleysimulation.com/

[2] Because of missing data from WMATA during programming, speed commands for Rosslyn Junction (K&C junction) to Virginia Square were presumed using the "guess trailing signal" tool in RTC, stepping up from a zero-speed command to 65 miles per hour (although maximum track speeds were overlaid as required).

- Track charts – C, D, G, K, N routes
- Circuit plans – C, D, G, K, N routes
- Speed commands – C, D, G, K, N routes
- Metrorail_Safety_Rules_and_Procedures_Handbook_2018
- Headway Sheets_8mins_Dec2017_BOGYS_WKDY
- GTFS Service schedules_FY16 and FY18
- SV PHASE II DRAFT HEADWAYS BOOK ALL CALC 2 YARDS.xlsx
- C3788_WMATA-Core-Capacity_20151130
- Metrorail_vehicle_information.xlsx
- 7000 Series Performance Curve Data.xlsx
- 7000series_Train_Performance_and_Running_Simulation_extract

After calibrating the operations to FY2018 schedules and running the models under deterministic conditions, each model was then run under randomized conditions. Each proposed alternative simulation was run under randomized conditions 30 times, and results were compiled for comparison.

RTC records detailed operating statistics from every train along its route, allowing users to compare performance from the individual train to system level. For this analysis, results were compiled by station, direction, and time period for the following operational metrics:

- Headway Adherence
    1) For each separate alternative simulation model and randomized run, recorded arrival and departure times for each daily trip were used to calculate the headway between successive trains at every station in each direction.
    2) This calculated headway was then averaged across each model's 30 simulation runs for every train and station by direction and summarized by time period.
    3) These simulated headways were then used to determine headway adherence by comparing the same calculated headways from the provided schedule data. These were broken down by station stop location in the core by direction and period of day.
- Delay Percentage
    1) Delay percentage is the recorded travel time for a given trip divided by its ideal run time or run time with no conflicts from other trains or operations, expressed as a percentage.

Assumptions

Assumptions consistent across all alternatives include:

- Operating Hours: 5:00 AM – 11:30 PM
- Service Patterns: Weekday only, AM peak/midday/PM peak/evening
- Peak Hours: Before 9:30 AM and 3:00 PM – 7:00 PM
- All 8-car 7000-series trainsets in service

- Silver Line Phase 2 is operational
- Automatic Train Operation (ATO) is in service
- Traction power supply issues are resolved

Each alternative used the headways shown in **Tables D-1** through **D-6**. The No-Build was modeled with two headway scenarios: the current eight-minute peak schedule (Option 2) and an assumed return to six-minute peak service by 2040 (Option 1). The Option 1 six-minute schedule is consistent with the current *Metrorail Fleet Management Plan* and assumptions in the *Visualize 2045 Regional Long-Range Transportation Plan.* The Option 1 scenario was used for CBA evaluation.

Table D-1: No-Build headway assumptions.

Line	Terminals		OPT-1 Headways		OPT-2 Headways	
	From	To	Peak	Off-Peak	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6	4	6
Green	Greenbelt	Branch Ave	6	12	8	12
Yellow	Huntington	Greenbelt	6	12	8	12
Blue	Franconia	Largo	12	12	8	12
Orange	Vienna	New Carrollton	6	12	8	12
Silver	Ashburn	Largo	6	12	8	12

Table D-2: LCC Alt headway assumptions.

Line	Terminals		Headways	
	From	To	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6
Green	Greenbelt	Branch Ave	6	12
Yellow	Huntington	Greenbelt	6	12
Blue	Franconia	Largo	-	12
Blue/	Franconia	Stadium Armory	10	-
Orange	Vienna	New Carrollton	6	12
Orange	Vienna	Largo	6	12
Silver	Ashburn	Largo	-	12
Silver/	Ashburn	West Falls Church	6	-

Table D-3: Alt 3A (Greenbelt) headway assumptions.

Line	Terminals		Headways	
	From	To	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6
Green	Greenbelt	Branch Ave	6	12
Yellow	Huntington	Greenbelt	6	12
Blue	**Franconia**	**College Park II**	**6**	**12**
Orange	**Vienna**	**New Carrollton**	**6**	**12**
Silver	**Ashburn**	**Largo**	**6**	**12**

Table D-4: Alt 3C (National Harbor) headway assumptions.

Line	Terminals		Headways	
	From	To	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6
Green	Greenbelt	Branch Ave	6	12
Yellow	**Franconia**	Greenbelt	6	12
Blue	**Huntington (Loop)**	**Huntington (Loop)**	**6**	**12**
Orange	**Vienna**	**New Carrollton**	**6**	**12**
Silver	**Ashburn**	**Largo**	**6**	**12**

Table D-5: Alt 5A (SV Express) headway assumptions.

Line	Terminals		Headways	
	From	To	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6
Green	Greenbelt	Branch Ave	6	12
Yellow	Huntington	Greenbelt	6	12
Blue	**Franconia**	**Largo**	**6**	**12**
Orange	**Vienna**	**New Carrollton**	**6**	**12**
Silver - ARL Express	**Ashburn**	**College Park II**	**12**	**12**
Silver - ARL Local	**Ashburn**	**College Park II**	**12**	**12**

Table D-6: Alt 5D (New Carrollton) headway assumptions.

Line	Terminals		Headways	
	From	To	Peak	Off-Peak
Red	Shady Grove	Glenmont	3	6
Green	Greenbelt	Branch Ave	6	12
Yellow	Huntington	Greenbelt	6	12
Blue	**Franconia**	**Largo**	**6**	**12**
Orange	**Vienna**	**New Carrollton**	**6**	**12**
Silver	**Ashburn**	**New Carrollton**	**6**	**12**

D.2 Bus Data for the Lower Capital Cost Alternative

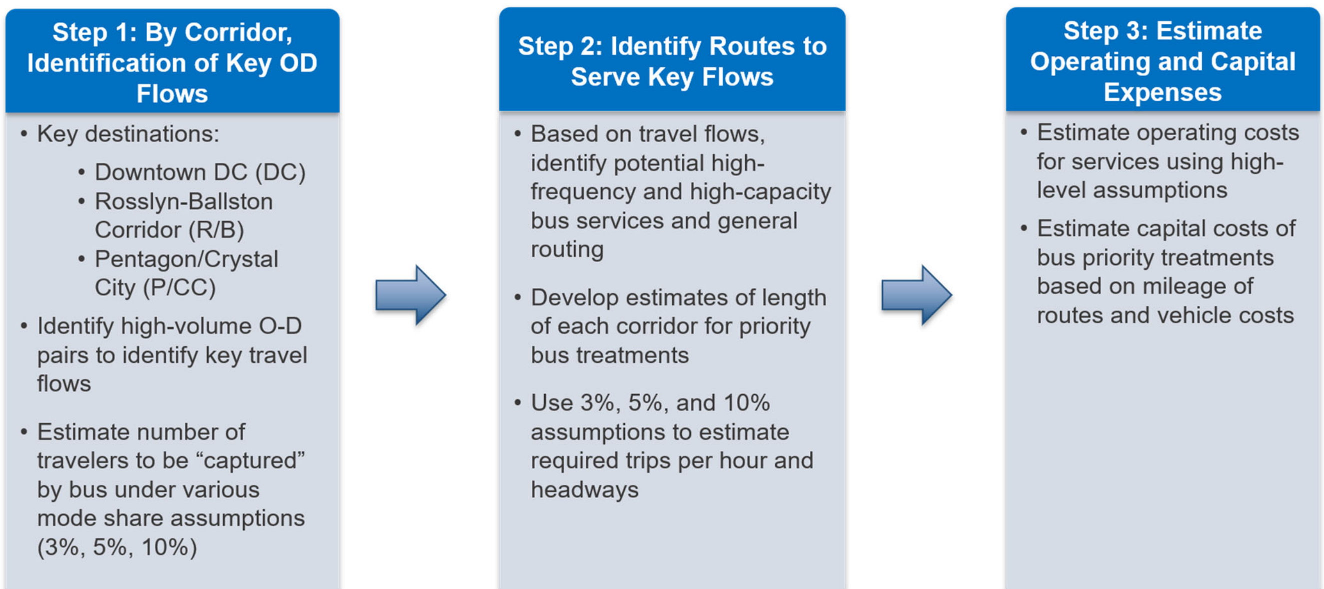
The LCC Alt includes an enhanced bus service component. The primary goal is to redirect approximately 3,000 commuters in the peak direction during the peak hour from BOS lines converging at Rosslyn to new commuter bus and BRT services.

Development of the Enhanced BOS Bus Element

Commuter trip flows from the latest version of the MWCOG/TPB travel demand model were reviewed to understand demand in three main corridors representing BOS rail service in northern Virginia: I-267/I-66, I-66, and I-95/I-395. Additionally, BOS commuter trip flows from closer-in areas of Arlington and Alexandria that are not attributable to those main highway corridors were analyzed. WMATA’s Metrorail passenger survey data on trip origins and destinations (O/Ds) was used to identify trips that could potentially be attracted to the new bus services. Trips with origins in the BOS corridor and destinations in either the Rosslyn/Ballston corridor, Pentagon/Crystal City, or Downtown DC were identified as an initial pool of trips that might be attracted to bus service if competitive travel times with Metrorail service could be provided. A review of existing service, existing and planned Park and Rides, and planned commuter services were also considered. The method for developing the Enhanced BOS Bus element is summarized in **Figure D-1**.

On the Maryland side of the corridor where capacity on BOS is less of an issue, areas where new commuter bus and BRT service could improve access to jobs, provide opportunities for economic development, and spur transit-oriented development were analyzed.

Figure D-1: Enhanced BOS bus method summary.



Stakeholder input was crucial to the development of the Enhanced BOS Bus element. Two meetings were held in early 2020 with jurisdictions and regional providers. The method for developing bus alternatives was presented at the first meeting. Based on the feedback received, a wide array of data and previous studies were analyzed and used to develop draft recommendations, which were presented at the next meeting. Feedback from that meeting, and additional written comments and comments received by phone, were used to adjust the draft recommendations to create the final Enhanced BOS Bus element.

The resulting bus services require 224 buses, of which 148 are commuter buses and 76 are BRT buses. Maps of these services are in section 2.0 Alternatives Evaluated.

Runtime

Travel time for each route was estimated using average speed by segment in GIS. Each of the 61 routes were split into segments based upon the type of road the route travels on, the number of stops along the segment, and historic speeds. For example, one route may begin at a Metrorail station on a local road before entering a facility with dynamic pricing to maintain speeds. In this instance, the segment on the local road is assigned one speed and the segment on the highway another. Pre-COVID-19 speeds were calculated using historic travel time data. In instances where travel time data was given as a timeframe, an average travel time was calculated and then used to calculate the segment's historic speed. Commuter routes with intermediary origin stop(s) have a time penalty that is converted into a lower average segment speed. These individual segments of varying lengths and speeds were then combined to determine the total travel time of one route.

Regional travel demand modelers were provided with routes, stops, a stop sequencing table which relates routes to the stops, and runtime for routes. This allowed inclusion of the LCC enhanced BOS bus network to be included with rail in modeling of the LCC Alt. Results of the model were discussed between modelers and bus network designers and adjustments were made to inputs to ensure ridership results were more realistic. In the first run, some BRT ridership was considerably over-estimated, and some commuter routes were considerably under-estimated. This is a common problem with the regional model because it is not calibrated to estimate bus ridership at the corridor or route level. After reviewing updated results, bus ridership estimates were used in aggregate (not broken down by route or corridor) and analysis proceeded.

Speeds and Bus Priority

After the route concepts were revised based on stakeholder feedback, congestion data was reviewed to identify where along the routes bus priority treatments are necessary to maintain relatively competitive speeds from origin to destination. The level of bus priority varies by location and context and includes TSP, queue jumps, and bus lanes. TSP is recommended at all major intersections along BRT corridors, while queue jumps are recommended at congested intersections where bus lanes are not present. Bus priority lanes are recommended for road segments with major congestion, and congestion was evaluated for both inbound and outbound trips during pre-COVID-19 AM and PM peaks. In some cases, bus priority treatments may be identified in the outbound direction to ensure cycle time reliability and to reduce deadhead time. Design also assumes other typical BRT treatments including real-time passenger information, branding, enhanced stops, off-board fare payment, automated enforcement, and all-door boarding (these assumptions impacted speed assumptions and will also impact costs on a per mile basis using industry standards).

In most cases the commuter bus route recommendations utilize toll roads that will be dynamically priced to maintain a specific speed. For these routes, information from tolling authorities about automobile speed was used, and reduced by ten percent to reach assumed bus speeds in order to account for typical bus operations. For example, I-66 will be tolled to maintain a minimum speed of 45mph for vehicles, so 40mph was assumed for buses. For arterials in northern Virginia and Prince George's County the speed and bus priority assumptions are highly context-sensitive given the widely varying nature of the facilities the buses will operate on. Information from BRT operations in Seattle, Minneapolis, and Albuquerque, in combination with existing speeds (pre-COVID-19), were used to develop average speed estimates for the BRT. These estimates range from 10-15 mph on average over the length of the corridor, but there are segments with higher speeds dependent on roadway and priority conditions. No segments will fall below 10mph due to bus priority treatments.

For DC, a network of peak-period bus lanes was assumed to ensure that both commuter routes and BRT could maintain relatively high speeds to their destination, as well as return to complete further runs. After reviewing existing data for the H St. NW & I St. NW bus lanes, planned operations of the 16th St. NW bus lanes, and in consultation with District Department of Transportation (DDOT), an average speed of 10mph on bus lanes in the District was identified for use in this study (including dwell time). Feedback from DDOT and Metro's Office of Bus Planning also informed the routing in DC and where priority treatments would be applied.

APPENDIX E: FLEXIBILITY METHOD

E.1 Avoiding Single Tracking

Ridership data (see Appendix C: Ridership Estimates and Capacity) was used to identify maximum load points in the AM peak hour for every alternative. Percent change was then calculated for each alternative relative to the No-Build.

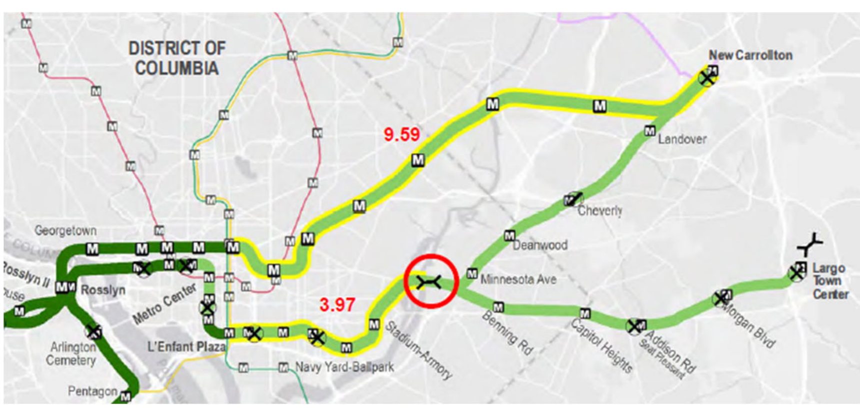
E.2 O&M Costs Per Revenue Mile

While O&M costs were estimated as useful standalone information (see section 9.2 Operating and Maintenance Costs), these values also served as one input into the calculation of O&M costs per revenue mile. Fare revenue was subtracted from O&M costs before dividing the resulting value by annual revenue car miles. Therefore, this measure assesses both the costs and revenue side of the equation for all alternatives to understand the net impact on Metro's operating costs.

E.3 Distance to Pocket Track

Pocket track locations from the existing system were assumed for all alternatives except for the LLC Alternative which specifically included two additional pocket tracks. Pocket track locations and AM peak direction ridership data in terms of PPC (see Appendix C: Ridership Estimates and Capacity) was plotted on GIS maps of alternative alignments. Track segments that are expected to have ridership under 50 PPC were highlighted and the distance to the nearest pocket track was measured. An example is shown in **Figure E-1**. Note this only shows a portion of the alternative. The light green areas show track segments with ridership less than 50 PPC and pocket tracks are denoted by the horizontal double-Y symbol. Red numbers denote distances between that were summed before calculating percent change from the No-Build.

Figure E-1: Distance to pocket track measurement example.



APPENDIX F: LAND USE AND DEVELOPMENT IMPACTS

F.1 Population and Employment

The analysis sought to evaluate the population and job density that is projected to exist within proposed station walksheds. As a baseline for 2040 jobs and population, the 2040 MWCOG travel demand model was used.

The following method was used to calculate the employment and household densities near stations based on 2040 MWCOG data:

1. Calculate proposed station walksheds at 0.5 miles. Walkshed buffers were drawn so that station walksheds do not overlap.
2. Determine overlap of station walksheds with MWCOG travel demand model Transportation Analysis Zones (TAZs).
3. Allocate proportionally employment and households from TAZs based on overlap with walksheds and sum all overlapping TAZs.
4. Divide by acreage of station areas.

F.2 Equity Populations

Analysis used Equity Emphasis Areas (EEAs), defined by the National Capital Region Transportation Planning Board (TPB), that identify significant concentrations of low income and/or minority populations. The following method was used to calculate equity populations within station walksheds:

1. Calculate proposed station walkshed at 0.5 miles. Walkshed buffers were drawn so that station walksheds do not overlap.
2. Identify EEA areas tracts with index scores greater than 4 as defined by TPB.
3. Proportionally allocate population from 2040 MWCOG projections based on overlap with EEA Tracts and sum all overlapping TAZs.
4. Proportionally allocate population from EEAs (Step 3) to station walksheds.

F.3 Employment Access

This analysis sought to evaluate the number of jobs accessible within 45 minutes from high-capacity transit stations in EEAs. For the purposes of this analysis, EEA stations are those that have more than one EEA person in the station walksheds based on the method above.

To develop 45-minute travel sheds, the following method was used:

1. Develop GTFS data for each alternative using hypothetical timetables of proposed Metrorail operations and existing WMATA bus operations.
2. Integrate the GTFS data into a Network dataset.
3. Run 45-minute Service Areas from each EEA Station departing at the station exactly at 8:00 AM.
4. Clip station service areas in step 3 to no more than 15 minutes walking distance from any Metro transit stop to limit service areas to transit-accessible locations only.

5. Proportionally allocate employment from 2040 MWCOG projections based on overlap of service areas from step 4 and sum all overlapping TAZs.

F.4 Induced Demand

Because some alignments are located in areas that were not originally planned to have Metrorail access, some of these future population and job projections were modified with "induced demand" projections based on observed induced demand growth trends at Metrorail stations in other parts of the region. This assessment of induced demand was an additional analysis performed at the request of jurisdictional stakeholders and is not included in the core CBA. It should be viewed as an informational addendum. A more robust and intensive analysis of land use and development impacts from the LPA can be undertaken during the project development phase, after conclusion of this study.

To account for induced demand, rather than using the 2040 employment and household projections from the travel demand model, the following method was used (also see **Figure F-1**):

1. Identify comparable station typologies from recent Metro expansion.
    a. Franconia-Springfield (1997) to represent western station areas.
    b. Largo Town Center (2004) to represent eastern station areas.
    c. NoMa-Gallaudet (2004) to represent core station areas.
2. Identify a 20-year growth rate for those station typologies using a combination of historic census data (1970 – 2010) and MWCOG TAZ growth (2020 – 2040). Twenty-year growth rates at each station are:
    a. Franconia-Springfield: +68 percent
    b. Largo Town Center: +51 percent
    c. Noma-Gallaudet: +207 percent
3. Apply station typology growth rates to 2020 employment and household projections from the MWCOG travel demand model within station walksheds (see Step 3 above).
4. Compare the results of steps 1-3 against those generated for 2040 by the MWCOG model and choose the higher of the two. Note the following points:
    a. In a few cases for stations that are considered eastern but are within the District of Columbia, the NoMa-Gallaudet growth rate rather than the Largo Town Center growth rate was applied because the Largo Town Center growth rate was lower than that of the MWCOG model. These stations include Ivy City and Union Market.
    b. The MWCOG rates were used for H St. NE as this area has already experienced new development with the DC Streetcar and adding the full impact of the rates derived from Largo Town Center seemed unrealistic.
    c. The stations where the MWCOG rate is retained are Bellevue, Buzzard Point, Forest Heights, Georgetown, Hyattsville, St. Elizabeth's, Stanton Park, Thomas Circle, and West End.

Figure F-1: Induced demand calculation method.

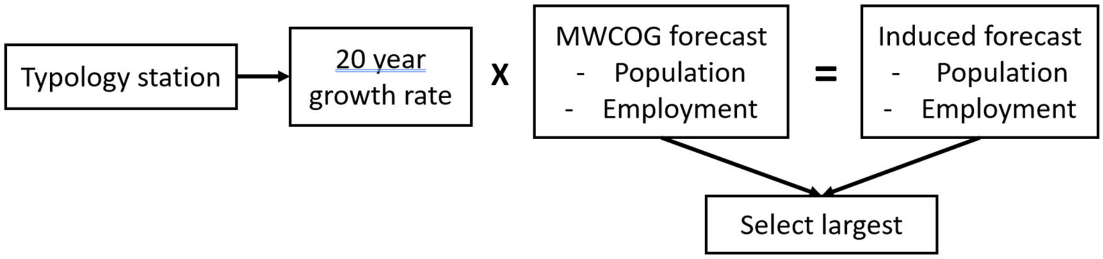


Table F-1 and **Table F-2** provide the results of calculating induced demand around the proposed Metrorail stations based on historic induced demand patterns. Per this analysis, Alt 5D (New Carrollton) would see the largest amount of growth in population and employment, followed by Alt 3A (Greenbelt). Alt 3C (National Harbor) is anticipated to have the least amount of induced demand because many of the station areas are already expected to grow in current plans, and thus accounted for in MWCOG's Cooperative Forecasts. For example, the area around the proposed station at St. Elizabeth's is already under redevelopment and growth has been factored into MWCOG forecasts. Therefore, using the MWCOG forecast captures much of the demand induced by a new Metrorail station. This can be seen in **Table F-1** where MWCOG and induced demand values are compared.

Table F-1: Percent growth between 2020 and 2040 for population and employment: MWCOG versus induced demand method.

	MWCOG Projected Growth: 2020 vs 2040		Induced Demand Method: 2020 vs 2040		Difference (percentage points)	
Alt	**Population**	**Employment**	**Population**	**Employment**	**Population**	**Employment**
3A	29%	18%	75%	50%	46%	32%
3C	41%	25%	44%	34%	3%	9%
5A	21%	13%	43%	41%	22%	28%
5D	33%	18%	86%	52%	54%	34%

Table F-2: Induced demand by new station walk area.

Station Name	Area	Subarea	Model	Station Included in Alternative				Walkshed Area	MWCOG Forecast				Induced Demand Method	
									2020		2040			
									Population	Employment	Population	Employment	Population	Employment
ARBORETUM	Urban	East	NOMA			5A		105	281	457	313	660	863	1,403
BELLEVUE	Urban	East	MWCOG		3C			207	3,594	355	4,565	552	4,565	552
BUZZARD POINT	Urban	East	MWCOG		3C			103	810	2,817	4,978	6,266	4,978	6,266
CARNEGIE	Urban	Core	NOMA	3A	3C	5A	5D	15	346	253	489	298	886	777
FOREST HEIGHTS	Suburban	East	MWCOG		3C			247	4,907	418	5,630	540	5,630	540
FORT LINCOLN	Urban	East	NOMA	3A		5A	5D	192	1,615	1,225	2,313	1,432	4,958	3,761
G.A.O.	Urban	Core	NOMA		3C	5A		30	1,456	1,248	2,144	1,668	2,140	3,831
GEORGETOWN	Urban	Core	MWCOG	3A	3C	5A	5D	244	5,101	13,380	6,609	14,944	6,609	14,944
H St NE	Urban	Core	MWCOG					366	13,416	1,304	16,714	2,544	16,714	2,544
HYATTSVILLE	Suburban	East	MWCOG	3A		5A		252	3,296	1,783	3,353	2,107	3,353	2,107
IVY CITY	Urban	East	NOMA	3A			5D	108	1,305	1,063	1,534	1,282	4,006	3,263
LANDOVER HILLS	Suburban	East	Largo				5D	99	824	228	837	241	1,116	344
MGM	Suburban	East	Largo		3C			84	224	1,044	253	1,285	338	1,128
NATIONAL HARBOR	Suburban	East	Largo		3C			106	516	515	625	787	779	778
PORT TOWNS	Urban	East	Largo	3A		5A	5D	183	889	1,291	927	1,302	1,342	1,949
ST. ELIZABETH'S	Urban	East	MWCOG		3C			126	924	3,943	1,382	4,245	1,382	4,245
STANTON PARK	Urban	East	MWCOG					285	11,992	3,580	14,732	3,866	14,732	3,866
THOMAS CIRCLE	Urban	Core	MWCOG	3A	3C	5A	5D	57	5,044	2,090	5,691	2,203	5,691	2,203
UNION MARKET	Urban	East	NOMA	3A			5D	134	3,137	1,888	5,803	3,594	9,631	5,796
WEST END	Urban	Core	MWCOG	3A	3C	5A	5D	16	367	1,073	497	1,184	497	1,184

APPENDIX G: NO-BUILD ALTERNATIVE OPTION 2 RESULTS

As described in section 2.0 Alternatives Evaluated: No-Build Alternative, two headway options were modeled for the No-Build (see Appendix D: Operating Scenarios and Impacts Assessment for details). The CBA used the No-Build Option 1 results because the mostly 6-minute headways proposed in this option were deemed the most likely to be operated in 2040 and is therefore a more appropriate baseline from which to compare the build alternatives. This Appendix shows the results for both No-Build options for informational purposes only.

The matrix below shows No-Build Option 1 results in the first column of data, followed directly by No-Build Option 2 results. Some measures are reported as percent changes from the No-Build which means that two sets of data must be reported for each build alternative: one set relative to No-Build Option 1 and the second set relative to No-Build Option 2. For these measures, there are two rows and the final column in the matrix indicates which No-Build Option baseline is used.

Goal	Measure	No-Build 1 Corridor	No-Build 2	LCC Alt Corridor	Alt 3A (Greenbelt) Corridor	Alt 3C (N. Harbor) Corridor	Alt 5A (SV Express) Corridor	Alt 5D (N. Carrollton) Corridor	Relative to:
1. Capacity	1. Passengers per car (PPC) at maximum load points	123	125	100	99	98	106	106	-
	2. Vertical circulation V/C ratio at Rosslyn, Metro Center, L'Enfant Plaza, Union Station (% change)	0%	-	-2%	-12%	-29%	-21%	-23%	No-Build 1
		-	0%	18%	6%	-15%	-5%	-8%	No-Build 2
	3. Percent of select OD pairs with additional route choices compared to No-build	0%	0%	16%	31%	28%	74%	27%	-
2. Reliability	1. Train headway adherence Rosslyn to Stadium-Armory	68.80%	51.50%	81.00%	75.59%	75.59%	69.31%	87.65%	-
	2. Total minutes saved (AM peak rail trips between select OD pairs)	0	-	-5	5	5	42	78	No-Build 1
		-	0	48	58	58	95	131	No-Build 2
	3. Delay percent of run time on BOS central corridor (AM peak)	0.70%	0.60%	0.80%	0.45%	0.45%	0.54%	0.73%	-
3. Flexibility	1. AM peak hour BOS passengers able to avoid single tracking at max load points (% change)	0%	-	-7.2%	-13.2%	-14.5%	-32.1%	-34.3%	No-Build 1
		-	0%	-9.8%	-15.4%	-16.7%	-34.1%	-36.2%	No-Build 2
	2. Operating and maintenance costs per revenue vehicle mile	$20.58	$22.48	$22.55	$20.12	$19.50	$19.81	$20.01	-
	3. Percent change in train-miles traveled to nearest pocket track after PPC drops below 50	0%	-	-46%	-7%	3%	-4%	36%	No-Build 1
		-	0%	-1%	68%	87%	73%	147%	No-Build 2
4. Sustainability	1. Transit mode share (AM peak work trips)	35%	35%	36%	36%	39%	36%	36%	-
	2a. Household density within one half mile station/stop walksheds	14.2	14.2	13.5	14.0	14.0	14.0	14.1	-
	2b. Employment density within one half mile station/stop walksheds	51.6	51.6	37.3	50.1	50.1	50.1	50.4	-
	3a. Number of people in EEAs with new access to HCT within one half mile station/stop walksheds	0	0	26,758	19,867	35,078	26,664	17,200	-
	3b. Average number of jobs accessible within 45 min from stations/stops in EEAs	1,273,208	1,244,687	1,043,842	1,236,584	1,296,993	1,277,631	1,278,048	-

Ridership, revenue, and costs	No-Build 1	No-Build 2	LCC Alt	Alt 3A (Greenbelt)	Alt 3C (N. Harbor)	Alt 5A (SV Express)	Alt 5D (N. Carrollton)	Relative to:
Annual total systemwide linked trips	247,982,878	244,513,984	252,538,858	274,422,434	299,473,174	287,839,266	274,843,998	-
Annual fare revenue over No-Build (2040)	$0	$0	$33,969,401	$79,174,920	$154,190,942	$119,352,470	$80,437,320	No-Build 1
	$0	$0	$44,357,223	$89,562,742	$164,578,764	$129,740,292	$90,825,142	No-Build 2
Annual O&M costs over No-Build (2040)	$0	$0	$78,091,238	$106,529,054	$176,375,217	$165,207,253	$115,654,073	No-Build 1
	$0	$0	$157,648,308	$186,086,125	$255,932,287	$244,764,323	$195,211,144	No-Build 2
Annualized capital cost over No-Build (2040)	$0	$0	$101,057,524	$407,762,944	$549,742,433	$584,002,125	$484,079,092	-
Total capital cost	$0	$0	$2,557,073,082	$16,514,577,820	$22,150,025,328	$23,757,643,224	$18,572,152,501	-
Total capital cost minus 25% contingency	$0	$0	$2,445,473,559	$13,211,662,256	$17,720,020,262	$19,006,114,579	$14,857,722,001	-
Annualized improvement cost over No-Build (2040)	$0	$0	$145,179,361	$435,117,078	$571,926,708	$629,856,908	$519,295,845	No-Build 1
	$0	$0	$214,348,609	$504,286,327	$641,095,956	$699,026,156	$588,465,094	No-Build 2