Washington Metropolitan Area Transit Authority

Metrorail Capacity White Paper

Prepared for:
WMATA

by:

LTK Engineering Services

Document Number: LTK.C3788.15.42.01

WMATA Task Order 15-CQ9205-CENV-42

November 11, 2015

Metrorail Capacity White Paper

Table of Contents

0 Revision History

Revision No.	**Date**	**Description of Revision**
0	April 24, 2015	Initial Release
1	June 30, 2015	Added dwell time summary, vehicles table, ATO narrative, executive summary
2	November 11, 2015	Incorporated consolidated WMATA review comments, added North American rapid transit line capacity peer review

1 Executive Summary

Metrorail ridership has grown substantially in prior years and despite recent declines the system still ranks as the second busiest rail transit network in the U.S. with average weekday rail ridership of 713,000 passengers. With this growth in ridership, Metrorail has encountered serious overcrowding on its trains and on the platforms of its core stations. (See Figure 1 for definition of the system core.) With its existing system infrastructure, Metrorail has reached the practical limits of its throughput capacity (in terms of trains per hour), particularly on the core segment between Rosslyn and Stadium-Armory stations.

As train and station congestion worsens, a question logically posed by stakeholders and the public is" "Why can't Metrorail add more trains to relieve the crowding?" The fundamental purpose of this White Paper is to present the root causes of Metrorail capacity constraints that limit service expansion in the core. The work presents the experience and performance of similar rail transit systems' efforts to boost rail system capacity absent the development of new rail lines. The work also evaluates, at a high level, the passenger-carrying capacity of the Metrorail train control system and the extent to which advanced technologies would improve this capacity.

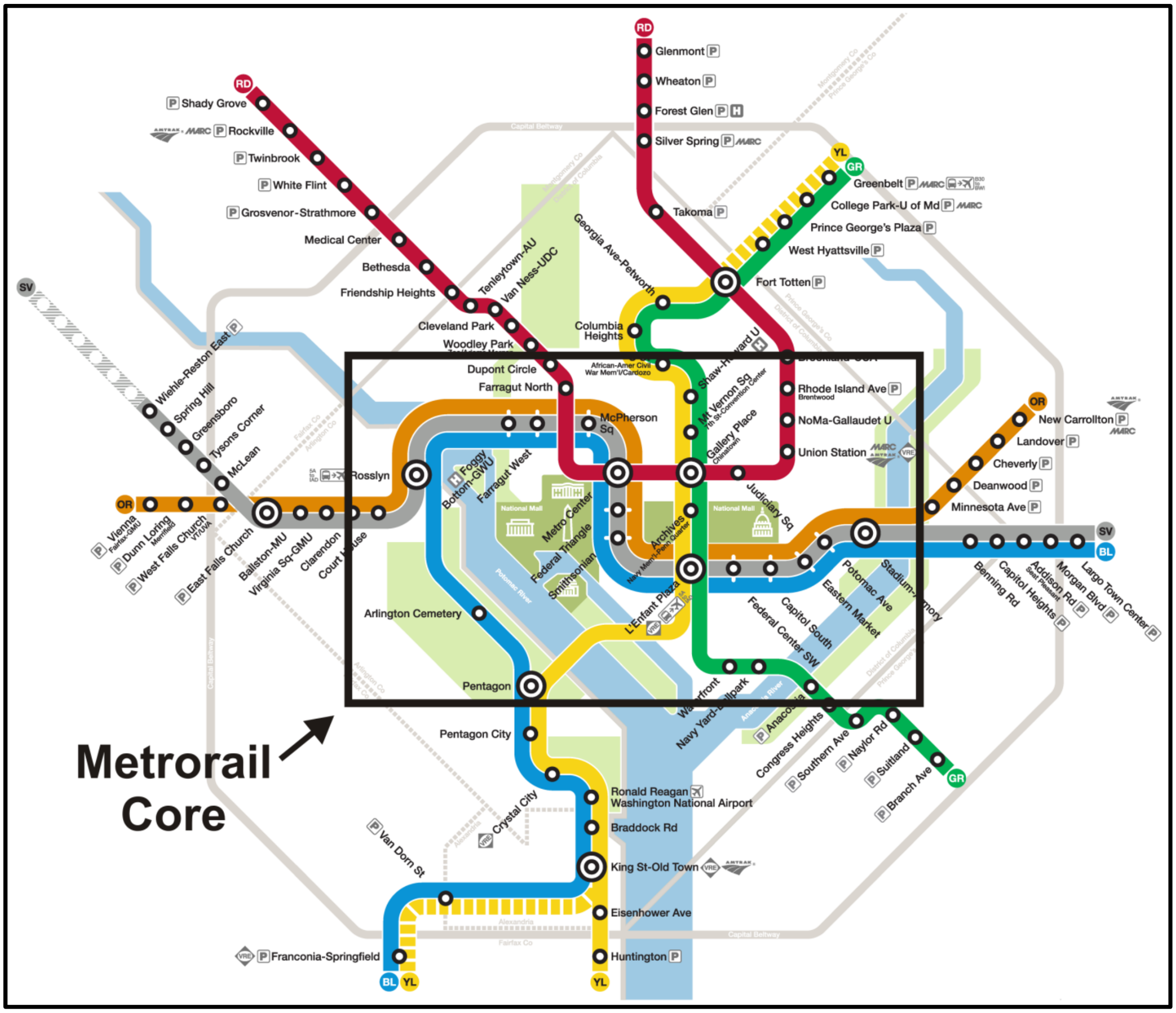


Figure 1 – Metrorail System Map and Definition of the Core

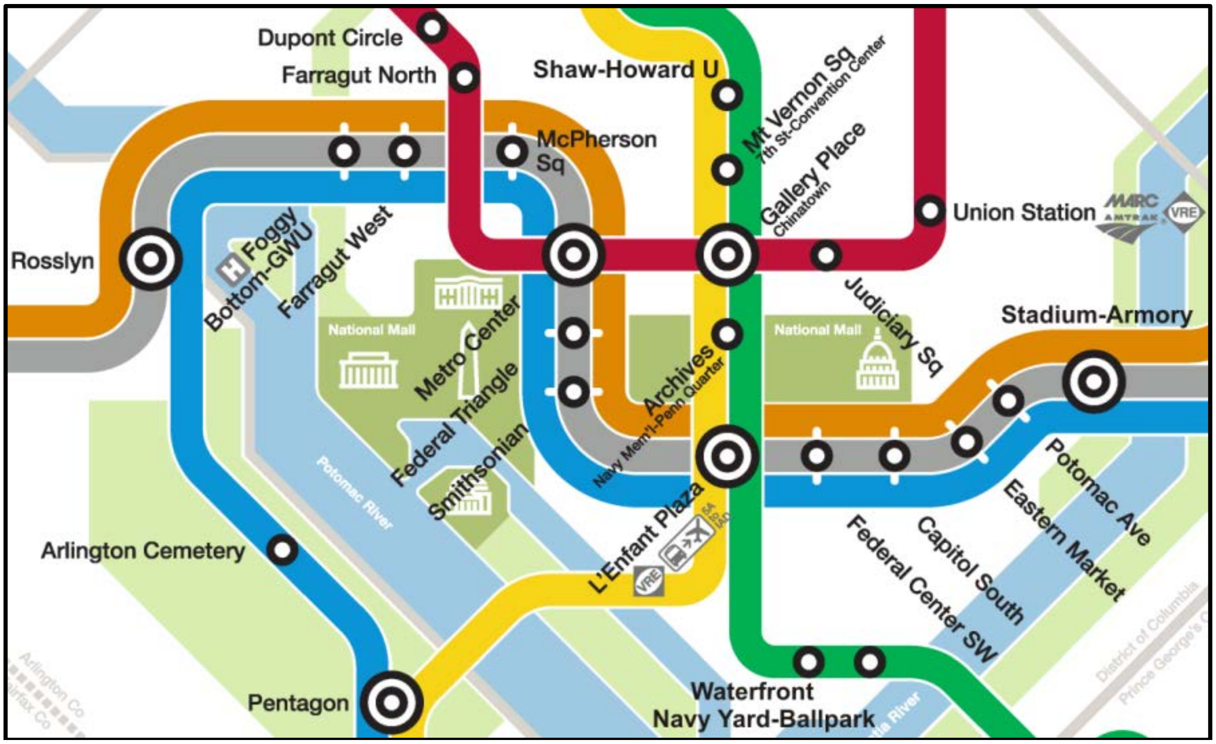


Figure 2 – Metrorail Core System

The results of the Metrorail Capacity White Paper indicate that there are multiple constraints on capacity expansion of the core and that no known technical or operational solutions exist to moderate these constraints. In a peer review of four comparable heavy rail rapid transit systems in the U.S., Metrorail scored well in terms of system design that maximizes passenger and train capacity. This includes terminal configurations, placement of yard/mainline interfaces and train control design. Previous studies have noted the capacity benefits of adding one door set per side of vehicle; however there are several challenges with this strategy. First, the benefits in terms of reduced dwell times would likely be in the range of 8-12 seconds for a 60 second dwell time (a 20-30% reduction in that portion of the dwell associated with passenger alighting/boarding with no effect on the base door cycle time dwell component of about 20 seconds). This is equivalent to a throughput gain of about 2 trains per hour, assuming all cars of all trains have four doors per side. Although this rolling stock change could be implemented incrementally as each Metrorail fleet type is retired, full implementation would require over 40 years due to the life cycles of the multiple Metrorail fleets. Second, implementing a new railcar design with four doors per side would result in a net seat reduction of approximately 28 percent, requiring more customers to stand.

Figure 3 highlights four of the most prominent sources of Metrorail system capacity constraints, including merging locations, long dwells at high-volume transfer stations, close station spacing and “slot swapping”, where northbound Yellow Line trains leave the Blue Line flow north of Pentagon and join the Green Line flow south of L’Enfant Plaza. Similarly, southbound Yellow Line trains leave the Green Line flow south of L’Enfant Plaza and join the Blue Line flow north of Pentagon. The “slot swapping” operation challenges overall Metrorail reliability because a Blue Line delay south of Pentagon, for example, will cascade to the Yellow Line (as the two services share tracks in this segment), then to the Orange Line and to the Green Line. Of the six Metrorail services, only the Red Line is operationally independent. In addition to the “slot swapping” merges, the figure highlights other key merge locations, including Falls Church, Rosslyn and Stadium-Armory.

Closely-spaced stations limit capacity because the Metrorail Automatic Train Control (ATC) system’s maximum speed control lines extend through two station platforms at these locations. That means that a train dwelling at either station will slow or stop a following train, limiting the achievable throughput. Minimum headway, which defines throughput, is limited to the total of the two station dwell times as well as the travel time between them. On the Red Line, closely-spaced stations most limit core capacity in the Metro Center/Gallery Place/Judiciary Square segment. On the Blue/Orange/Silver Line, closely-spaced stations are most prominent in the Foggy Bottom/Farragut West/McPherson Square/Metro Center/Federal Triangle/Smithsonian segment.

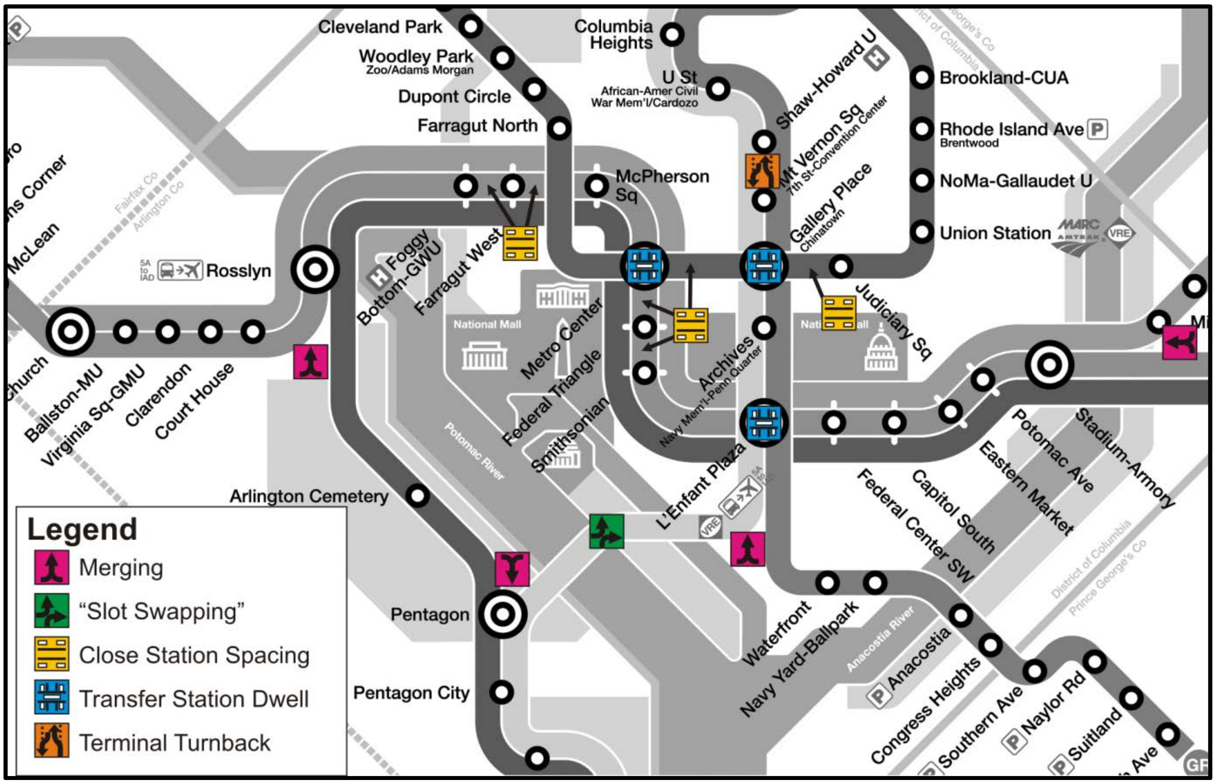


Figure 3 – Metrorail Core System Leading Capacity Constraints

The Yellow Line turnback operation at Mount Vernon Square, coupled with limited terminal capacity at the alternative terminal (Greenbelt) represents another core capacity constraint. Yellow Line trains change direction at the single Mount Vernon Square turnback track every six minutes during morning and evening peak periods. This turnback time includes about two minutes of interlocking occupancy time entering the turnback, two minutes of dwell (during which one operator must close up their operating compartment while the other operator gets ready to operate the train from the opposite end) and two minutes of interlocking occupancy time exiting the turnback. Because there is no “overrun” track at the north end of the Mount Vernon Square turnback, ATC speed commands require a safety stop entering the track, further challenging high capacity operation. The alternative terminal at the end of the Green and Yellow Lines, Greenbelt, has two station tracks. There is insufficient capacity at this location to turn all 26 Yellow/Green peak hour trains at Greenbelt (a train every four minutes on each of the two tracks), which would be required if peak period Yellow Line trains were extended from Mount Vernon Square in the peak.

The greatest opportunity for Metrorail capacity expansion in terms of passengers per hour (but not trains per hour) is conversion of all remaining peak period 6-car trains to 8-car trains. Support of 100 percent 8-car train operation during peak periods requires traction power upgrades, currently in progress, and fleet expansion, which could be implemented through a future 8000-series fleet and capacity expansion program.

The greatest opportunity for improving the consistent delivery of scheduled train volumes is restoration of Automatic Train Operation (ATO) on Metrorail. Restoration of system-wide ATO will give Metrorail Operations Planners greater confidence to schedule train volumes that are close to the practical capacity of the system, potentially resulting in a small 1 to 2 trains per hour capacity improvement.

1.1 Metrorail Capacity Limits and Associated Peer Review

The service junctions at Rosslyn, L'Enfant Plaza and Stadium-Armory are recognized as leading Metrorail system constraints. Junction configurations constrain system capacity because each merge point is a potential delay location. All three Metrorail capacity-critical junctions (Rosslyn, L'Enfant Plaza and Stadium-Armory) are “flying junctions” – configured with flyover trackage that avoids movement conflicts between trains moving in opposite directions. The Metrorail junctions utilize capacity-promoting speeds for both routes, enforced with a compatible ATC speed command. These junction speeds are consistent with industry practice for critical junctions where revenue services merge. Rebuilding of these junctions for higher diverging speeds would yield little or no system capacity benefit while being extraordinarily costly and disruptive.

Terminals represent system capacity constraints on most heavy rail rapid transit systems, including Metrorail, due to time-consuming train “turning” (change of direction) operations. Traditional terminals generally require more than one track for simultaneous train “turning” operation because the “turning” requires more time than the scheduled headway. Metrorail was found to be comparable to the four peer systems in terms of terminal configurations that support high capacity operations. Five of nine Metrorail terminals have capacity-enhancing yard leads that serve as continuation of terminal tracks. All nine terminals have crossovers on the revenue side of the platforms and six of the nine also have crossovers on the non-revenue side. Crossover speeds are in the range of 15 to 28 MPH, optimal speeds in terms of maximizing interlocking traversal speeds while minimizing overall interlocking length.

The architecture of the ATC system and, especially, its speed commands, plays an important role in determining system capacity. Fixed block ATC systems require fine granularity in their speeds in order to promote close headways and high capacity. Metrorail utilizes 11 distinct ATC speed commands providing excellent coverage of civil speed restrictions and successive speed targets for enforced speed reductions. The peer review found that, of the five systems surveyed in depth, WMATA has the largest number of speed commands, which supports close-headway, fixed-block operations. It also has the tightest average spread (speed gap between successive speed commands) of the five systems, with an average spread of 7.5 MPH. These attributes support high capacity operation and reduce the theoretical advantage of the continuous speed command capability of CBTC.

LTK also performed a peer review of rapid transit scheduled versus actual throughput and found that there are only 10 locations in North America (five of which are in New York) where heavy rail rapid transit operating volumes approach or exceed Metrorail volumes. In cases where the volume is notably above the Metrorail practical throughput of 26 trains per hour, the higher throughput is explained by unique circumstances. In Chicago, for example, there are 29 actual trains per hour through Clark/Lake Station but many are short 4-car trains. In the PATH network in New Jersey, a short segment supports 30 trains per hour but there is only one lower ridership station in the segment. For services that are analogous to Metrorail (train lengths around 600 feet, merges of multiple lines, closely-spaced stations in the urban core), the peer review confirms that a 26 trains per hour volume is the approximate limit of rapid transit capacity. The review also found that most of these high-volume lines have difficulty delivering the scheduled train volume, a typical challenge where passenger crowding is prevalent and rail service planners schedule service at or beyond the line's practical capacity.

Table 1 – Peer Review of Rapid Transit Scheduled versus Actual Throughput (Lines with Scheduled 25+ Trains per Hour)

System	Line	Train Type	Scheduled Throughput (TPH)	Actual Throughput (TPH)	Notes
WMATA	Blue/Orange/Silver	6 to 8-car trains (75' cars)	26	24-26	Constrained by Rosslyn merge, close station spacing and long dwells in core
CTA	Clark/Lake Inner Loop (Elevated)	4-car 48' cars (Pink Line), 6-car 48' cars (Purple and Green Line), 8-car 48' cars (Orange Line)	32	29	Peak service is in the PM peak.
NYCT	Queens Boulevard Line Express (E and F)	10-car trains 60' cars, some 8-car 75' trains	30	29	Services merge and diverge at both ends of line, AM peak southbound, PM peak northbound
NYCT	Flushing Line (No. 7)	11-car 51' cars	27	26	AM peak southbound, PM peak northbound
NYCT	Lexington Avenue Line Express (No. 4 and No. 5)	10-car 51' cars	27	23-27	Services merge in the Bronx, diverge in Brooklyn
NYCT	53rd Street Tunnel (E and M)	8-car and 10-car 60' cars	25	24	AM peak southbound only
NYCT	Cranberry Street Tunnel	8-car 60' and 8-car 75' cars	26	24-25	AM peak northbound only
NYCT	6th Avenue Local (F and M)	Primarily a mix of 10 60' and 8 60' cars, with a few trains of 8 75' cars	25	25	AM peak southbound only
PATH	Main Line, Exchange Place to Grove Street	7 to 10-car 51' cars	30	29-30	Includes only one lower ridership station within segment with maximum throughput
TTC	Yonge/University/Spadina	6-car 75' cars	26	24-25	Limiting factor is dwell time at Bloor-Yonge transfer station

1.2 Capacity Impacts of Advanced Train Control

Two of the most capacity-constrained locations on the Metrorail system -- the junction at Rosslyn and the core section of the Orange/Blue/Silver Line – were evaluated to determine if Advanced Train Control would mitigate the existing capacity constraints. Rosslyn serves as the junction of the Orange/Silver and Blue Lines while the core segment between Metro Center and Federal Center has closely-spaced stations with relatively long dwell times.

LTK applied a hypothetical advanced train control solution, Communications-Based Train Control (CBTC), to the two capacity-constrained locations of the Metrorail system. CBTC programs are currently being advanced in New York (NYCT and PATH), Toronto (TTC) and San Francisco (BART) as the next generation in Advanced Train Control, though there is little or no indication of the capacity benefits of these programs. While initially appealing to transit planners due to their “moving block” attributes and perception that throughput would improve as a result, CBTC systems have more recently been advanced for reasons other than improved capacity. These include simpler wayside installations due to the absence of ATC insulated joints and bond locations, elimination of track circuits with their associated signal hardware, and greater ability to regulate train performance,

Typical North American CBTC functional criteria in terms of safe braking distance margin, system response time, positional accuracy and safety buffers were used. The systems, as applied to Rosslyn and a portion of the Metrorail core, were compared in terms of both delay-free operations and “crush” operations, where trip time is sacrificed in order to maximize the volume of trains operated. Delay-free operations represent typical Metrorail operation where trains are free-flowing and not subject to repeated “stop and go” type delays.

The existing fixed block system was found to have an advantage in terms of wayside equipment response times (known as “system latency”) as fixed blocks communicate in parallel at a very short update interval, based upon the absolute position of trains within those fixed blocks. In CBTC moving block, each train in the system is dependent upon receiving information from the train ahead, which in turn depends on the information it receives from the train ahead. This leads to an additive latency throughout the system, which causes trains under CBTC to react to information that the fixed-block system would not see. Although CBTC has the advantage of moving blocks, the combination of positional uncertainty under CBTC and the very short fixed-block lengths in use today within the Metrorail core segment, prevent the CBTC system from seeing a large enough benefit to offset the drawbacks of latency. In addition, important existing Metrorail capacity constraints (extended dwells at transfer stations, close spacing of stations within the core, multiple rail serves merging at junctions) are unaffected by the theoretical moving block benefits.

Table 2 – Comparison of Core Segment Capacity Measures

Performance Measure		Fixed-Block		CBTC Moving Block	
		Crush	Delay-Free	Crush	Delay-Free
Headway (Seconds)	**Theoretical**	100	107	100	119
	Practical	125	134	125	149
System Capacity (TPH)	**Theoretical**	36	33	36	30
	Practical	28	26	28	24
Federal Center to Metro Center Travel Time		0:06:06	0:05:49	0:06:59	0:05:48

In terms of practical system capacity measured under “crush” operations (the willingness to modestly increase trip time in the interest of moving more passengers), the current core segment supports a throughput of 28 trains per hour. With CBTC, including elimination of all fixed block constraints and recomputation of all civil speed restrictions on a “clean slate” basis, throughput is unchanged. Though speeds through civil speed restrictions are better optimized with CBTC, the CBTC simulation shows a “crush” operation trip time that is almost a minute longer through the core than the fixed block system. This is due to the increased latency of the CBTC system, meaning that once a delay associated with a train ahead begins, it takes longer for the following train to resume delay-free operation.

In terms of practical system capacity measured under “crush” operations (the willingness to modestly increase trip time in the interest of moving more passengers), the Rosslyn merge segment (Court House and Arlington Cemetery Stations through Rosslyn to Farragut West Station) supports 28 trains per hour under the current fixed block ATC system. Under CBTC, throughput increases modestly to 29 trains per hour.

Theoretical versus Practical Capacity

As the term implies, *Theoretical Capacity* is not possible to achieve in actual operations. It requires perfectly uniform performance by all Metrorail vehicles, operators, passengers and wayside equipment. In contrast, *Practical Capacity* makes reasonable allowance for variability in Train Operator efficiency, train performance and dwell times (but does not reflect the possibility of train breakdowns, en-route medical emergencies or other significant operating challenges). This White Paper focuses on *Practical Capacity* metrics because the referenced throughput is achievable and because they correlate to Metrorail’s maximum train volumes used for planning purposes.

Table 3 – Comparison of Junction Capacity Measures

Performance Measure		Fixed-Block		CBTC Moving Block	
		Crush	Delay-Free	Crush	Delay-Free
Headway (Seconds)	**Theoretical**	100	134	99	130
	Practical	125	168	123	163
System Capacity (TPH)	**Theoretical**	36	26	36	27
	Practical	28	21	29	22
Court House to Farragut West (Orange) Travel Time		0:06:50	0:06:43	0:07:21	0:06:51
Arlington Cemetery to Farragut West (Blue) Travel Time		0:06:49	0:06:20	0:07:03	0:06:18

In conclusion, implementation of an Advanced Train Control system on Metrorail would produce minimal gains in system capacity. Based on extensive peer review, the current Metrorail train control system was designed to be extremely “capacity friendly” and exceeds the capabilities of peer systems. Other potential capital investments to existing lines – reconfigured junctions, expanded terminals, improved transfer station pedestrian flow – are unlikely to increase the throughput of the Metrorail system in terms of the practical number of trains per hour operating on each line.

2 Introduction

The purpose of this White Paper is to discuss and clearly communicate the capacity constraints of the existing Metrorail System, including presentation of a peer review to document the experience and performance of similar rail transit systems' efforts to boost rail system capacity absent the development of new rail lines. A secondary purpose is to evaluate, at a high level, the passenger-carrying capacity of the Metrorail train control system and the extent to which advanced technologies would improve this capacity.

Metro's Office of Planning has developed a draft long range plan, which includes proposals to develop new core Metrorail lines in downtown DC and in Northern Virginia. The new Metrorail lines represent potentially tens of billions of new investment, with such investment needed by 2040 to reduce congestion and crowding on the existing system. The proposed new core Metrorail lines are primarily meant to address passenger crowding on the Metrorail system, both in the regional core, and on the Orange/Silver Line in Virginia.

Projected levels of crowding are based on the assumption that capacity-constraining segments of the Metrorail network are capable of operating up to 26 eight-car trains per hour (TPH) per direction. Crowding projections reflect current infrastructure, systems, and rolling stock capacity constraints – as well as current loading guidelines for defining thresholds for crowding. These system capacity constraints are largely based on the 2001 WMATA Core Capacity Study[1], as adjusted for current operating conditions.

A question logically posed by stakeholders is "why can't Metrorail simply increase capacity by running more trains?" This White Paper responds to this question by identifying train and passenger-carrying capacity constraints on Metrorail. It provides industry context to these constraints by identifying what peer agencies have gained by making core capacity-focused investments, along with the associated capital costs.

The service planning leading to the July 26, 2014 opening of the Silver Line renewed attention on the 26 TPH constraint, especially at the junction of the Silver/Orange and Blue Lines at Rosslyn. Because of the merging constraint at that location, the addition of new Silver Line service necessitated reduction in peak period Blue Line service and the redirection of some of this service to the Yellow Line. This was necessary in order to accommodate the Silver Line and increase cross-Potomac capacity.

Figure 4 shows the weekday morning peak variability in actual Metrorail service delivery at Rosslyn during the period from July 21, 2014 to December 31, 2014. With a scheduled throughput of 26 trains, many days exhibited a shortfall in service delivery while a few days exhibited more than 26 trains (likely due to earlier delays and bunched trains in Virginia that then operated through Rosslyn).

The distribution of Rosslyn throughput in terms of peak trains per hour is shown in Figure 5. Metrorail failed to achieve the scheduled throughput of 26 trains per hour more than 60 percent of the sampled weekdays.

---

[1] http://www.wmata.com/pdfs/planning/CoreCapacity_ExecSum.pdf

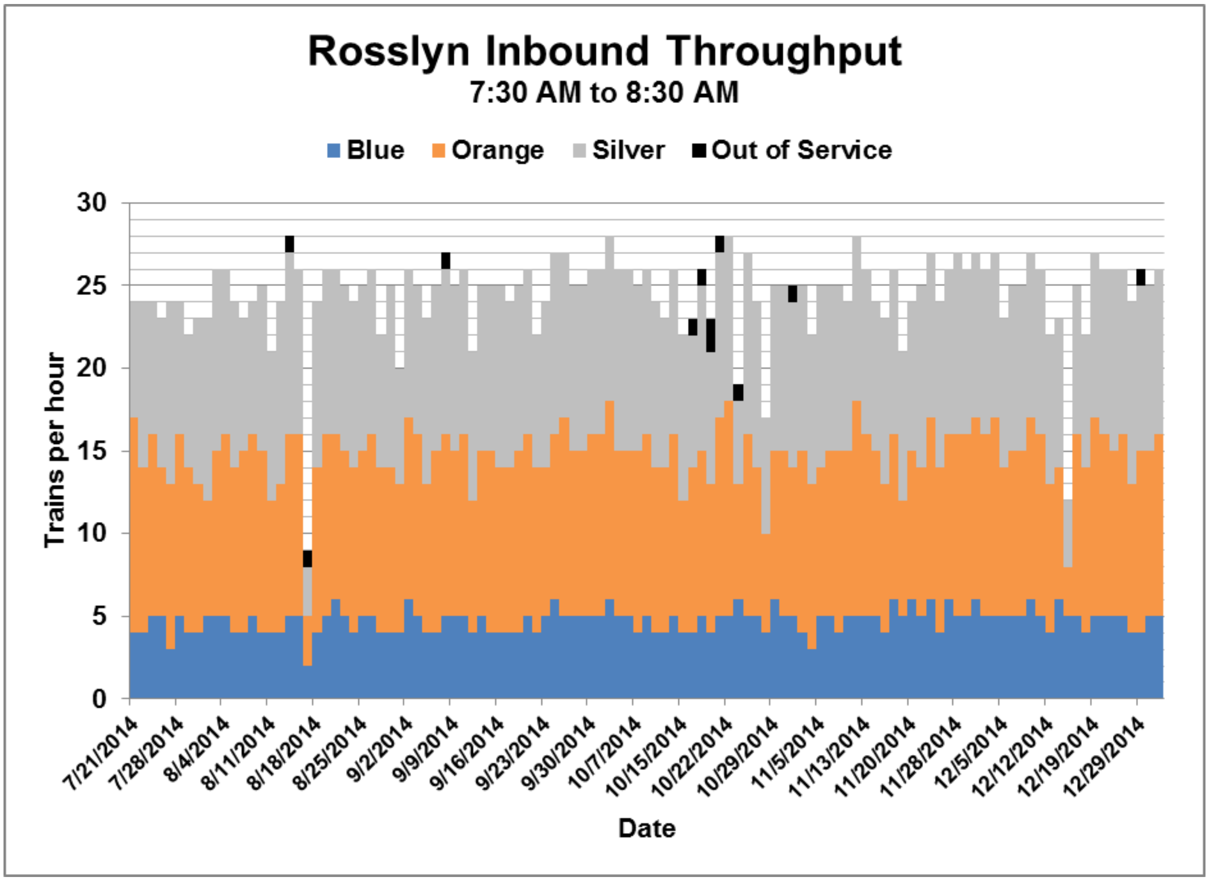


Figure 4 – Actual Metrorail Service Delivery at Rosslyn

The results of Figure 4 and Figure 5 demonstrate the challenges Metrorail faces in terms of delivering 26 TPH in the peak and in terms of providing consistent service delivery. The variability in day-to-day Fall 2014 service delivery confirms the practical throughput limits of Metrorail as variability tends to increase as scheduled service matches – or exceeds – practical capacity of the network.

A contributing factor to the service delivery shortfall is the reliability of the Metrorail fleet and limited number of “hot standby” cars. Figure 4 shows a number of out of service trains passing through Rosslyn during the peak, an indication of fleet reliability issues. In addition, other fleet reliability issues (such as doors that require repeated closings in order to obtain a “doors closed” indication) are likely to negatively influence Rosslyn throughput even as the trains continue in revenue service. While the full deployment of the 7000 series cars, now being delivered and tested, will help to resolve the issue, additional investment will be required before the reliability of the entire fleet reaches levels that will promote consistent throughput.

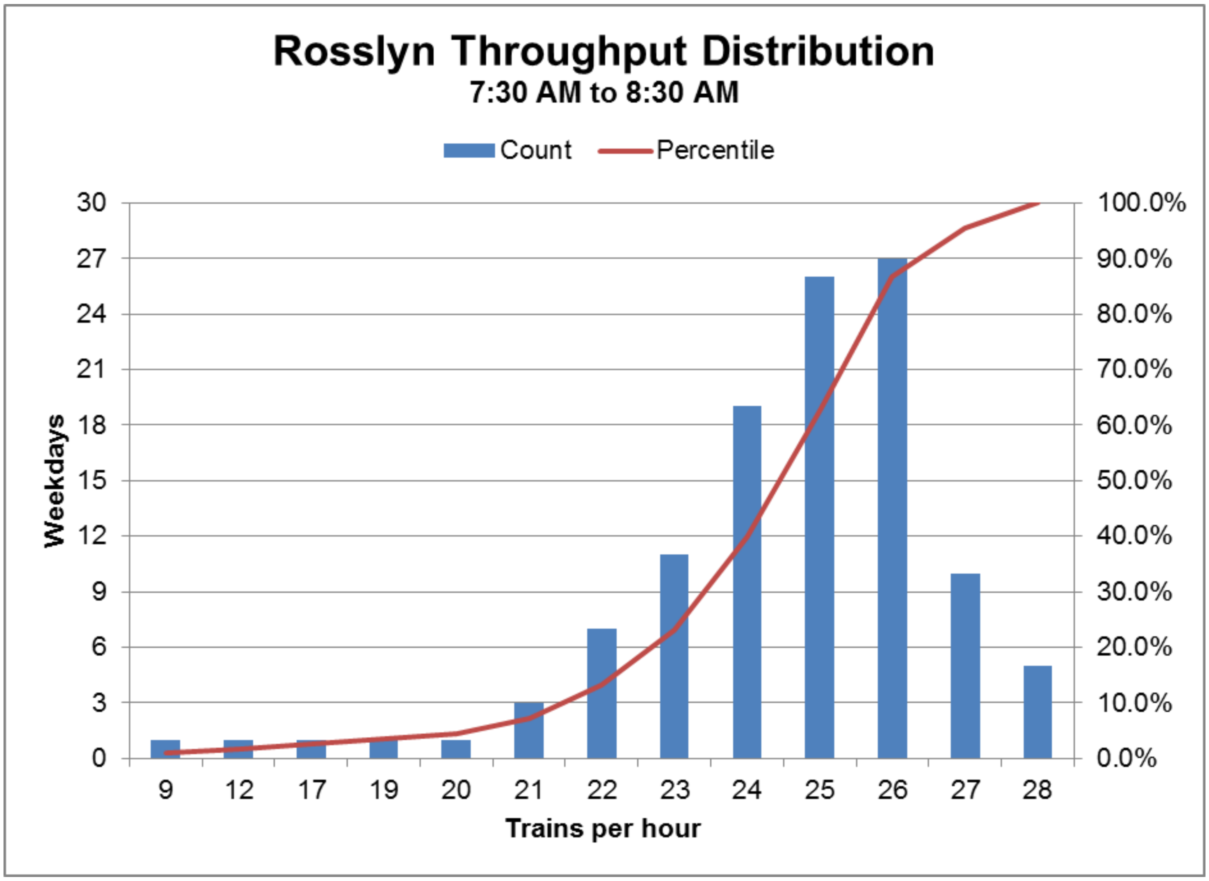


Figure 5 – Distribution of Rosslyn Service Delivery during Morning Peak Hour

With the anticipated presentation of the long-range plan to stakeholders, there is a need to more clearly describe the current system's constraints in terms of infrastructure, systems, and rolling stock. There is a general awareness of the availability and claimed benefits of Communications Based Train Control (CBTC) and other advanced train control technologies. Given the cost of the long range plan anticipated from the Office of Planning, there is a need to be able to clearly communicate the current limitations of the Metrorail System as well as document the performance benefits and associated capital costs associated with a hypothetical installation of advanced train control systems on capacity-constrained segments of Metrorail.

3 Documentation of Metrorail Capacity Constraints

This chapter presents an overview of capacity constraints on the Metrorail system, including junction configurations, terminal configurations, vehicle configuration and Automatic Train Control (ATC) architecture.

Dwell times (the time from wheel stop to wheel start at stations) are a major driver in the determination of Metrorail capacity. As such, potential reductions in dwell times represent opportunities to reduce headways (the minimum time between successive trains on the same track) and increase Metrorail capacity. However, there are significant structural limitations to reducing dwell times, including Metrorail's long-term commitment to the current door configuration of vehicles, platform circulation/passenger distribution challenges, and vertical circulation limits.

It should be noted that, while present WMATA traction power limitations could preclude some service growth given resolution of dwell times, vehicle and train control constraints, there are on-going traction power system investments to support 26 eight-car trains system-wide on the Metrorail network.

This chapter also presents the results of a peer review of other US systems that function similarly to Metrorail with a focus on their capacity-constraining attributes. Peer systems were considered only if they have similar characteristics to Metrorail such as the presence of multiple junctions where individual services diverge and merge.

LTK worked to identify the specific core capacity strategies employed by each transit agency along with the performance achieved in actual operation. This work sought to identify peer system performance measures, including:

- Increased trains per hour
- Capital cost
- Percent increase in passenger carrying capacity achieved

Resources utilized in this analysis included:

- WMATA Core Capacity Study
- Recent WMATA Deputy General Manager for Operations simulation work performed by LTK and related to planned and unplanned system outages,
- FTA Rail Capacity Improvements Study for Heavy Rail Operations[2]
- BART Sustainable Communities Operational Analysis[3]

LTK reviewed capital improvement projects of all heavy rail rapid transit networks in North America, including:

- MBTA (Boston) Blue, Orange and Red Lines,
- NYCT (New York, including Staten Island Railway)
- PATH (New York)

---

[2] http://www.fta.dot.gov/images/FTA_Report_No._0035.pdf

[3] http://www.bart.gov/sites/default/files/docs/BART%20SCOA%20Final%20Report%20June%202013.pdf

- SEPTA (Philadelphia), Market-Frankford and Broad Street Subway
- PATCO (Philadelphia)
- MTA (Baltimore)
- MARTA (Atlanta)
- GCRTA (Cleveland) Red Line
- CTA (Chicago)
- BART (San Francisco)
- LACMTA (Los Angeles)
- TTC (Toronto)
- STCUM (Montreal)
- BC Transit (Vancouver)

Only four systems – NYCT, PATH, TTC and BART – have or are actively pursuing major capacity enhancement projects. None of these projects has sufficient history or context to quantify capacity improvements and capital cost.

The Chicago Transit Authority (CTA) has received Federal Transit Administration (FTA) Core Capacity funding for its Red and Purple Modernization Project. This project is primarily focused on resolving historical structural limitations on capacity, such as very narrow platforms. As such, it might be termed more of a State of Good Repair Project, rather than a Capacity Enhancement Project.

Unlike Metrorail, much of the CTA Red and Purple Line is a four-track configuration with the Purple Line on the outside tracks and the Red Line on the inside, The Brown Line joins the Red/Purple Lines at a junction but, unlike all junctions at Metrorail, the configuration is a so-called “flat junction”. The at-grade configuration means that outbound trains to the Brown Line delay both following Red/Purple Line outbound trains but also inbound Red/Purple Line trains. The inbound trains are blocked by the path of the outbound Brown Line trains, a source of delays that will be addressed by the project in the form of a two block long aerial flyover at Clark Junction. Though CTA is not known to have performed any computer network simulation of this planned improvement, manual analysis has estimated a 30% increase in Red/Purple/Brown Line capacity.

The project will also eliminate 1.3 miles of slow speeds through track geometry and track structure improvements. To date, the project has received $35 million for project development from the FTA. The construction of the initial phase of the project is estimated to be $1.85 billion, based on year of expenditure dollars (not current dollars).

New York City Transit

In New York, NYCT activated CBTC on its L Line (Canarsie Line) linking Manhattan and Brooklyn in February 2009. Full automatic operation was not achieved until 2012. The Canarsie Line was chosen for CBTC not because of passenger crowding issues but because it is only one of two non-shuttle lines that are stand-alone. In other words, it does not include multiple services on multiple routes that would complicate CBTC implementation. NYCT has reported that it has not tested following-move headway capacity to determine theoretical or practical capacity of the system. Peak scheduled headways of 4 to 5 minutes (approximately 13 trains per hour) are operated on the line. The fixed block system that was replaced by CBTC was capable of supporting headways of 3 minutes or closer so capacity enhancement was not a justification for the project. Siemens was the prime contractor for the project.

Figure 6 – NYCT Canarsie Line with CBTC Wayside Equipment on Right

In the last four years, NYCT has been pursuing CBTC on the other non-shuttle, stand-alone line – the Flushing Line. The Flushing Line schedules approximately 26 trains of 11 cars per hour and is operating at or beyond its practical capacity. In 2013, NYCT announced that completion of Flushing Line CBTC has been delayed from the fourth quarter of 2016 until the second quarter of 2017. The project budget is $550 million. The prime contractor is the Thales Group. NYCT is procuring a new fleet of R188 cars for the CBTC-equipped line. No known capacity improvement quantification has been performed for the Flushing Line CBTC project.

Port Authority Trans Hudson

Also in New York, Port Authority Trans Hudson (PATH) is presently constructing a new CBTC system for its entire network in New York and New Jersey. CBTC will replace the current fixed-block mechanical trip stop system at an overall cost (in 2009 dollars) of $580 million. This cost does not include system-wide replacement of the entire PATH fleet with 340 “CBTC ready” PA-5 cars.

Figure 7 – CBTC-Ready PATH PA-5 Train at Newark Penn Station

The largest contract, with a value of $321 million, was awarded to Siemens for the design, manufacture and installation of the new signal technology, as well as for the removal of the old system. The Siemens Team is a joint venture of Siemens Transportation Systems, Safetran Systems Corp. and D/A Builders, LLC.

The project includes signal replacement throughout the system's 43 track miles and 13 stations. On-board CBTC equipment will be installed on 130 of the new PATH railcars that have an operating compartment.

The project started in 2009 with testing of the new signals initiated in 2013. Old signals will be removed in interlocking-to-interlocking segments as the new system becomes operational. The project is scheduled to be finished in 2017.

PATH and its parent, Port Authority of New York and New Jersey, estimate that CBTC will yield a 20 percent increase in system passenger-carrying capacity. It is not clear if this estimate is based on simulation analysis or reflects professional judgment. PATH's principal midtown Manhattan terminal at 33rd Street is severely capacity-constrained; CBTC will have little or no impact on this capacity constraint. This is because the 33rd Street constraints are physical, rather than being related to train control. The end-of-the-line station features three terminal tracks and no tail tracks. Trains operate slowly in and out of the terminal due to inbound operation against a bumping block (end of track) and due to low speed track geometry for the crossovers at the terminal throat.

Toronto Transit Commission

At the June 2014 American Public Transportation Association (APTA) Rail Conference, TTC representatives described implementation of ATC/CBTC on a portion of their busiest subway line, known as the Yonge Line or Line 1. Yonge Line CBTC is expected to be in service in

2015 on the Wilson to Dupont segment (Phase 1) with the original signaling (60 years old) to be retired. CBTC has been implemented largely in response to growing ridership and system crowding. TTC ridership has increased from 403 million (2003) to 525 million (2013) when all modes are tallied.

Figure 8 – TTC Yonge Line Train at Davisville

The Yonge Line CBTC project requires interfacing with 14 existing interlockings. This work is being performed by Ansaldo on a “like for like” basis (no changes to track layout, no functional improvements). Alstom is the prime contractor for the new ATC/CBTC system itself, including vehicle-based equipment.

The existing minimum signal system headway is 140 seconds. The CBTC system is designed for a 108 second practical headway and a 90 second theoretical headway. The major transfer station at Bloor-Yonge typically experiences peak period dwells of 50 to 60 seconds, limiting the headway improvement achievable with any train control system.

The system features conventional wayside signals (on a somewhat longer block spacing than at present) and a Speed Control System for fallback operations. The fallback system is designed for 150 second headway. The Speed Control System is being provided by Thales. Conversion of existing interlockings to be “CBTC ready” is being performed by Ansaldo.

Phase 2 of the project will cover the South Yonge Subway from Bloor-Yonge to St. George.

Current completion of ATC/CBTC on this segment is forecast for 2019. Completion of CBTC across the entire Yonge/University/Spadina Line is projected for 2020.

In early 2015, TTC announced significant project delays with its CBTC program. It is currently in the process of switching signaling suppliers in order to streamline the implementation of ATC. This will eliminate the current structure where Alstom, Ansaldo and Thales are all performing portions of the program but no single supplier is in the lead.

TTC's other major subway line, the Bloor-Danforth Line, may follow. The ATC/CBTC system design includes provisions for possible future driverless operation.

Bay Area Rapid Transit District (BART)

BART's operations are capacity-constrained by the merging of train flows at the Oakland Wye and the capacity of the Transbay Tube. The Transbay Tube capacity limitations are closely linked to the tight station spacing of multiple stations on Market Street in downtown San Francisco. BART has been pursuing CBTC research since the late 1980s. In 1998, it awarded a major contract to Harmon Industries (now General Electric Global Signaling) for CBTC development but this was later cancelled after Harmon requested additional funding.

The 1998 contract for Advanced Automatic Train Control (AATC) included two phases -- a development phase and an implementation phase -- with a combined value of approximately $45 million. The project was planned for completion in 2001 and the AATC System was advertised as enabling BART to significantly increase train and passenger capacity without adding tracks.

AATC, as proposed by Harmon, was based on a wireless data radio network known as the Enhanced Position Location Reporting System (EPLRS), which was originally developed for the military. EPLRS technology was selected because of is its ability to accurately determine the position of trains without relying on conventional track circuits. Harmon licensed the technology for use in railroad applications from Raytheon (formerly Hughes

Aircraft) in September, 1997. AATC was estimated to support BART trains moving at 90-second headways at speeds of 80 MPH.

In 1999, GE Harris (a 50-50 partnership) purchased Harmon and was renamed GE Harris Harmon. In mid-2001, GE purchased Harris' 50 percent stake in the business, creating a new GE subsidiary known as GE Transportation Systems (GETS). The train control business is now known as GETS Global Signaling. Shortly thereafter, GETS requested additional development funds from BART, a request that was denied.

Figure 9 – BART Trains on the Capacity-Constrained "M" Line Between West Oakland and San Francisco

BART did not pursue CBTC again until 2013, when it engaged engineering consultants to develop a Train Control Modernization Program (TCMP). The TCMP notes that, by 2025, BART's core system will need to support a 2 minute headway (30 trains per hour) to meet projected ridership demand. The analysis in the report indicates that the capacity of the present fixed block system (including a redundant overlay system required by the California Public Utilities Commission) is 22.2 trains per hour. The report goes on to estimate CBTC core capacity as 26.4 to 28.5 trains per hour. In early 2015, BART awarded a General Engineering Consultant contract specific to advanced train control as the next step in pursuing CBTC. BART has not yet selected a CBTC architecture or engaged a supplier.

3.1 Peer Review of Practical Train Throughput

LTK performed a peer review of North American heavy rail rapid transit properties to determine to what extent other networks are scheduling train volumes above the generally-accepted practical Metrorail limit of 26 trains per hour. A secondary purpose of this peer review was to determine how close to scheduled train volumes each system is achieving in terms of regular service delivery. Only systems with scheduled train volumes of 25 or more trains per track per direction in the peak hour are included in the peer review summary, shown in Table 4.

Table 4 – Peer Review of Rapid Transit Scheduled versus Actual Throughput (Lines with Scheduled 25+ Trains per Hour)

System	Line	Train Type	Scheduled Throughput (TPH)	Actual Throughput (TPH)	Notes
WMATA	Blue/Orange/Silver	6 to 8-car trains (75' cars)	26	24-26	Constrained by Rosslyn merge, close station spacing and long dwells in core
CTA	Clark/Lake Inner Loop (Elevated)	4-car 48' cars (Pink Line), 6-car 48' cars (Purple and Green Line), 8-car 48' cars (Orange Line)	32	29	Peak service is in the PM peak.
NYCT	Queens Boulevard Line Express (E and F)	10-car trains 60' cars, some 8-car 75' trains	30	29	Services merge and diverge at both ends of line, AM peak southbound, PM peak northbound
NYCT	Flushing Line (No. 7)	11-car 51' cars	27	26	AM peak southbound, PM peak northbound
NYCT	Lexington Avenue Line Express (No. 4 and No. 5)	10-car 51' cars	27	23-27	Services merge in the Bronx, diverge in Brooklyn
NYCT	53rd Street Tunnel (E and M)	8-car and 10-car 60' cars	25	24	AM peak southbound only
NYCT	Cranberry Street Tunnel	8-car 60' and 8-car 75' cars	26	24-25	AM peak northbound only
NYCT	6th Avenue Local (F and M)	Primarily a mix of 10 60' and 8 60' cars, with a few trains of 8 75' cars	25	25	AM peak southbound only
PATH	Main Line, Exchange Place to Grove Street	7 to 10-car 51' cars	30	29-30	Includes only one lower ridership station within segment with maximum throughput
TTC	Yonge/University/ Spadina	6-car 75' cars	26	24-25	Limiting factor is dwell time at Bloor-Yonge transfer station

The results of the peer review of rapid transit scheduled versus actual throughput show that there are 10 locations in North America where heavy rail rapid transit operating volumes approach or exceed Metrorail volumes. In cases where the volume is notably above the Metrorail practical throughput of 26 trains per hour, the higher throughput is explained by unique circumstances. In Chicago, for example, there are 29 actual trains per hour through Clark/Lake Station but many are short 4-car trains. In the PATH network in New Jersey, a short segment supports 30 trains per hour but there is only one lower ridership station in the segment; the services split on both sides of core segment to lower volume lines. For services that are analogous to Metrorail (train lengths around 600 feet, merges of multiple lines, closely-spaced stations in the urban core), the peer review confirms that a 26 trains per hour volume is the approximate limit of rapid transit capacity.

Another important finding of the throughput peer review is that most of these high-volume lines have difficulty delivering the scheduled train volume. This is typical of line segments where passenger crowding is prevalent; rail service planners schedule service at or beyond the practical capacity limit in order to accommodate as many customers as possible on trains.

The system often considered to be the closest peer of WMATA – BART – presently schedules 23 trains per hour through its heaviest ridership link – the Transbay Tube. Because it falls short of the 25 TPH threshold, BART is not included in in Table 4. BART capacity is limited by its ATC system, close station spacing/long dwells in downtown San Francisco and the negative capacity impacts of merging routes at the Oakland Wye in downtown Oakland.

3.2 Metrorail Track Alignment Capacity Constraints

3.2.1 Junction Configurations

This section presents LTK's peer review of heavy rail rapid transit systems with respect to critical junction speeds and track geometry. The survey results are compared with those at Metrorail, including capacity-critical junctions at Rosslyn, L'Enfant Plaza and Stadium-Armory.

Metrorail Capacity Implications

Junction configurations constrain system capacity because each merge point is a potential delay location. If trains are scheduled too close together, trains will wait at the junction until the route is established, prompting customer complaints about perceived delays. If one line feeding the junction experiences delays, trains will not arrive at the correct time to use their operating slot through the junction. This results in overall loss of system capacity as these empty slots carry through the system.

Capacity at junctions depends on whether or not "flying junctions" are used and the track geometry of the physical merge. Capacity is also influenced by the length of the interlocking governing the junction and any nearby speed restrictions, including station stops. All of the Metrorail revenue junctions are "flying junctions", meaning that it is not necessary to cross one track at grade in order to access a different track where the actual traffic merge takes place. Older systems such as NYCT and CTA feature numerous merges using so-called "flat junctions" because "flying junctions" are cost-prohibitive or geometrically infeasible (refer to the CTA discussion at the beginning of Chapter 3).

Track geometry is indicated by the number (also known as "size" or "frog angle") of the turnout, where a larger number indicates a gentler diverging speed and, hence, faster speed (refer to Figure 10). North American rapid transit turnouts range from #4 to #20, while some North American railroads use even faster #26, #30 or #32.7 turnouts. Most turnouts are lateral, where one "leg" (branch) of the turnout has diverging (curved) connection and the other leg is straight. Some turnouts are equilateral, featuring two diverging connections.

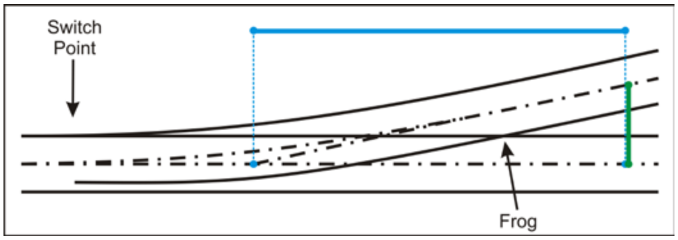


Figure 10 – Frog Angle, defined as the ratio of blue line and the green line. Higher-numbered frog angles have gentler angles and faster diverging speeds.

The maximum operating speeds through the diverging legs of junction turnouts is limited by vehicle performance and ride comfort considerations. In addition, the maximum diverging speed must be enforced by the network's ATC system (refer to Section 3.3). Because each network uses a different set of ATC speed commands, a given frog angle may be enforced at different speeds, depending on the system's ATC architecture.

All three Metrorail capacity-critical junctions (Rosslyn, L'Enfant Plaza and Stadium-Armory) are "flying junctions" with #15 lateral turnouts. All three locations are enforced with the 28 MPH ATC speed command (refer to Section 3.3.1).

Comparison with Peer Systems

The merging track geometry and ATC speeds at the critical Rosslyn, L'Enfant Plaza and Stadium-Armory junctions were found to be comparable to – or superior to – similar critical junctions at other systems. Metrorail peers Bay Area Rapid Transit District (BART) in Oakland/San Francisco, Massachusetts Bay Transportation Authority (MBTA) in Boston, Los Angeles Country Metropolitan Transportation Authority (LACMTA) and Metropolitan Atlanta Rapid Transit Authority (MARTA) were found to have similar revenue merge configurations. The BART network is often referred to as WMATA's "sister network" as the two systems were designed at the same time and share many common operating characteristics. The junction configuration comparison with peer systems found that there is very little opportunity to improve Metrorail core capacity through junction reconfiguration. Not only are the present Metrorail junctions consistent with the best junction configurations of peer transit systems, but any such reconfiguration would be costly and extraordinarily disruptive to operations for months or years.

BART: The BART network, which dates from the late 1960s and early 1970s, includes a critical complex merge in downtown Oakland, known as the Oakland Wye. A three track line and a two track line merge to form a two track line that passes through West Oakland and then enters the Transbay Tunnel to San Francisco. The turnout sizes are not all the same at the Oakland Wye so not all merging speeds are the same. Critical turnouts include switch 123 (a #15 with a 36 MPH diverging speed), switch 323 (a #15 with a 36 MPH diverging speed), switch 227 (a #15 with a 27 MPH diverging speed) and switch 211 (a #10 with an 18 MPH diverging speed). Switch 227 has a lower diverging speed, despite its #15 frog angle, than the others because the track speeds ahead are limited to 18 MPH. The 27 MPH speed command through the turnout is, in essence, profiling the train to a more restrictive speed ahead.

MBTA: Originally opened in 1912, the Red Line of the MBTA was a simple linear system without revenue junctions until the opening of the first section of the South Shore Line in 1971. At that time, the MBTA inaugurated a grade-separated junction north of Columbia Station (now JFK/UMass Station) for a new branch from Columbia Junction to Quincy Center. The revenue turnouts were designed with #20 frogs, supporting a diverging speed of 40 MPH. The two other MBTA heavy rail rapid transit lines (Blue and Orange Lines) are physically separate from the Red Line and do not include any revenue junctions.

MARTA: The MARTA network in the Atlanta metropolitan region has two revenue junctions: the merging of the Red and Gold Lines north of downtown (at a location known as Canterbury Junction) and the merging of the Green and Blue Lines west of downtown (at a location known as Ashby Junction). Both locations are fully grade-separated (meaning that they are "flying junctions") and were designed with #20 frogs, supporting a diverging speed of 37 MPH.

LACMTA: The LACMTA Red and Purple Lines are Los Angeles' only true heavy rail rapid transit lines, forming a "Y" shaped system with the base focused on Los Angeles Union Passenger Terminal, the terminal for Metrolink commuter rail trains. The fork of the "Y" is located at Wilshire/Vermont with the two branches extending to North Hollywood (Red Line) and Wilshire/Western (Purple Line). The junction is grade-separated and uses #12 equilateral turnouts with a diverging speed of 40 MPH.

3.2.2 Terminals and Yard Access

Terminals represent system capacity constraints on most heavy rail rapid transit systems, including Metrorail, due to time-consuming train "turning" (change of direction) operations. A few heavy rail systems, such as the SEPTA Market-Frankford Line at 69th Street, employ loop tracks to avoid the capacity impacts of traditional terminal layouts. Traditional terminals generally require more than one track for simultaneous train "turning" operation because the "turning" requires more time than the scheduled headway. This requires the terminal to have two or more tracks which generally results in at-grade crossing conflicts between outbound and inbound trips.

The presence or absence of yard leads at terminals also influences capacity. Where terminal tracks continue past the terminal as non-revenue yard leads, capacity is generally enhanced because yard "put-ins" and "take-outs" can be implemented without any at-grade conflicts.

There is much debate within the transit industry with respect to whether "revenue side" (towards the system core) crossovers or "non-revenue side" (away from the system core) crossovers provide optimal capacity. Some systems include both sets of crossovers, though their presence provides little overall gain in capacity. Where terminal train "turn" times are significantly longer than the line's headway, sufficient terminal capacity can be achieved through stacked track configurations where a terminal may have a total of four station tracks – two stacked on top of two tracks. NYCT's 179th Street Terminal (on the four-track Queens Boulevard Line) takes this concept to the extreme with a stacked four over four terminal configuration.

There is also much debate within the transit industry with respect to optimal terminal crossover speeds with respect to capacity. Because trains are stopping at the nearby terminal station, terminal crossover speeds rarely exceed 30 MPH. Speeds higher than 30 MPH cannot generally be attained due to station stopping requirements. Because every alternating set of inbound/outbound trips will conflict at the terminal crossovers, it is important that the overall interlocking length be as compact as possible. Faster crossover speeds require longer interlockings; transit planners generally agree that terminal interlockings designed for diverging speeds of 20-30 MPH represent the optimal balance between compact interlockings (short occupancy times) and reasonable entrance/exit speeds.

Metrorail Capacity Implications

Table 5 summarizes WMATA terminal operations in terms of number of platform tracks, number of non-revenue tail tracks and terminal operating speeds. At some terminals, ATC speed commands are not provided and the train operates in yard mode. This is shown as a 15 MPH maximum speed in the table below.

Table 5 – Metrorail Terminal Configurations

	Terminal	# of Platform Tracks	# of Non-Revenue Tail Tracks	Interlocking on Revenue Side of Platform?		Interlocking on Non-Revenue Side of Platform?		Yard on Non-Revenue Side?
				Maximum Diverging Speed	Frog Number	Maximum Diverging Speed	Frog Number	
WMATA	Shady Grove	2	2	28	10	15	10	Yes
WMATA	Vienna	2	2	28	10	No	No	No
WMATA	Franconia-Springfield	2	3	15	10	15	10	No
WMATA	Huntington	2	2	28	10	No	No	No
WMATA	Glenmont	2	2	22	10	15	10	Yes
WMATA	Greenbelt	2	2	22	10	No	No	Yes
WMATA	New Carrolton	2	2	28	10	15	8	Yes
WMATA	Largo Town Center	2	3	28	10	15	10	No
WMATA	Branch Avenue	2	2	28	10	15	10	Yes

The Yellow Line turnback operation at Mount Vernon Square, coupled with limited terminal capacity at the alternative terminal (Greenbelt) represents another core capacity constraint. Yellow Line trains change direction at the single Mount Vernon Square turnback track every six minutes during morning and evening peak periods. This turnback time includes about two minutes of interlocking occupancy time entering the turnback, two minutes of dwell (during which one operator must close up their operating compartment while the other operator gets ready to operate the train from the opposite end) and two minutes of interlocking occupancy time exiting the turnback. Because there is no “overrun” track at the north end of the Mount Vernon Square turnback, ATC speed commands require a safety stop entering the track, further challenging high capacity operation. The alternative terminal at the end of the Green and Yellow Lines, Greenbelt, has two station tracks. There is insufficient capacity at this location to turn all 26 Yellow/Green peak hour trains at Greenbelt (a train every four minutes on each of the two tracks), which would be required if peak period Yellow Line trains were extended from Mount Vernon Square in the peak.

Comparison with Peer Systems

Table 6 provides the same information as Table 5 but for four peer systems – BART, MBTA (Red Line only), LACMTA and MARTA. Not all information is available for all systems.

The comparison of Table 6 with Table 5 indicates that the WMATA network is comparable to the four peer systems in terms of terminal configurations that support high capacity operations. Five of nine Metrorail terminals have capacity-enhancing yard leads that serve as continuation of terminal tracks. All nine terminals have crossovers on the revenue side of the platforms and six of the nine also have crossovers on the non-revenue side. Turnout sizes are almost all No. 10 (the non-revenue crossovers at New Carrollton are No. 8) supporting terminal speeds in the range of 15 to 28 MPH. As was noted above, these terminal speeds, paired with crossovers compactly located near the terminal platform, are generally considered to be optimal in terms of maximizing interlocking traversal speeds while minimizing overall interlocking length.

Table 6 – Peer System Terminal Configurations

System	Terminal	# of Platform Tracks	# of Non-Revenue Tail Tracks	Interlocking on Revenue Side of Platform?		Interlocking on Non-Revenue Side of Platform?		Yard on Non-Revenue Side?
				Maximum Diverging Speed	Frog Number	Maximum Diverging Speed	Frog Number	
BART	Richmond	2	2	No	No	Yes	Yes	Yes
BART	Pittsburg/Bay Point	2	3	No	No	Yes	Yes	No
BART	Dublin/Pleasanton	2	2	No	No	Yes	Yes	No
BART	Fremont	2	2	Yes	Yes	No	No	No
BART	Millbrae	2	3	Yes	Yes	Yes	Yes	No
MBTA	Alewife	2	3	Yes	Yes	Yes	Yes	No
MBTA	Braintree	2	2	Yes	Yes	Yes	Yes	No
MBTA	Ashmont	2	2	No	No	Yes	Yes	Yes
MARTA	North Springs	2	2	Yes	10	No	No	No
MARTA	Airport	2	2	Yes	10	No	No	No
MARTA	Doraville	2	3	Yes	10	No	No	No
MARTA	Indian Creek	2	2	Yes	10	No	No	No
MARTA	Bankhead	2	1	No	No	Yes	10	No
MARTA	Hamilton E. Holmes	2	2	Yes	10	Yes	10	No
LACMTA	North Hollywood	2	3	25	8.25	10	10	No
LACMTA	Wilshire/Western	2	2	25	8.25	X	X	No
LACMTA	Union Station	2	2	9	10	10	25	Yes

3.3 Train Control Capacity Constraints

The architecture of the ATC system and, especially, its speed commands, plays an important role in determining system capacity. Unlike fixed block ATC, CBTC provides an infinite (or nearly infinite) range of operating speeds. Fixed block ATC systems require fine granularity in their speeds in order to promote close headways and high capacity. Selection of ATC speed commands for a given system requires:

- Matching (or coming close) to all civil (curve, bridge and tunnel) speed restrictions in the system,
- Matching (or coming close) to all interlocking crossover and turnout diverging speeds in the system,
- Providing reasonable compatibility with signal block length increments corresponding to different speed commands leading to stop signal/block occupied ahead enforcement.

Providing signal block length increments corresponding to different speed commands (which in turn must be compatible with the rail system's civil speeds and interlocking diverging speeds) requires engineering judgment and compromise. For example, a simple braking model that has 5.0 seconds of reaction time and a 1.5 MPHPS deceleration rate yields the following braking distances:

- 20 MPH: 343 feet,
- 30 MPH: 660 feet
- 39 MPH: 1030 feet
- 46 MPH: 1372 feet.

The train control architect may choose a basic signal block length of 350 feet in this example. This would require one block of braking distance for 20 MPH, two blocks for 30 MPH, three blocks for 39 MPH and four blocks for 46 MPH. Each of these provided braking distances provides some excess distance; in practical application, the excess braking distances can be more significant (longer) than this simple example.

3.3.1 Gradation of Speed Commands

Metrorail Capacity Implications

Metrorail utilizes 11 distinct ATC speed commands providing excellent coverage of civil speed restrictions and successive speed targets for enforced speed reductions. These reductions are needed both for civil speed enforcement (including diverging movements at interlockings) and interlocking stop signal/block occupied ahead enforcement. The 11 speed commands are 0, 15, 22, 28, 35, 40, 45, 50, 55, 65 and 75 MPH.

Comparison with Peer Systems

Table 7 provides a summary of peer review with respect to ATC speed command gradation. The MARTA results are based on its seven speed commands of 0 15, 25, 37, 50, 60 and 70 MPH. The MBTA Red Line results are based on its six speed commands of 0, 10, 15, 25, 40 and 50 MPH. The BART results are based on its eight speed commands of 0, 6, 18, 27, 36, 50, 70 and 80 MPH while the LACMTA Red and Purple Line results are based on nine speed commands of 0, 9, 15, 25, 30, 40, 45, 55, 70 MPH.

The table shows that WMATA has the largest number of speed commands, which supports close-headway, fixed-block operations. It also has the tightest average spread (speed gap between successive speed commands) of the five systems, with an average spread of 7.5 MPH.

Table 7 – Peer Review of ATC Speed Command Gradation

System	Number of Speed Commands	Minimum Spread (MPH)	Maximum Spread (MPH)	Average Spread (MPH)	Standard Deviation of Spread (MPH)
WMATA	11	5	15	7.5	3.1
MARTA	7	10	15	11.7	1.9
BART	8	6	20	11.4	4.2
LACMTA	9	5	15	8.8	3.2
MBTA	6	5	15	10.0	3.2

3.3.2 Signal Design Safe Braking Distances

This section presents LTK's peer survey of heavy rail rapid transit systems to determine the extent to which the existing Metrorail train control system falls within or outside of industry norms. Metrics utilized in the evaluation include:

- Typical minimum and average signal block (track circuit) lengths both within and outside of stations in capacity-constrained areas,
- Train control design braking rates used,
- Train control reaction/response times and modes (maintain speed, coast, "worst case" run-away acceleration, etc.) used.

Metrorail Capacity Implications

Capacity is enhanced when the signal design safe braking distances are as short as possible, consistent with adhesion and vehicle performance considerations. Signal design safe braking distances coupled with a site-specific signal block layout determines how fast and how close a following train can operate with a train ahead. All North American rapid transit systems subscribe to the “brick wall” design philosophy with respect to signal block layout, meaning that the train ahead is always assumed to be stopped (a “brick wall”, in essence). No North American rapid transit systems provide speed command “credit” based on the fact that the train ahead may be known to be moving forward at a certain velocity. The “brick wall” design philosophy protects against the possibility of sudden deceleration of the train ahead due to, for example, a derailment or emergency brake application.

Table 8 – WMATA Signal Design Safe Braking Distances

Initial Speed (MPH)	Signal Design Safe Braking Distance (Ft., Level Tangent Track)	Overall Effective Deceleration Rate (MPHPS)
22	561	0.633
40	1288	0.911
50	1717	1.068
75	3109	1.327

Table 8 summarizes signal design safe braking distances and overall effective deceleration rates for four WMATA ATC speed commands. The overall effective deceleration computation ignores the fact that some of the signal design safe braking distance reflects equipment reaction times and “worst case” run-away acceleration. Ignoring reaction times and assuming level track, the WMATA signal design safe braking deceleration rate is 1.65 MPHPS for speeds of 0 to 50 MPH, tapering linearly to 1.24 MPHPS between 50 and 75 MPH. The deceleration rates shown in Table 8 are lower because they include the initial reaction times of the train prior to the brakes being fully applied.

Comparison with Peer Systems

WMATA’s signal design safe braking rate compares favorably from a capacity-centric perspective (meaning that a higher rate is better) with peer systems. BART uses two rates that bracket the WMATA rate – 1.5 MPHPS for exterior (above ground) applications and 2.0 for interior (underground) applications. CTA uses a 1.495 MPHPS signal design safe braking distance rate but then applies an additional 35 percent safety factor to the resultant distances. This is equivalent to a 1.107 MPHPS signal design safe braking distance rate when specified in equivalent terms to the WMATA 1.65 rate. The MBTA utilizes a 1.4 MPHPS signal design safe braking distance rate which is less capacity-friendly than the Metrorail rate. The LACMTA and MARTA signal design safe braking distance rates could not be obtained.

3.4 Dwell Time Related Capacity Constraints

3.4.1 Metrorail Vehicle Configuration

One factor contributing to dwell time length is the rate at which passengers can board and alight from a car during a platform stop, which is largely determined by the number and size of doors present on a given car (other factors include platform configuration, platform side clearances and passenger distribution along the platform but the dwell time impacts of these factors are difficult to quantify). As shown in Table 9, relative to car length, the boarding and alighting capacity of Metrorail vehicles closely matches the capabilities of peer systems'' vehicles. WMATA's rolling stock matches the median of those sampled for both the number of doors per unit car length, and the total door width per unit car length, though both of these values are slightly below the mean. While procuring or modifying vehicles to increase the number and size of doors may conceivably increase the rate at which passengers could board and alight, it would be an unconventional method for increasing total passenger carrying capacity.

Previous studies have noted the capacity benefits of adding one door set per side of vehicle however there are several challenges with this strategy. First, the benefits in terms of reduced dwell times for a 60 second dwell time would likely be in the range of 8-12 seconds (a 20-30% reduction in that portion of the dwell associated with passenger alighting/boarding with no effect on the base door cycle time dwell component of about 20 seconds). Assuming all cars of all trains have four doors per side, this is equivalent to a throughput gain of about 2 trains per hour. Although this rolling stock change could be implemented incrementally as each Metrorail fleet type is retired, full implementation would require over 40 years due to the life cycles of the multiple Metrorail fleets. Second, implementing a new railcar design with four doors per side would result in a net seat reduction of approximately 28 percent, requiring more customers to stand.

Table 9: Comparison of Vehicle Entrances Per Vehicle Length Among Peer Rapid Transit Systems

Operator	Vehicle(s)	Number of Doors	Width of Opening, in	Total Passenger Opening Width, in	Car Length, ft	Number of Doors/Foot of Car Length	Inches of Door Width/Foot of Car Length
WMATA	Rohr 1000, Breda 2000, Breda 3000, Breda 4000, CAF 5000, Alstom 6000, Kawasaki 7000	3	50	150	75	0.04	2.00
BART	Rohr A2	2	54	108	75	0.027	1.44
BART	Rohr B2, Soferval C1, MKI C2	2	54	108	70	0.029	1.54
CTA	Budd 2600, MKI 3200, Bombardier 5000	2	-	-	48	0.042	-
MBTA Red Line	Pullman 1500, Pullman 1600, UTDC 1700	3	48	144	69.5	0.043	2.07
MBTA Red Line	Bombardier 1800	4	52.5	210	69.5	0.058	3.02
LACMTA Red/Purple Line	Breda A650	3	50	150	75	0.04	2.00
MARTA	SFB CQ 310, Hitachi CQ 311, Breda CQ 312	3	50	150	75	0.04	2.00
NYCT	Alstom/Kawasaki R-160	4	50	200	60.5	0.066	3.31
TTC	Bombardier Toronto Rocket, Bombardier T-1	4	60	240	75	0.053	3.20

3.4.2 Transfer Stations

Metrorail Capacity Implications

Transfer stations generally have the longest dwells in the Metrorail network and, as such, serve as the one of the chief capacity constraints in the system. During the month of

October 2014, dwell time data was collected daily for all stops on both tracks at the 21 stations listed in Table 10, including Metro Center, Gallery Place, Rosslyn, and L'Enfant Plaza transfer stations. Using Metrorail Central Control's automated data logging capabilities, this totaled to 313,801 station dwell time records. After removing times from the Columbus Day holiday, 305,216 dwell time records remain. Table 10 includes the 90th percentile dwell times at each station during the AM and PM peak periods, defined as 7:30-8:30 AM and 4:30-5:30 PM, respectively. The 90th percentile refers to the minimum duration which is longer than 90% of platform stops; 10% of platform stops lasted at least this long or longer. Based on the longer average dwell, Table 10 also categorizes the peak direction of travel at each station during the AM and PM peak period. In cases where the average dwell durations are within 10%, no such categorization is made.

The raw data consisted of the time interval during which the passenger doors were open at the platform. All recorded dwell times were adjusted upward by five seconds to account for the additional elapsed time between the train's arrival and departure from the platforms and the door opening and closing. The stations at which recording took place do not match up precisely with the core capacity definition used elsewhere in this White Paper, though all transfer stations are captured. In particular, no data is available for the shared stations along the Green and Yellow lines, while data was collected beyond the core extents at Woodley Park-Zoo, Potomac Avenue, and Stadium-Armory stations. The data from these additional stations has been italicized in Table 10.

Table 10: October 2014 Peak Period 90th Percentile Dwell Times

Line	Station	Transfer Station	AM Peak Period			PM Peak Period		
			Eastbound 90th Percentile Dwell Time, s	Westbound 90th Percentile Dwell Time, s	Peak Direction	Eastbound 90th Percentile Dwell Time, s	Westbound 90th Percentile Dwell Time, s	Peak Direction
Red	*Woodley Park-Zoo*		*28*	*31*	*Within 10%*	*28*	*35*	*West*
Red	Dupont Circle		44	34	East	37	37	Within 10%
Red	Farragut North		38	40	Within 10%	41	43	Within 10%
Red	Metro Center	Yes	63	56	East	74	51	East
Red	Gallery Place	Yes	61	68	West	63	63	Within 10%
Red	Judiciary Square		32	38	West	33	36	Within 10%
Red	Union Station		55	53	Within 10%	56	53	Within 10%
Red	NoMa-Gallaudet U		33	37	West	33	35	Within 10%
Blue/Orange	Rosslyn	Yes	38	35	Within 10%	36	40	Within 10%
Blue/Orange	Foggy Bottom		34	31	Within 10%	33	34	Within 10%
Blue/Orange	Farragut West		26	30	West	12	32	West
Blue/Orange	McPherson Square		33	35	Within 10%	37	34	Within 10%
Blue/Orange	Metro Center	Yes	41	46	West	46	42	Within 10%
Blue/Orange	Federal Triangle		25	39	West	28	42	West
Blue/Orange	Smithsonian		28	28	Within 10%	30	30	Within 10%
Blue/Orange	L'Enfant Plaza	Yes	40	45	West	44	38	East
Blue/Orange	Federal Center		26	28	Within 10%	25	31	West
Blue/Orange	Capitol South		26	29	West	26	31	West
Blue/Orange	Eastern Market		26	28	Within 10%	26	26	Within 10%
Blue/Orange	*Potomac Avenue*		*26*	*30*	*West*	*26*	*28*	*Within 10%*
Blue/Orange	*Stadium-Armory*		*30*	*32*	*Within 10%*	*28*	*35*	*West*

For a more detailed comparison of the dwell times measured in this study, Appendix B – October 2014 Dwell Time Distribution Curves For Core Stations of the Red, Blue and Orange Lines, 7:30AM-8:30AM consists of histograms which display the distribution of dwell times recorded at each station in the peak direction during the AM peak periods. In general,

Transfer station congestion has grown notably worse in recent years and will continue to result in longer train dwell times as ridership grows in the future. Metrorail is embarking on a station improvement project designed to:

- Address passenger crowding,
- Anticipate safety concerns,
- Maximize station capacity, and
- Facilitate access and transfers,

As part of this work, WMATA anticipates that transfer stations Metro Center and Gallery Place will exceed their practical capacity by 2020. In addition, non-transfer stations Farragut North, Farragut West and Union Station are anticipated to exceed their practical capacity (Union Station serves as a transfer station between commuter rail and heavy rail rapid transit but not between Metrorail lines). By 2025, WMATA anticipates that transfer station L'Enfant Plaza and non-transfer stations Foggy Bottom-GWU and McPherson Square will join this list.

The three major crossing transfer stations are Metro Center, Gallery Place and L'Enfant Plaza. Gallery Place has a unique configuration with "T" type arrangement, rather than a more traditional cross-type transfer. Metrorail's 2030 modeling shows platform crowding that is so severe that it prevents passengers from being able to get on and off trains, resulting in catastrophic pedestrian and train grid lock.

WMATA architectural consultants have investigated the following solutions at Gallery Place:

- Platform edge barriers,
- Pedestrian tunnel between Gallery Place and Metro Center,
- Diagonal "shortcut" passageway in the northwest quadrant of the transfer
- Bridges between mezzanines
- Reconstructing some escalators in an orientation 180 degrees from present to eliminate queuing.

The diagonal "shortcut" passageway shows the greatest promise in terms of cost-benefit analysis. Pedestrian flow modeling has shown that no solutions will bring passenger crowding and resultant dwell times below today's level, meaning that all future scenarios have worsening dwell times and, hence, reduction in trains per hour. However, WMATA's plans, notably the diagonal shortcut at Gallery Place, may reduce the rate of increase in dwell time, stemming the resultant loss of train throughput.

Comparison with Peer Systems

The Bloor-Yonge transfer of the TTC Yonge/University/Spadina and Bloor-Danforth Lines is the most analogous station layout to the three principal Metrorail transfer stations. Unlike the master-planned Metrorail system, the TTC station evolved from its initial construction as an in-line station in 1954 to a transfer station with the opening of the Bloor-Danforth Line in 1966. Similar to Metrorail transfer stations, Bloor-Danforth has one level with side platforms (the Yonge/University/Spadina Line) and one level with an island platform (the Bloor-Danforth Line). Dwells at Bloor-Yonge are typically in the 50 to 60 second range in peak periods, according to the TTC. These dwells effectively serve as the system constraint on train throughput for both lines.

The TTC has implemented several widening programs for the side platforms since the 1970s with only limited success in reducing dwell times. In recent years, the TTC has also experimented with so-called "Platform Guards", "light duty" personnel who are charged with clearing the way for alighting passengers and discouraging last-minute boarding passengers from entering the train while doors are closing. These measures have not reduced long-term dwell times but have controlled dwell time increases as ridership has grown.

The BART rail network does not have any crossing type transfer stations though there are "stacked" (same track orientation) stations in downtown Oakland. These generally do not constrain train throughput. The MARTA network has cross-type transfer stations but its average weekday ridership is less than a third of the Metrorail network; passenger crowding is not a significant issue in Atlanta.

Boston's MBTA has a number of crossing type transfer stations. The most notable is Downtown Crossing, a cross type arrangement with both levels having siding platforms. The location is the believed to be the busiest station in the network in terms of passenger transfers and the second busiest station in terms of passenger entrances with an average of 23,478 entries each weekday in 2013. As part of another project, LTK performed dwell time observations during the morning peak period at this location in June, 2015. The Orange Line level showed an average dwell time of 58 seconds, with a range of 41 to 100 seconds. The Red Line level showed an average dwell time of 45 seconds, with a range of 30 to 66 seconds.

Another busy cross type transfer station in the MBTA network is Park Street, where the heavy rail Red Line crosses the light rail Green Line. The Green Line level features a complex four-track arrangement with two center island platforms, pedestrian at-grade crossing of some tracks and loops for "turning" trains. The Red Line Park Street configuration is unique in that platforms are available on both sides of the car with doors on both sides opening simultaneously. Despite the high passenger alighting and boarding capacity, LTK-recorded dwells averaged 50 seconds, with a range of 33 to 63 seconds. Consultation with MBTA Subway Operations managers indicated that the observed dwell times are considered to be "normal" with no known capital improvement project or operational change targeted at reducing them.

In conclusion, while the TTC has been the most ambitious in working to control transfer station dwell times, it does not appear that any specific strategies have reduced transfer station dwell times. The recent introduction of Toronto Rocket rolling stock, with wider doors and open gangways between cars, has had no discernible impact on dwell times. While the door openings are wider than the cars they replaced, the 60" door width nonetheless limits movement to two passenger streams per door opening. Door openings of at least 84" are required in order to achieve quantifiable dwell time reductions as this is the estimated minimum width at which each door opening could support three passenger streams. Door openings of this width have no precedence in North America and are known to exist only in some Japanese heavy rail systems. As such, heavy rail systems with growing ridership can work to reduce the growth in transfer station dwells and associated loss of train throughput but not to gain train throughput through these measures.

3.4.3 *Platform Passenger Distribution and Train Length Variability*

Metrorail Capacity Implications

During peak periods, Metrorail operates a mixture of 6-car and maximum length 8-car trains on the six lines, owing to traction power limitations and insufficient fleet to operate all 8-car trains. While platform "count-down" clocks provide notice to passengers regarding the lengths of approaching trains, not all passengers are aware of this information or know to position themselves at the correct location on the platform. Occasional customers are further challenged by the lack of markings on the station platforms regarding berthing locations and the station-to-station variation in berthing locations (which can be front, center or rear depending on WMATA's ATO programming).

Train length variability and resultant non-uniform boarding distribution of passengers has a negative impact on capacity. The precise impact on capacity is difficult to quantify but can be seen by frequent door holding and passenger bunching at the extremities of 6-car trains. This source of Metrorail capacity constraints, while minor, will come to an end as WMATA's traction power upgrades and fleet expansion programs are planned..

Comparison with Peer Systems

TTC, MBTA, MARTA and LACMTA operate consistent full length trains during peak periods, thereby avoiding any capacity loss associated with variable length trains. BART does operate variable length trains. BART attempts to mitigate capacity losses associated with non-uniform platform passenger distribution through passenger information displays and frequent automated platform announcements. Metrorail utilizes passenger information displays but does not make announcements.

In conclusion, Metrorail's variable train length and associated non-uniform passenger distribution along platforms is not a major capacity constraint. As Metrorail plans for eventual implementation of 100% 8-car operation during peaks, this capacity constraint will be eliminated. As Metrorail approaches (but has not yet achieved) 8-car operation, automated platform announcements regarding approaching 6-car trains should be implemented to avoid passenger crowding at the end of the 6-car trains. These announcements are effective in encouraging BART customers to properly distribute themselves along the platform when trains shorter than maximum length are approaching.

3.4.4 Automatic Train Operation

Metrorail Capacity Implications

Automatic Train Operation (ATO) provides automated train driving using the Metrorail ATC system to assure safe train separation and compliance with all civil speed restrictions. ATO also provides for profiling of trains to station berths. As Metrorail has moved to 8-car trains in the last decade, the ATO system has been refined to provide enhanced stopping precision necessary for the berthing of 600-foot trains on 600-foot platforms. ATO provides for automatic door opening when a train is properly berthed, leaving only door closing and monitoring of safe train movement as Metrorail Operator responsibilities.

Since the opening of Metrorail in 1976, all Metrorail trains have had the capability of being operated in ATO or in Manual mode, where the Operator follows ATC speed command limits for safe train separation/civil speed enforcement and manually berths the train at each station stop. In the 1990s, Metrorail experienced intermittent problems with vital signal relays that support the ATC system. Operators were directed to operate only in Manual mode so that they would be more attentive to the possibility of a “false proceed” ATC speed command. Metrorail resumed full ATO once all of the relays were replaced. The June 22, 2009 accident near Fort Totten on the Red Line, attributed to incompatible ATC track circuit equipment, again resulted in a system-wide reversion to Manual Operation. Metrorail is resuming ATO on the Red Line this year after a six year absence, with ATO slated to resume on the other five lines starting in 2017.

The presence or absence of ATO does not have a direct effect on rail system capacity but does provide for more consistent operation, which promotes uniform headways. The lack of consistent train speed profiles under non-ATO (Manual) operation can lead to train bunching. Should a relatively cautious Operator opt not to operate close to maximum authorized speed during the peak, a service gap ahead of the train can build, resulting in lost “slots” through the system.

During interviews for this WMATA Core Capacity Analysis, Metrorail Train Control Engineers noted that the ATO brake rate for station stopping is necessarily reduced to account for worst-case or near-worst-case adhesion conditions approaching stations. In contrast, under Manual operation, Operators are free to choose the appropriate brake rate for station stops since station stops are not enforced by ATC or any other non-ATO system. On most days, when inclement weather is not an issue, the Manual station stop brake rate is more aggressive than the ATO rate. This phenomenon may actually mitigate some of the capacity loss associated with the non-ATO (Manual) operation.

Comparison with Peer Systems

No North American peer property has had significant experience with prolonged peak period operation of both ATO and non-ATO operation on the same lines. As such, comparison with peer systems is difficult. The RATP Paris Metro, which evolved from a Manual operation to one equipped with ATO, has a strict policy that all peak period trains are to operate in ATO (unless subject to equipment failure) for consistent service delivery. At the same time, all Paris Metro Operators must operate at least one daily trip in Manual mode to maintain their proficiency in such operation; the timing of this trip is limited to off-peak periods.

MARTA is equipped with ATO and has run consistently in that mode for more than two decades. MARTA does require that each Operator make their first trip of the morning in Manual mode to maintain their qualifications. In some cases, this trip can extend into the morning peak. MARTA does not schedule headways closer than 4 minutes (15 trains per hour) so capacity implications of this policy are less important than at more capacity-constrained networks.

LACMTA Red/Purple Lines operate in ATO mode during peak periods with Manual operation the norm during off-peak periods. As with other systems, this policy is designed to maintain a high degree of operator proficiency in Manual operation given the possibility that ATO needs to be disabled on a specific train or system-wide. LACMTA has had issues with proper ATO berthing of minimum length trains, which typically operate late at night, at terminal stations. This underlines the need to operate in Manual during off-peak periods.

BART operates every day, all day, in full ATO. “Road Manual” mode is operated as a training practice for selected off-peak trains and never in the peak. “Sweeper” train duty (first non-revenue train in the morning that drops off station agents at in-line stations) is often operated in non-ATO mode for this reason. BART noted that its first generation train control that dates from the late 1960s and early 1970s, especially its ATO overlay, is increasingly prone to reliability issues. This requires peak period operation in “Road Manual” which BART Operations otherwise strives to avoid.

In conclusion, consistent peak period operation in ATO is desirable to maintain service uniformity and to increase the likelihood that actual throughput matches scheduled throughput. The Orange/Silver/Blue Line service delivery variability shown in Figure 4 is very likely due, in part, to all trains being operated in Manual mode and differences in individual driving styles. Restoration of system-wide ATO will give Metrorail Operations Planners greater confidence to schedule train volumes that are close to the practical capacity of the system, potentially resulting in a small 1 to 2 trains per hour capacity improvement.

4 Hypothetical Metrorail Advanced Train Control Analysis

LTK evaluated hypothetical capacity improvement strategies applied to two capacity-constrained section of Metrorail. LTK utilized its existing WMATA TrainOps® operations simulation model to evaluate two of the most capacity-constrained locations on the Metrorail system -- the junction at Rosslyn and the core section of the Orange/Blue/Silver Line. This section has closely-spaced stations that limits throughput.

LTK then applied a hypothetical advanced train control solution, Communications-Based Train Control, to the two capacity-constrained locations. Typical North American CBTC functional criteria in terms of safe braking distance margin, system response time, positional accuracy and safety buffers were used.

This chapter concludes with a discussion of the comparative Metrorail capacity of the two train control alternatives – the existing fixed block system and the hypothetical CBTC installation. It includes an explanation of the throughput differences under both delay-free operations and "crush" operations, where trip time is sacrificed in order to maximize the volume of trains operated.

4.1 Simulation Software

The throughput analysis was performed with TrainOps® operations simulation software under ideal voltage conditions (e.g. no degraded train performance due to traction power system limitations). The software was run with a timestep of 0.5 seconds for all analyses. TrainOps allows for the same simulation model to be run with CBTC and fixed block cab signaling by disabling the response of trains to cab signaling.

TrainOps has been successfully used to evaluate CBTC and PTC system capacity benefits, most recently for a Metro Trains Melbourne (Australia) candidate test line, and for Caltrain's future Communications-based Overlay Signal System (CBOSS).

When run with CBTC enabled, TrainOps brakes for speed limits and trains ahead according to a user-defined multi-stage safe braking distance curve, and programmed system transmission and processing times. Transmission times reflect communications latency for the train ahead to communicate its known position to wayside equipment and for wayside equipment, in turn, to communicate an updated movement authority to the following train.

Braking for station stops is unaffected under CBTC. This is because an overshoot of a station does not pose a safety risk, though it obviously causes operational disruption and delays due to safety procedures that must be satisfied as part of the train backing up.

TrainOps also allows for the use of a per-trip *schedule margin* as a mechanism for calibration and accounting for the possibility of unexpected delays and less-than-ideal operator or equipment performance. When a percent schedule margin is used in the simulation, the resulting run times at any point are longer by the schedule margin over the ideal case. This requires that dwells be increased by the percent schedule margin, speeds be decreased by multiplying by the factor 1/ (1+schedule margin), and acceleration rates be decreased by multiplying by the factor $1/(1+\text{schedule margin})^2$. Calibration of previous Metrorail terminal-to-terminal trips determined that a 10% schedule margin was appropriate for the capacity analysis.

4.2 Simulation Data Sources

The simulation data sources provided to LTK by WMATA are covered in this section. The majority of the simulation data was pre-existing from previous work performed by LTK. As part of the Capacity White Paper work, all data applicable to the two study areas (Rosslyn and the core Orange/Blue/Silver Line) was reviewed for accuracy.

4.2.1 Alignment

The alignment data for this simulation was sourced from the WMATA Track Plans for the C, D, and K lines. The alignment data includes wayside signal locations, ATC bond (non-wayside signal) locations, grades, curves, switch points, and platform limits. Speed enforcement in WMATA's fixed block signaling system can only provide for speed changes at block limits and only for speeds that match ATP speed commands. One advantage of CBTC moving-block train control is that speed resolution is much finer and speed change points need not correspond to block limits.

To model the "clean slate" input of civil speed limits in the CBTC model, the maximum safe speeds for all curves in the study area were calculated according to the recommended AREMA (American Railway Engineering and Maintenance-of-Way Association) formula shown in Equation 1. *Ea* is the actual super-elevation of the curve, *Eu* is the unbalanced super-elevation (also referred to as cant deficiency), and D is the degree of curvature. The unbalanced super-elevation component is determined by vehicle capabilities; for WMATA rolling stock a maximum unbalanced super-elevation of 4.5 inches is used for the calculation of *V-max.* These inputs were found to closely match the civil speed limits enforced by the current ATC system.

$$V_{max} = \sqrt{\frac{Ea + Eu}{0.0007D}}$$

Equation 1- AREMA Safe Curve Speed Formula

4.2.2 Rolling Stock

Figure 11 – WMATA 7000 Series Train

The capacity simulations used the 7000 series rolling stock, which is the newest model in the Metrorail fleet. The 7000 models include AC motors with similar performance to the other classes of WMATA rolling stock. The relevant specifications for the 7000 series car appear in Table 11. The simulated tractive effort curve is shown in Figure 12. A maximum length eight car consist was used for the simulations.

Table 11 – 7K Series Specifications for Simulation

Specifications	WMATA 7000 Series
Length (feet)	75
Weight (pounds)	85000
Number of Axles	4
Maximum Adhesion (percent)	28
Continuous Power (HP)	884
Maximum Speed (mph)	80
Initial Acceleration Limit (mph/s)	2.8
Service Brake Rate (mph/s)	2.2
Rotational Mass (percent)	6.6
Frontal Area (square feet)	110
Seated Capacity	65 passengers
Maximum Capacity	232 passengers

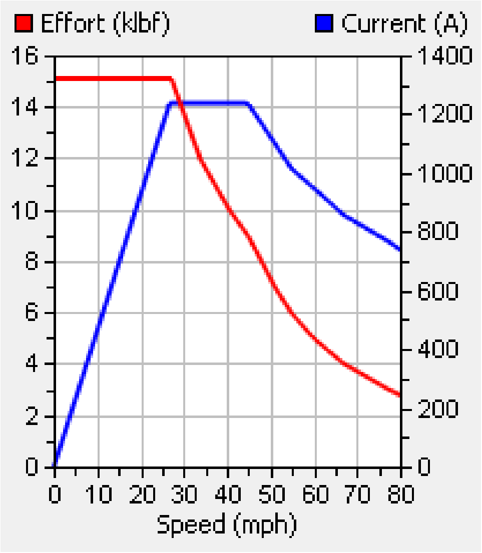


Figure 12 – 7K Series Tractive Effort Curve

4.2.3 Train Control

The WMATA fixed block signaling system uses dual code audio frequency track circuits with eight frequencies (two sets of four) and ten possible ATP speed commands. The system supports Automatic Train Operation (ATO.) Prior to 2015, the ATO system had not been used in several years but was recently restored on the Red Line (other WMATA lines will have ATO restored in the future). ATC signal block lengths in the core section of the network are very short, in many cases being less than 200 feet, and at most being 600 feet. The system was originally designed to support theoretical headways of 75 seconds and practical headways of 90 seconds. The practical design headway produces a throughput of 40 trains per hour per direction. However, the underlying design criteria for determining the headways of the train control system reflect much shorter dwell times than are typically experienced today.

Fixed-block control lines in the simulation model are entered to match the GRS/Alstom signal control line plans. An example is shown in Figure 13. As presently in service on the Metrorail network, several overlapped blocks of stop/0 speed commands are included. For both D2-34W and D2-32W shown in Figure 13, two blocks of stop commands are provided between trains.

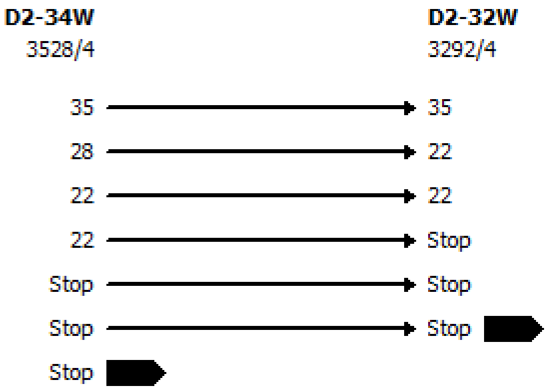


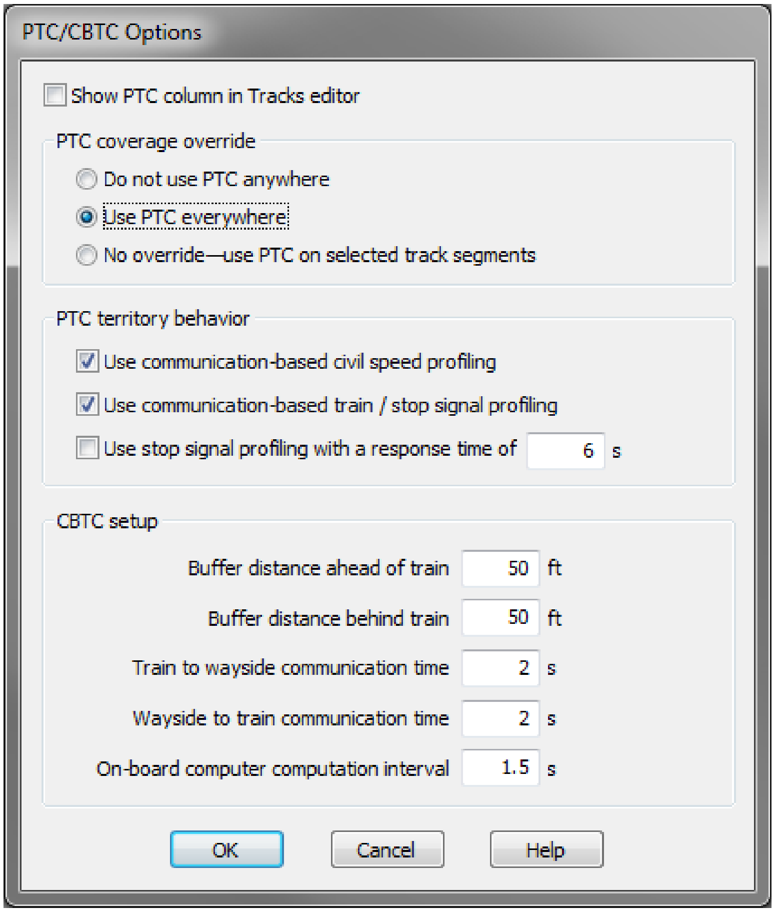
Figure 13 – Example of Site-Specific Simulation Signal Control Lines

WMATA ATC Block Design Document 16913 was used as an input to the capacity system for both the fixed-block and CBTC models. The recommended *ideal train* parameters are used for the capacity (headway) related simulation of both CBTC and fixed-block signaling, while the *worst case train* is used for the CBTC safe braking model. The fixed-block layout and associated speed commands similarly reflects *worst case train* performance in its underlying design over the 40+ years of WMATA network development.

For fixed-block signaling, an ideal train reaction time of 2.9 seconds was used for reacting to a speed command requiring deceleration. The 2.9 seconds is composed of 0.8 seconds to decode and detect the speed command, 0.5 seconds for the speed governor reaction time, 1.0 seconds for power removal, and 0.6 seconds for brake build up. The specified acceleration reaction time for fixed-block signaling is 1.0 seconds. As recommended by WMATA, a signal-to-signal communication time of 0.5 seconds was used with all fixed blocks communicating in parallel.

For the CBTC model, several communication times and processing times apply. The CBTC system parameters used in the TrainOps simulation are shown in Figure 14. These are based on a synthesis of North American rapid transit CBTC systems, including NYCT Canarsie Line and the PATH system between New York and New Jersey.

Figure 14 shows that the time for the wayside to communicate to the rail vehicles and for the rail vehicles to communicate to the wayside is set at two seconds in both cases. In the case of fixed signals (limited to home signals at the entrances to interlockings), only the wayside to train communication interval applies. The onboard computation interval is set to 1.5 seconds. This value represents the time for the train to process and respond to the information received from the wayside. Also shown are the buffer distances ahead of and behind the train. These values represent the maximum positional accuracy tolerance (locational uncertainty) of the CBTC system and were assumed to apply at all locations within the Metrorail network.



☐ Show PTC column in Tracks editor

PTC coverage override

○ Do not use PTC anywhere
● Use PTC everywhere
○ No override—use PTC on selected track segments

PTC territory behavior

☑ Use communication-based civil speed profiling
☑ Use communication-based train / stop signal profiling
☐ Use stop signal profiling with a response time of 6 s

CBTC setup

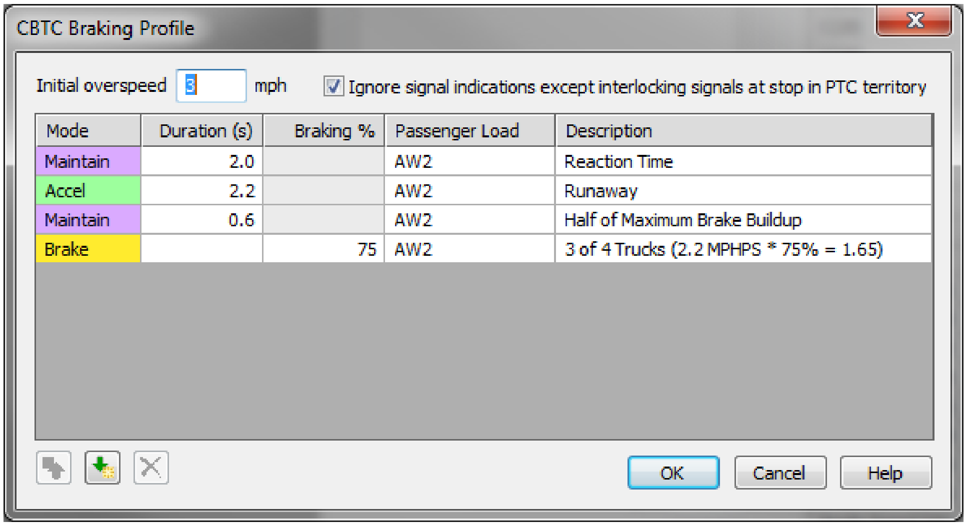
Buffer distance ahead of train 50 ft
Buffer distance behind train 50 ft
Train to wayside communication time 2 s
Wayside to train communication time 2 s
On-board computer computation interval 1.5 s

Figure 14 – CBTC System Parameters for Simulation

In the typical case of one train following another under CBTC, the train ahead will report its position to the wayside system. This information is received by the wayside equipment in two seconds which then relays the information to the following train two seconds later. The following train sees the train ahead as possibly being 50 feet behind its reported distance, and the following train itself as possibly being 50 feet closer than it is. In total this subtracts 100 feet from the possible braking distance. Knowing the worst case distance to the train ahead, the train computes whether to apply the brakes, maintain speed, or continue to accelerate based on the train ahead being stopped, the alignment data, and the safe braking distance curve. This process takes 1.5 seconds in the simulation.

The CBTC safe braking distance curve parameters shown in Figure 15 match the worst case train definition in the safe braking distance model used by WMATA for fixed-block designs. The overspeed is set to 3.0 MPH as a worst case value that would not trigger overspeed detection. Running at 3.0 MPH overspeed, the worst case train fails to respond to an ATP or CBTC command for two seconds and then begins accelerating (assuming worst-case request for propulsion rather than brake). The acceleration continues for 2.2 seconds, before power is removed and brake-build up begins, for which 0.6 seconds is allotted. During the braking phase of the curve, only three out of each four trucks function, providing 75% of the full service brake rate.

WMATA train control engineers noted that the 2.2 second acceleration is reduced at higher initial speeds under its fixed block ATC design criteria. However, CBTC algorithms generally provide the same reaction times, regardless of initial speed. Therefore, the 2.2 second value was used at all initial speeds in the TrainOps CBTC modeling.



Initial overspeed 3 mph ☑ Ignore signal indications except interlocking signals at stop in PTC territory

Mode	Duration (s)	Braking %	Passenger Load	Description
Maintain	2.0		AW2	Reaction Time
Accel	2.2		AW2	Runaway
Maintain	0.6		AW2	Half of Maximum Brake Buildup
Brake		75	AW2	3 of 4 Trucks (2.2 MPHPS * 75% = 1.65)

Figure 15 – CBTC Safe Braking Distance Curve

For assessing the capacity at junctions, an interlocking route establishment time of 6.0 seconds is included in the simulation based on a review of Metrorail Central Control data logs. The 6.0 seconds is made up of 5.0 seconds for switch movement, 1.0 second for interlocking route establishment and display of the home signal. In addition, a route release time after a train clears interlocking limits of 6.0 seconds applies. The 6.0 seconds is composed of 5.0 seconds of loss of shunt, and 1.0 second for the actual route release process.

Under both fixed block and CBTC systems, the trains will not stop precisely at the interlocking home signal in case of an interlocking conflict. In the case of fixed block systems, one or more 0/Stop speed commands are received prior to reaching the interlocking home signal; the train will stop at a location based on its response to these 0/Stop speed commands (with the interlocking home signal at stop). In the case of CBTC systems, the assumed buffer distance ahead of train, reflecting positional uncertainty, will cause the train to stop before the interlocking home signal at stop.

Trains will respond and begin moving once the interlocking route has been established and an interlocking home signal aspect more favorable than stop is displayed. For fixed block, this will be 0.5 seconds for signal system update and 1.0 second for cab signal acceleration reaction. For CBTC, the train will respond after the 2.0 seconds for wayside to train communication and the onboard computation interval of 1.5 seconds have elapsed.

4.2.4 Dwell Times

Although the WMATA signal design documents provide generic dwell time criteria for assessing signal system designs, a review of current Metrorail dwell times reviewed that the signal design dwell time criteria are too optimistic. The station dwell times used in the simulation are the 90th percentile of the observed station dwell times during October 2014 operations, The assumed dwell times are based on 90% of the trips stopping at a station dwelling for this interval or less. Because system throughput is constrained by the longest dwells and slowest-moving trains, use of the 90th percentile (rather than the average value or 50th percentile value) is appropriate.

The dwell times used in the simulation are presented in Table 12. Data was not available for stations west of Rosslyn junction. At these locations, shown in italics, a dwell time of 45 seconds was applied to transfer stations and a time of 30 seconds applied at all other stations. These assumed west-of-Rosslyn dwell times are based on an observed average 90th percentile dwell of 39.8 seconds at transfer stations, and 30.3 seconds at non-transfer stations.

Table 12 – Advanced Train Control Analysis Dwell Time Assumptions

Station	Transfer?	Abbreviation	Eastbound	Westbound
Arlington Cemetery		*C06*	*30*	*30*
Rosslyn	Transfer	C05	38	40
Foggy Bottom		C04	34	34
Farragut West		C03	26	32
McPherson Square		C02	33	34
Metro Center	Transfer	C01	41	42
Federal Triangle		D01	25	42
Smithsonian		D02	28	30
L'Enfant Plaza	Transfer	D03	40	38
Federal Center		D04	26	31
Capitol South		D05	26	31
Eastern Market		D06	26	26
Potomac Avenue		D07	26	28
Stadium Armory	Transfer	D08	30	35
Court House		*K01*	*30*	*30*

4.2.5 Operating Plans

The operating plans used for the study consist of alternating merging trains run at headways that have been iteratively determined to be the minimum for the crush and delay free headway situations. The headways for the two merging lines are set to be equal for this analysis, although in present operations, a lower volume of trains is operated on the Blue Line. Trains are operated in the westbound direction for the core segment capacity evaluation and in the eastbound direction for the Rosslyn junction capacity evaluation.

The advanced train control capacity evaluation is based on two types of operation – “crush” and “delay free”. Crush headway is defined as the minimum headway for which successive trains traverse the study area without increasing lateness but where increased trip time versus unimpeded operation is acceptable (e.g. sacrificing trip time in order to maximize throughput). Delay free headway is defined as the headway for which each train has the same travel time through the study area as a train operating unimpeded.

The trains in the operating plans used for the advanced train control capacity evaluation were simulated with a crush load, bringing the vehicle weight to 119,800 lbs. per car. This assumption is consistent with WMATA ATC Block Design Document 16913 and its procedures for capacity evaluation.

4.3 Simulation Calibration

In addition to the use of 90% dwell times, the simulation was calibrated by two measures. The ATC speed commands were encoded 2 MPH under the actual speed. This captures the performance of trains with human operators in place of ATO and is based upon previous LTK travel time calibration studies of Red Line end-to-end travel times from December 2011 and January 2012 data.

A 10.0 percent schedule margin was applied in the simulation. The effects of schedule margin were described previously. A previous analysis of Red Line end-to-end travel times from Shady Grove to Glenmont, calibrated best with a 14.0 percent schedule margin and 2 MPH underspeed. The results of this calibration are shown in Table 13. For this study, the fastest train from the calibration data was used as our basis, since the calibration exercise included the entire Red Line trip from Glenmont to Shady Grove, where delays, construction, and other interruptions may be more likely than in the core. Therefore, simulated trains are run with a 10.0 percent schedule margin which is more consistent with industry standards than the higher 14.0 percent value.

Table 13 – Trip Calibration Percent Difference Summary Calibrated to 14% Margin

Trip	Origin	Destination	Dispatch Time	Time Period	Percent Difference – Simulated vs. WMATA Operations
157	Glenmont	Shady Grove	5:20 AM	Early AM	2.20%
120	Glenmont	Shady Grove	7:07 AM	AM Peak	-1.10%
111	Glenmont	Shady Grove	12:32 PM	Midday	0.90%
130	Glenmont	Shady Grove	3:44 PM	PM Peak	2.20%
158	Glenmont	Shady Grove	6:43 PM	Evening	0.40%
159	Shady Grove	Glenmont	5:11 AM	Early AM	4.30%
123	Shady Grove	Glenmont	7:31 AM	AM Peak	-3.30%
105	Shady Grove	Glenmont	12:28 PM	Midday	-3.60%
122	Shady Grove	Glenmont	4:31 PM	PM Peak	-4.30%
132	Shady Grove	Glenmont	6:39 PM	Evening	-3.70%
Average Percent Difference					-0.60%

4.4 Rosslyn Junction Results

This analysis evaluates capacity of the Rosslyn Junction with Blue and Orange Line trains arriving at equal intervals. It contrasts fixed block ATC results with advanced train control (CBTC) results.

4.4.1 Fixed Block Train Control

Table 14 displays simulation results in the form of capacity measures for the Rosslyn Junction modeling of fixed block ATC. In addition to the two measures of headway (“crush” and “delay-free”), the table introduces the distinction between theoretical measures and practical measures that include some ability to recover from minor system disruptions. Practical headways are based on the theoretical headways results but with 25 percent added.

The system capacity (trains per hour) figures in Table 14 represent the headway values divided into 3600 seconds per hour. The practical crush system capacity of 28 trains per hour represents the best fixed block ATC benchmark against which to compare the benefits of advanced train control. The 28 trains per hour value is slightly above the 26 trains per hour value generally considered by Metrorail professionals as the practical capacity of the junction. The difference of 2 trains per hour between the junction capacity simulation results and the Metrorail professional experience may be the result of the simulations not including sufficient practical capacity margin to account for dwell time, route establishment, train performance and train operator variability.

Table 14 – Fixed-block Train Control Junction Capacity Measures

Performance Measure		**Capacity Type**	
		Crush	**Delay-Free**
Headway (Seconds)	**Theoretical**	100	134
	Practical	125	168
System Capacity (TPH)	**Theoretical**	36	26
	Practical	28	21
Court House to Farragut West (Orange) Travel Time		0:06:50	0:06:43
Arlington Cemetery to Farragut West (Blue) Travel Time		0:06:49	0:06:20

Table 14 also shows the travel time penalty of the crush headway operation, which maximizes throughput, versus the delay-free headway operation. For the Orange Line between Court House and Farragut West Stations, the additional travel time is only seven seconds. For the Blue Line between Arlington Cemetery and Farragut West Stations, the additional travel time is a more significant 29 seconds.

Figure 16 displays the TrainOps simulation results in the form of a velocity versus distance profile for the last train in the fixed block ATC crush headways simulation. The red trace shows the maximum civil speed profile for the simulation segment between Arlington Cemetery and Farragut West. The purple trace shows the actual ATC speed commands received by the simulated train (at some locations, the maximum available ATC speed command may be higher). The green trace shows the simulated velocity of this crush headway train; some train delay is evident in the approach to Rosslyn Interlocking and also in the stopping profile for Foggy Bottom-GWU Station.

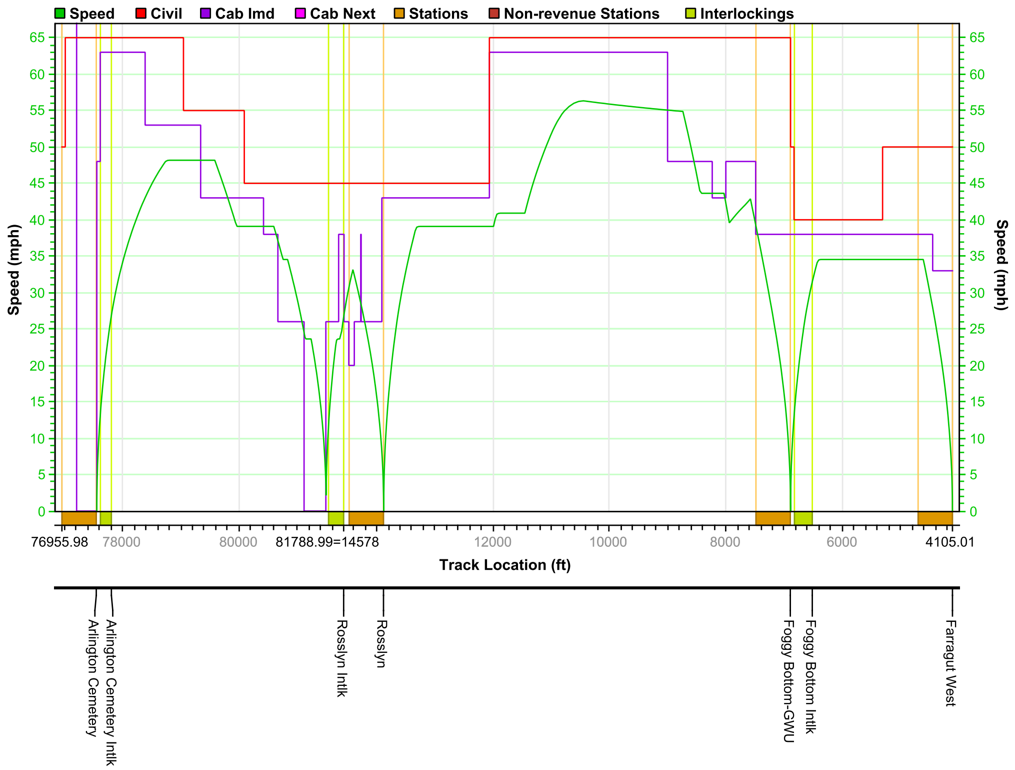


Figure 16 – Speed Profile - Final Train Fixed Block Crush Junction Headway

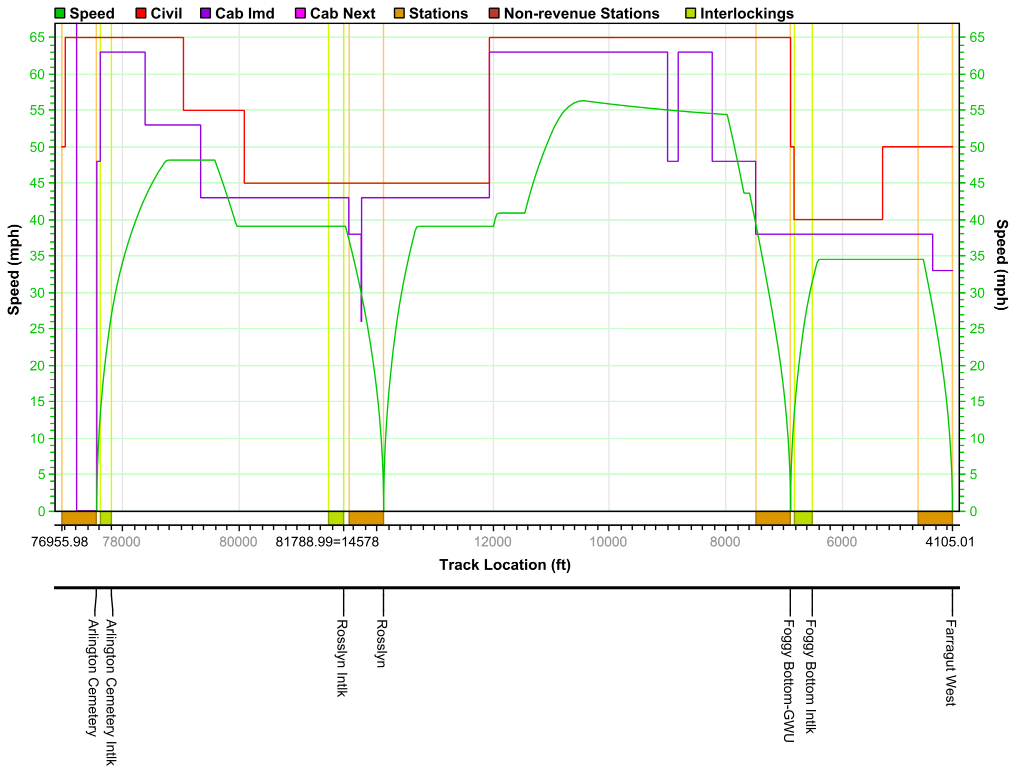


Figure 17 – Speed Profile - Final Train Fixed Block Delay-Free Junction Headway

Figure 17 displays the same TrainOps output as Figure 16 except that it is for “delay-free” operation rather than “crush” operation. It should be noted that “delay-free” operation does not necessarily mean that the train receives the best-available ATC speed command at each location. Rather, “delay-free” operation means that the train receives an ATC speed command at each location that does not increase trip time versus the unimpeded train. The downward purple “spike” at Rosslyn Station may represent an ATC downgrade (which has no delay effect on the train because it is slowing for the station stop anyway).

4.4.2 Communications-Based Train Control

Table 15 displays the same Rosslyn Junction capacity simulation results as Table 14 except that it reflects CBTC advanced train control. Using the practical crush system capacity as the best fixed block ATC benchmark against which to compare the benefits of advanced train control, Table 15 shows a gain of 1 train per hour versus the fixed block ATC results (29 trains per hour versus 28 trains per hour).

Table 15 – CBTC Train Control Junction Capacity Measures

Performance Measure		**Capacity Type**	
		Crush	**Delay-Free**
Headway (Seconds)	**Theoretical**	99	130
	Practical	124	163
System Capacity (TPH)	**Theoretical**	36	27
	Practical	29	22
Court House to Farragut West (Orange) Travel Time		0:07:21	0:06:51
Arlington Cemetery to Farragut West (Blue) Travel Time		0:07:03	0:06:18

Table 15 also shows the travel time penalty of the advanced train control crush headway operation, which maximizes throughput, versus the delay-free headway operation. For the Orange Line between Court House and Farragut West Stations, the additional travel time is 30 seconds. For the Blue Line between Arlington Cemetery and Farragut West Stations, the additional travel time is 45 seconds.

Figure 18 displays the TrainOps simulation results in the form of a velocity versus distance profile for the last train in the advanced train control (CBTC) crush headways simulation. The red trace shows the maximum civil speed profile for the simulation segment between Arlington Cemetery and Farragut West. The purple trace shows the ATC speed commands that the train would receive if ATC (rather than the actual CBTC system) were in effect. The green trace shows the simulated velocity of this crush headway train; some train delay is evident in the approach to Rosslyn Interlocking and also in the stopping profile for Foggy Bottom-GWU Station. The rapid up/down oscillations of the train under crush headway conditions are typical of trains under CBTC as the system is reevaluating each train’s speed authorization (“movement authority”) each 1.5 seconds of simulated time.

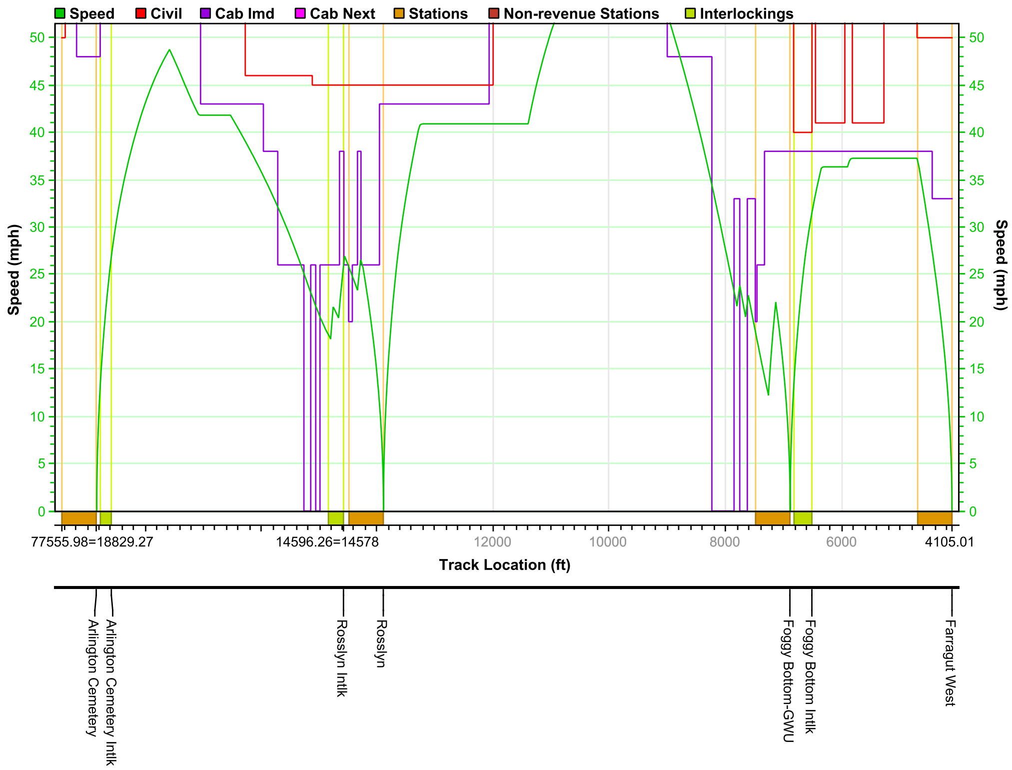


Figure 18 – Speed Profile - Final Train CBTC Crush Junction Headway

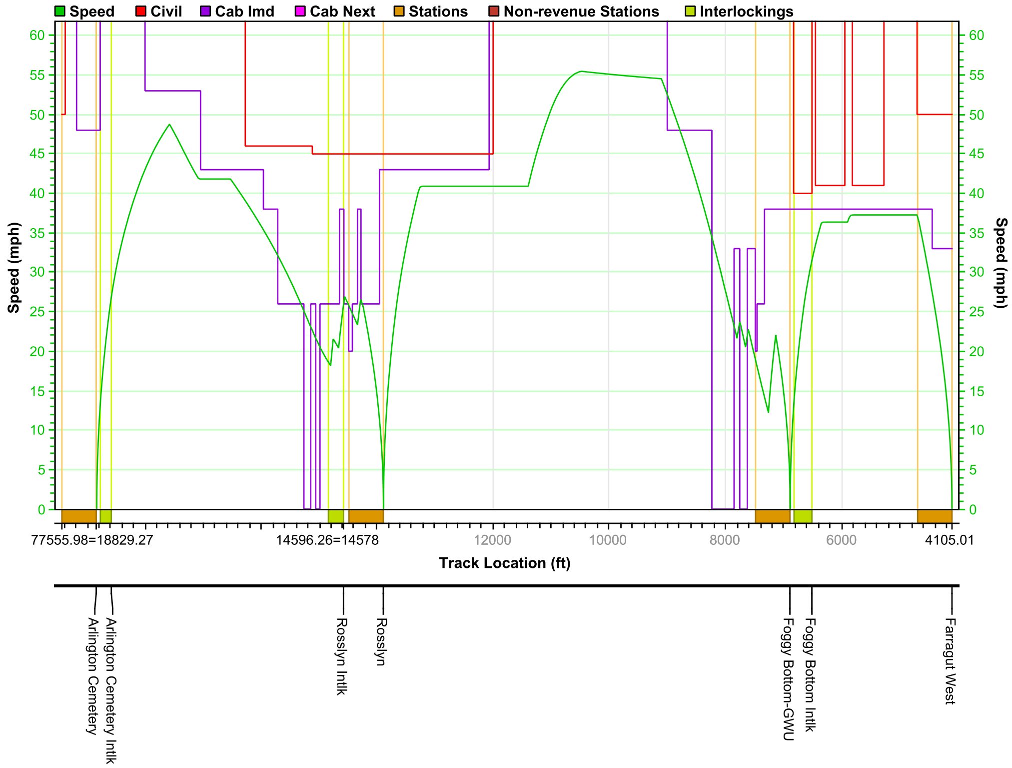


Figure 19 – Speed Profile - Final Train CBTC Delay-Free Junction Headway

Figure 19 displays the same TrainOps output as Figure 18 except that it is for “delay-free” operation rather than “crush” operation. It should be noted that “delay-free” operation does not necessarily mean that the train receives the best-available CBTC speeds at each location. Rather, “delay-free” operation means that the train receives a CBTC speed at each location that does not increase trip time versus the unimpeded train. The downward purple “spikes” approaching Rosslyn Interlocking and Foggy Bottom-GWU Station represent CBTC speed downgrades (which have no delay effect on the train because it is slowing anyway).

4.5 Orange/Blue/Silver Core Segment Results

The Orange/Blue/Silver Line analysis focuses on line capacity in the core Metrorail segment between Federal Center and Metro Center. As with the Rosslyn Junction analysis, capacity is evaluated in terms of both crush and delay-free headways. These values, in turn, are presented as both theoretical and practical values.

4.5.1 Fixed Block Train Control

The results for the fixed-block core segment capacity analysis appear in Table 16. The fixed block system falls far short of its design headway of 75 seconds and practical design headway of 90 seconds due to the significantly longer 90th percentile dwells used in the analysis. Under the crush scenario, the fixed-block system is able to deliver 36 TPH on a theoretical basis, which after applying a 25% headway provision for operating variability yields 28 trains per hour.

Due to the tightly spaced blocks in the core section, the delay free headway is only 7 seconds longer than the crush headway. Under delay free operation, the core section can support 26 trains per hour on a practical basis. This is approximately the current total operating level in the core section for the Orange, Blue, and Silver lines during the peak.

Table 16 – Fixed-block Train Control Core Segment Capacity Measures

Performance Measure		**Capacity Type**	
		Crush	**Delay-Free**
Headway (Seconds)	**Theoretical**	100	107
	Practical	125	133
System Capacity (TPH)	**Theoretical**	36	33
	Practical	28	26
Federal Center to Metro Center Travel Time		0:06:06	0:05:49

Figure 20 shows the simulated velocity profile for the last train operating in the crush headway simulation. The speed of the train is shown in green and the ATC speed commands are shown in purple. The train sees the most delay between the approach to Smithsonian station and the departure from Federal Triangle station, but does not come to a complete stop at any point during the trip. The closely spaced stations with long dwell times result in low average speeds, which limit the system throughput.

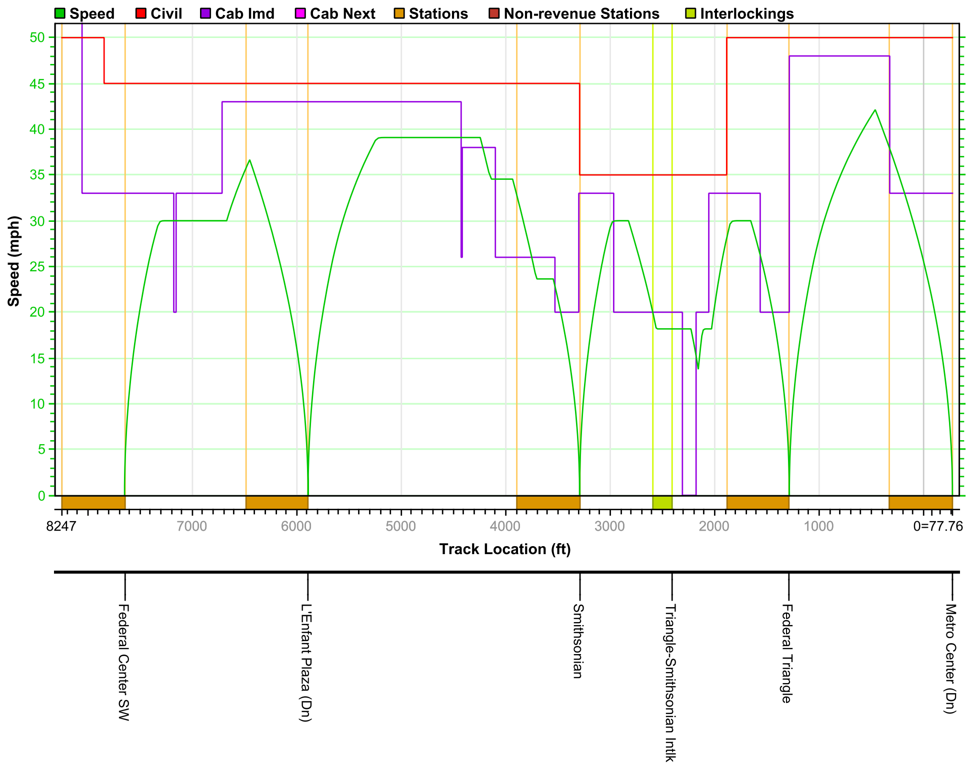


Figure 20 – Speed Profile - Final Train Fixed Block Crush Core Segment Headway

Figure 21 shows the speed profile for the same train running under fixed-block ATC at the delay free headway. In this simulation, the train receives two speed commands to brake between Smithsonian and Federal Triangle, but due to assumed vehicle and operator reaction times does not react before the speed command returns to normal.

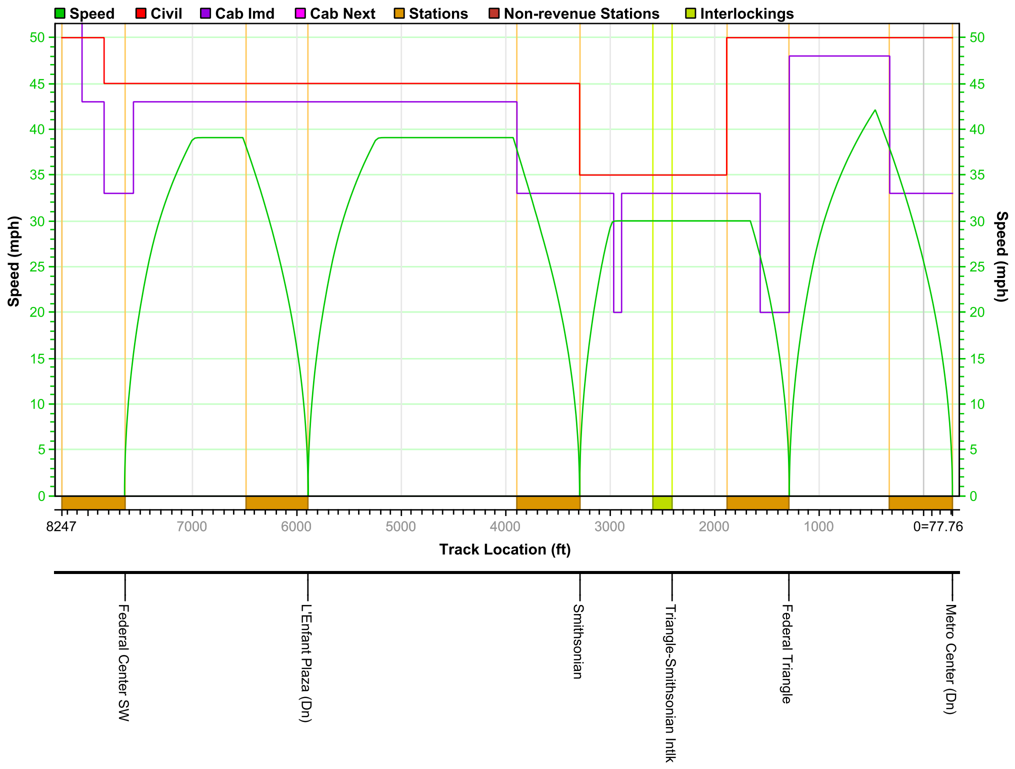


Figure 21 – Speed Profile - Final Train Fixed Block Core Segment Ideal Headway

4.5.2 Communications-Based Train Control

Table 17 summarizes the simulated the capacity measures for the Federal Center to Metro Center segment with the hypothetical CBTC system in place. The crush headway is 100 seconds, with a theoretical capacity of 36 TPH, and a practical capacity of 28 TPH. In terms of capacity, the CBTC results for crush headway are identical to the simulation model with fixed block signaling. In terms of travel times, crush headway trains under CBTC signaling consume an additional 53 seconds to move through the core than do trains operating under the existing fixed block ATC. This is due to the longer CBTC system response times to restore normal (maximum speed) operations after a delay occurs.

The delay free headway for the CBTC system is 119 seconds with a practical capacity of 24 TPH. This is 2 TPH less than the delay free headway under fixed block ATC. As was noted above, this is due to the longer CBTC system response times versus fixed block ATC to restore normal (maximum speed) operations after a delay occurs. The travel time under CBTC is slightly decreased to 5:48 from 5:49 under the fixed block ATC system. The shorter travel time is a benefit of the infinitely-variable speeds possible within CBTC and the recomputed AREMA formula-based curve speeds.

Table 17 – CBTC Train Control Core Segment Capacity Measures

		Capacity Type	
Performance Measure		**Crush**	**Delay-Free**
Headway (Seconds)	**Theoretical**	100	119
	Practical	125	149
System Capacity (TPH)	**Theoretical**	36	30
	Practical	28	24
Federal Center to Metro Center Travel Time		0:06:59	0:05:48

Figure 22 presents a simulated velocity profile of a crush headway train running under CBTC. The train's speed is shown in green and the ATC speed commands that the train would receive under fixed-block signaling are shown in purple for comparison. The CBTC's continuous calculation based upon new information is evident in the up and down nature of the train's velocity profile. In the approach to Smithsonian, the train starts braking earlier than the fixed block system calls for. This is due to the delay in receiving information from the wayside system; the train is reacting to a train ahead that has just moved outside of the safe braking curve, but the onboard equipment of the train has yet to receive an update. The train alternates between accelerating and braking as it attempts to follow the train ahead, which itself is behaving in the same manner as it follows its own preceding train. The train under CBTC uses a reduced braking curve, whereas the train in fixed block ATC brakes at the service rate for speed downgrades. Trains under CBTC react earlier to the presence of a train ahead than the same train in fixed block ATC which drags down the average speed of the train. This, in turn, results in the longer travel times seen in the results.

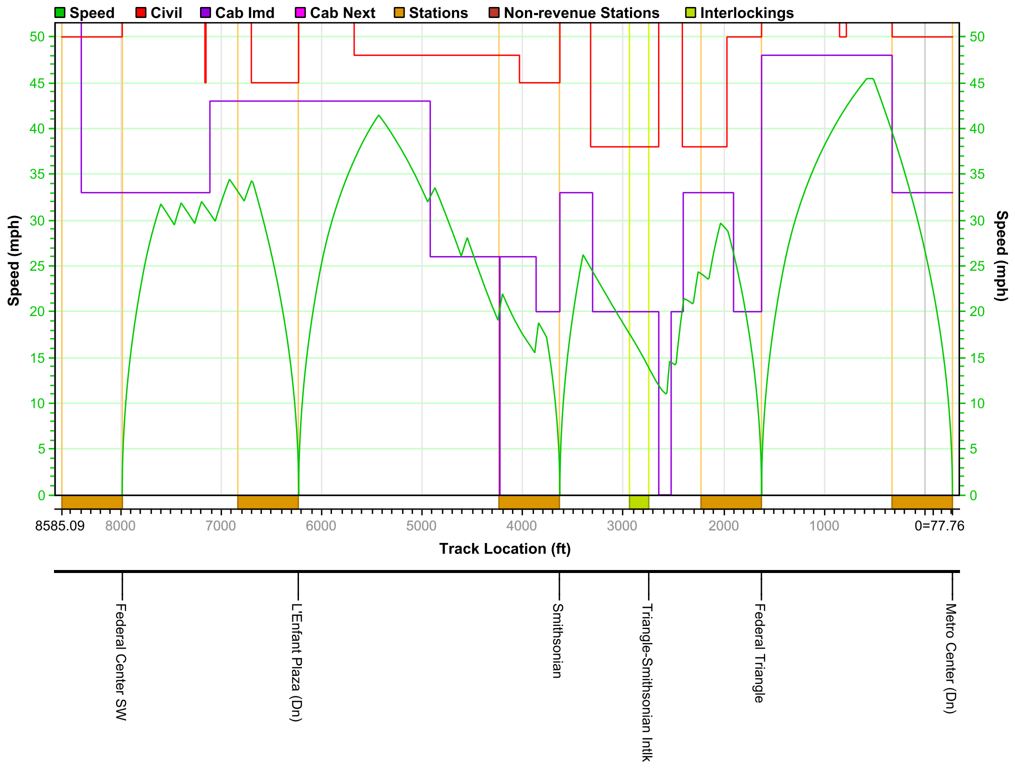


Figure 22 – Speed Profile - Final Train CBTC Crush Core Segment Headway

Figure 23 shows the delay free speed profile for a train operating under CBTC. The train is able to achieve a higher speed between L'Enfant Plaza and Smithsonian than the fixed block ATC system would allow. The train then brakes for an upcoming 45 MPH speed limit before making a stop at Smithsonian. The train also achieves a higher speed between Smithsonian and Federal Triangle, operating just above the ATC speed limit of 33 MPH (35 MPH speed command with 2 MPH underspeed). The rest of the profile closely matches the fixed block case.

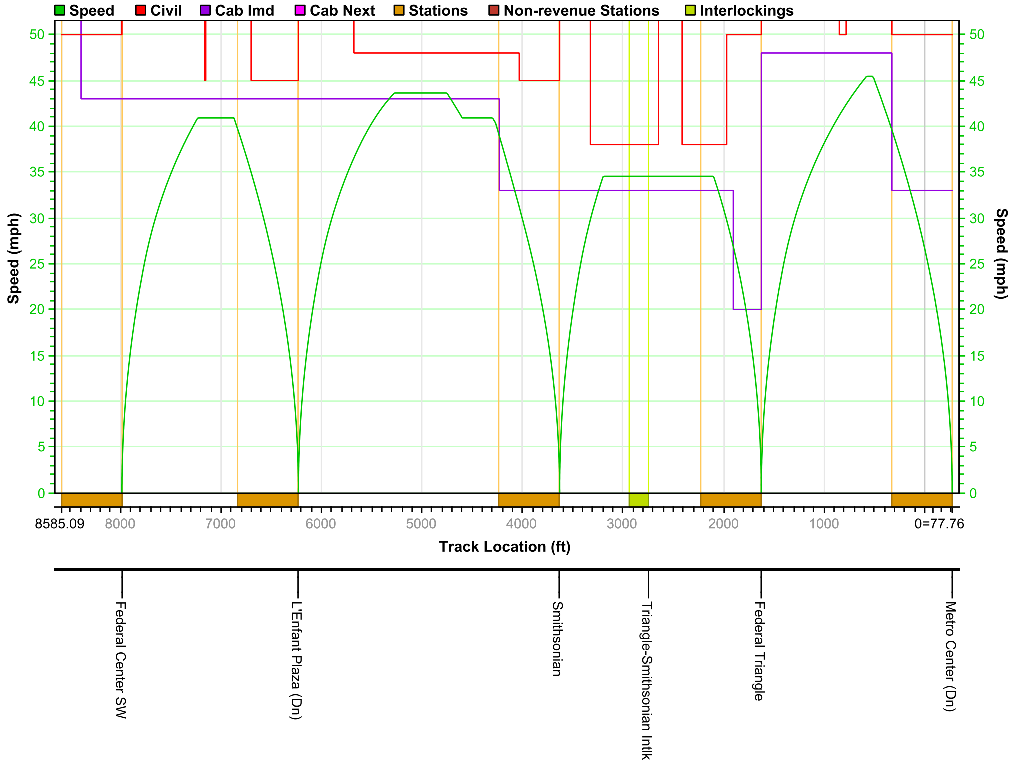


Figure 23 – Speed Profile - Final Train CBTC Ideal Core Segment Headway

5 Conclusions

The results of the Metrorail Capacity White Paper indicate that there are multiple constraints on capacity expansion of the core and that no known technical or operational solutions exist to moderate these constraints. In a peer review of four comparable heavy rail rapid transit systems in the U.S., Metrorail scored well in terms of existing capacity-enhancing design. This includes terminal configurations, placement of yard/mainline interfaces and train control design. Previous studies have noted the capacity benefits of adding one door set per side of vehicle but this change would require some 40 years to fully implement and would result in a net seat reduction of approximately 28 percent. Such reduction in seated capacity runs counter to the increased average time on WMATA resulting from the second phase of the Silver Line extension and other potential line extensions.

5.1 Metrorail Capacity Limits and Associated Peer Review

LTK's peer review of heavy rail rapid transit systems included critical junction speeds and track geometry as the junctions at Rosslyn, L'Enfant Plaza and Stadium-Armory are recognized as leading Metrorail system constraints. Junction configurations constrain system capacity because each merge point is a potential delay location. If trains are scheduled too close together, trains will wait at the junction until the route is established, prompting customer complaints about perceived delays. If one line feeding the junction experiences delays, trains will not arrive at the correct time to use their operating slot through the junction. This results in overall loss of system capacity as these empty slots carry through the system.

All three Metrorail capacity-critical junctions (Rosslyn, L'Enfant Plaza and Stadium-Armory) are "flying junctions" with #15 lateral turnouts, enforced with the 28 MPH ATC speed command. This frog angle and ATC speed is consistent with industry practice for critical junctions where revenue services merge. Rebuilding of these junctions for higher diverging speeds would yield little or no system capacity benefit while being extraordinarily costly and disruptive.

Terminals represent system capacity constraints on most heavy rail rapid transit systems, including Metrorail, due to time-consuming train "turning" (change of direction) operations. Traditional terminals generally require more than one track for simultaneous train "turning" operation because the "turning" requires more time than the scheduled headway. This means two or more terminal tracks which generally results in at-grade crossing conflicts between outbound and inbound trips. The presence or absence of yard leads at terminals also influences capacity. Where terminal tracks continue past the terminal as non-revenue yard leads, capacity is generally enhanced because yard "put-ins" and "take-outs" can be implemented without any at-grade conflicts.

Metrorail was found to be comparable to the four peer systems in terms of terminal configurations that support high capacity operations. Five of nine Metrorail terminals have capacity-enhancing yard leads that serve as continuation of terminal tracks. All nine terminals have crossovers on the revenue side of the platforms and six of the nine also have crossovers on the non-revenue side. Turnout sizes are almost all No. 10 supporting terminal speeds in the range of 15 to 28 MPH. These terminal speeds are generally considered to be optimal in terms of maximizing interlocking traversal speeds while minimizing overall interlocking length.

The architecture of the ATC system and, especially, its speed commands, plays an important role in determining system capacity. Fixed block ATC systems require fine granularity in their speeds in order to promote close headways and high capacity. The original Metrorail designers selected a near-optimal set of speed commands that are compatible with all civil (curve, bridge and tunnel) speed restrictions in the system, that are compatible with the interlocking crossover and turnout diverging speeds needed and that provide good following move capacity for straight routes leading to stop signal/block occupied ahead enforcement.

Metrorail utilizes 11 distinct ATC speed commands providing excellent coverage of civil speed restrictions and successive speed targets for enforced speed reductions. The peer review found that, of the five systems surveyed in depth, WMATA has the largest number of speed commands, which supports close-headway, fixed-block operations. It also has the tightest average spread (speed gap between successive speed commands) of the five systems, with an average spread of 7.5 MPH. These attributes support high capacity operation and reduce the theoretical advantage of the continuous speed command capability of CBTC.

5.2 Capacity Impacts of Advanced Train Control

LTK utilized its existing WMATA TrainOps® operations simulation model to evaluate two of the most capacity-constrained locations on the Metrorail system -- the junction at Rosslyn and the core section of the Orange/Blue/Silver Line. This section has closely-spaced stations that limits throughput. The evaluation sought to confirm existing limitations on throughput and to understand what, if any, capacity growth could be achieved through Advanced Train Control.

LTK then applied a hypothetical advanced train control solution, Communications-Based Train Control, to the two capacity-constrained locations. Typical North American CBTC functional criteria in terms of safe braking distance margin, system response time, positional accuracy and safety buffers were used. The systems, as applied to Rosslyn and a portion of the Metrorail core, were compared in terms of both delay-free operations and “crush” operations, where trip time is sacrificed in order to maximize the volume of trains operated.

The fixed block system was found to have an advantage in latency as fixed blocks communicate in parallel at a very short update interval, based upon the absolute position of trains. In CBTC moving block, each train in the system is dependent upon receiving information from the train ahead, which in turn depends on the information it receives from the train ahead. This leads to an additive latency throughout the system, which causes trains under CBTC to react to information that the fixed-block system would not see. Although CBTC has the advantage of moving blocks, the combination of positional uncertainty under CBTC and the very short fixed-block lengths in use within the core segment, prevent the CBTC system from seeing a large enough benefit to offset the drawbacks of latency.

Table 18 – Comparison of Core Segment Capacity Measures

Performance Measure		Fixed-Block		CBTC Moving Block	
		Crush	Delay-Free	Crush	Delay-Free
Headway (Seconds)	**Theoretical**	100	107	100	119
	Practical	125	134	125	149
System Capacity (TPH)	**Theoretical**	36	33	36	30
	Practical	28	26	28	24
Federal Center to Metro Center Travel Time		0:06:06	0:05:49	0:06:59	0:05:48

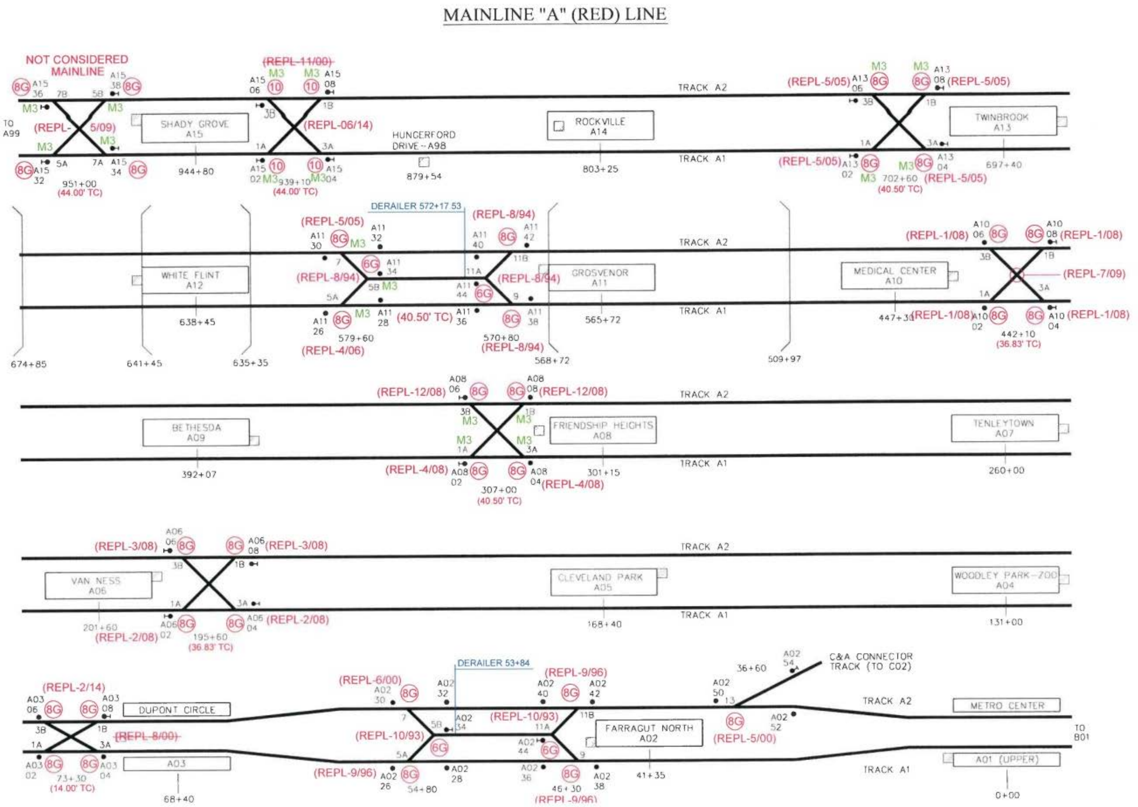
In terms of practical system capacity measured under “crush” operations (the willingness to modestly increase trip time in the interest of moving more passengers), the current core segment supports 28 trains per hour. Under the hypothetical CBTC model, including elimination of all fixed block constraints and recomputation of all civil speed restrictions on a “clean slate” basis, throughput is unchanged. Though speeds through civil speed restrictions are better optimized with CBTC, the CBTC simulation shows a “crush” operation trip time that is almost a minute longer through the core than the fixed block system. This is due to the increased latency of the CBTC system, meaning that once a delay associated with a train ahead begins, it takes longer for the following train to resume delay-free operation.

Table 19 – Comparison of Junction Capacity Measures

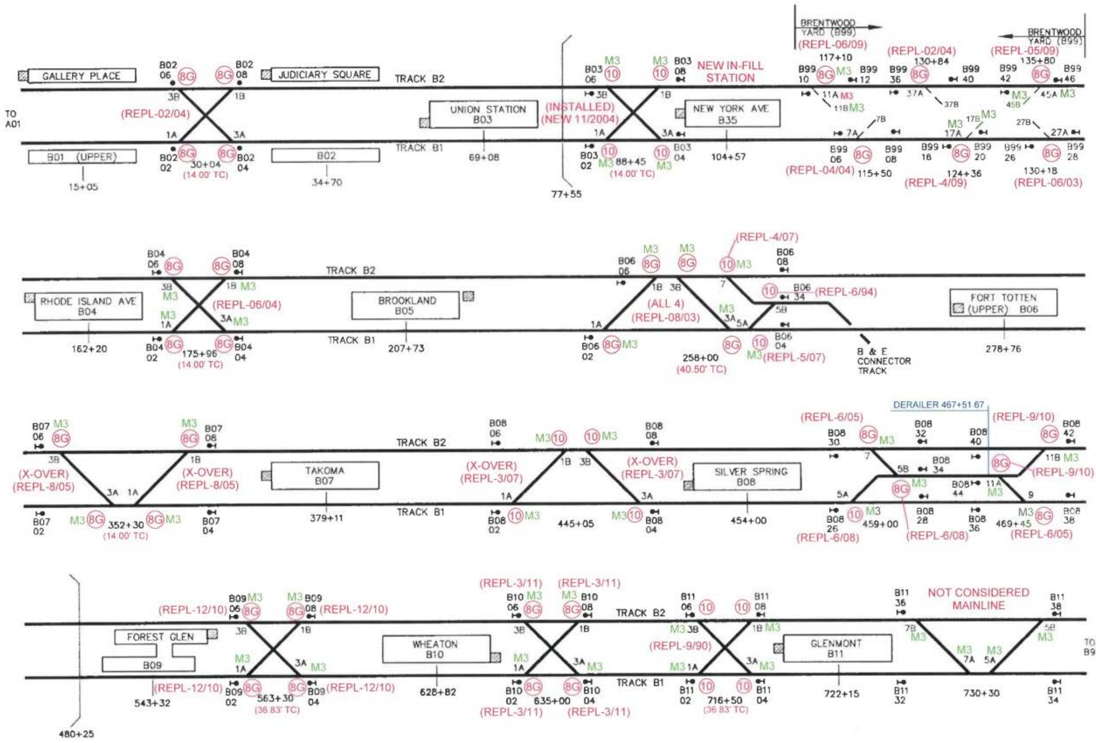
Performance Measure		Fixed-Block		CBTC Moving Block	
		Crush	Delay-Free	Crush	Delay-Free
Headway (Seconds)	**Theoretical**	100	134	99	130
	Practical	125	168	123	163
System Capacity (TPH)	**Theoretical**	36	26	36	27
	Practical	28	21	29	22
Court House to Farragut West (Orange) Travel Time		0:06:50	0:06:43	0:07:21	0:06:51
Arlington Cemetery to Farragut West (Blue) Travel Time		0:06:49	0:06:20	0:07:03	0:06:18

In terms of practical system capacity measured under “crush” operations (the willingness to modestly increase trip time in the interest of moving more passengers), the Rosslyn merge segment (Court House and Arlington Cemetery Stations through Rosslyn to Farragut West Station) supports 28 trains per hour under the current fixed block ATC system. Under the hypothetical CBTC model, including elimination of all fixed block constraints and recomputation of all civil speed restrictions on a “clean slate” basis, throughput increases modestly to 29 trains per hour. The CBTC simulation shows a “crush” operation trip time that is 14 seconds longer through the Rosslyn segment.

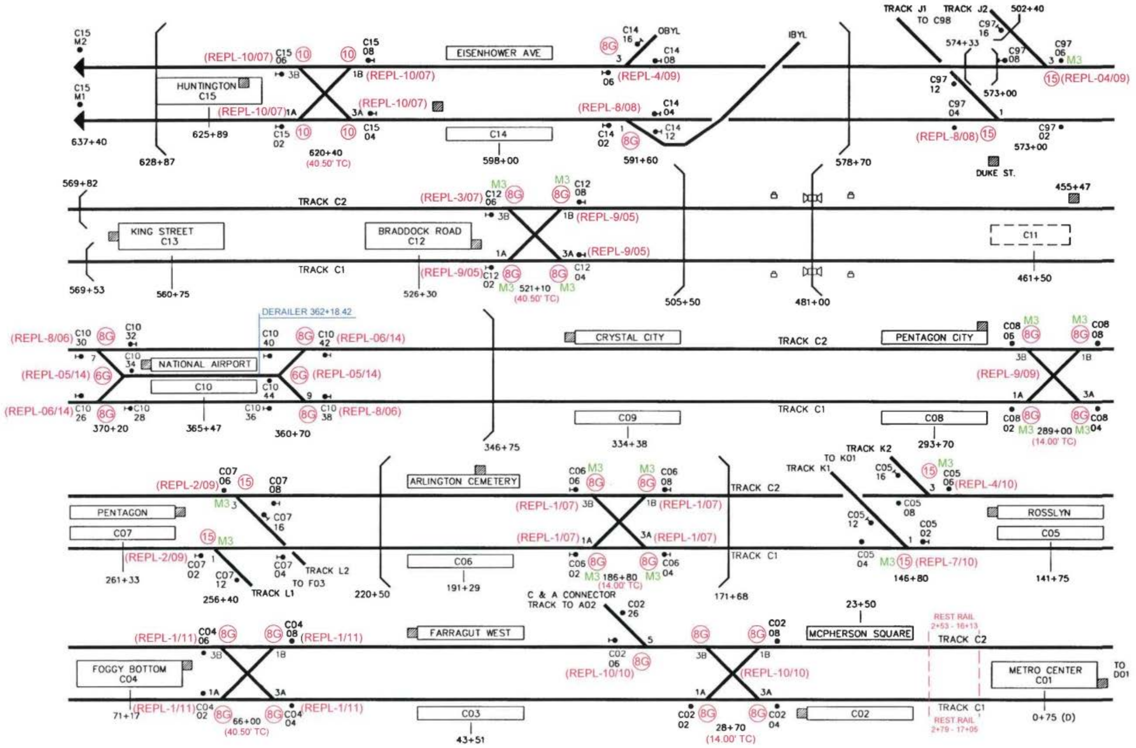
6 Appendix A – Metrorail System Schematics Including Dulles Corridor Phases 1 and 2



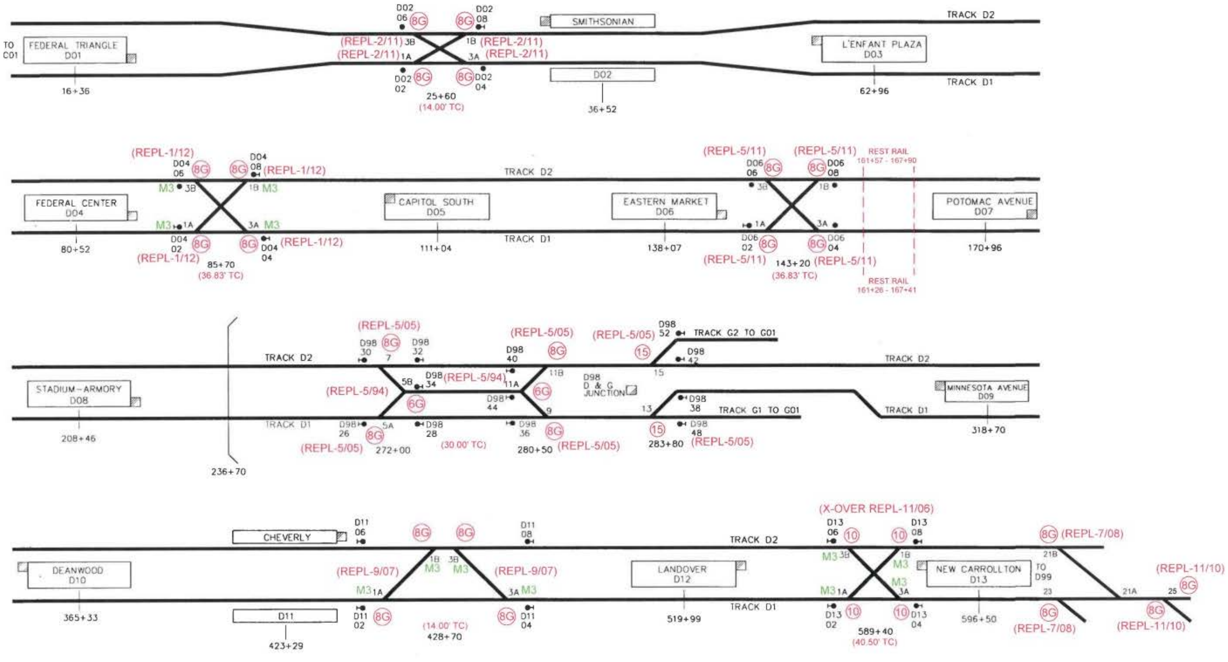
MAINLINE "B" (RED) LINE



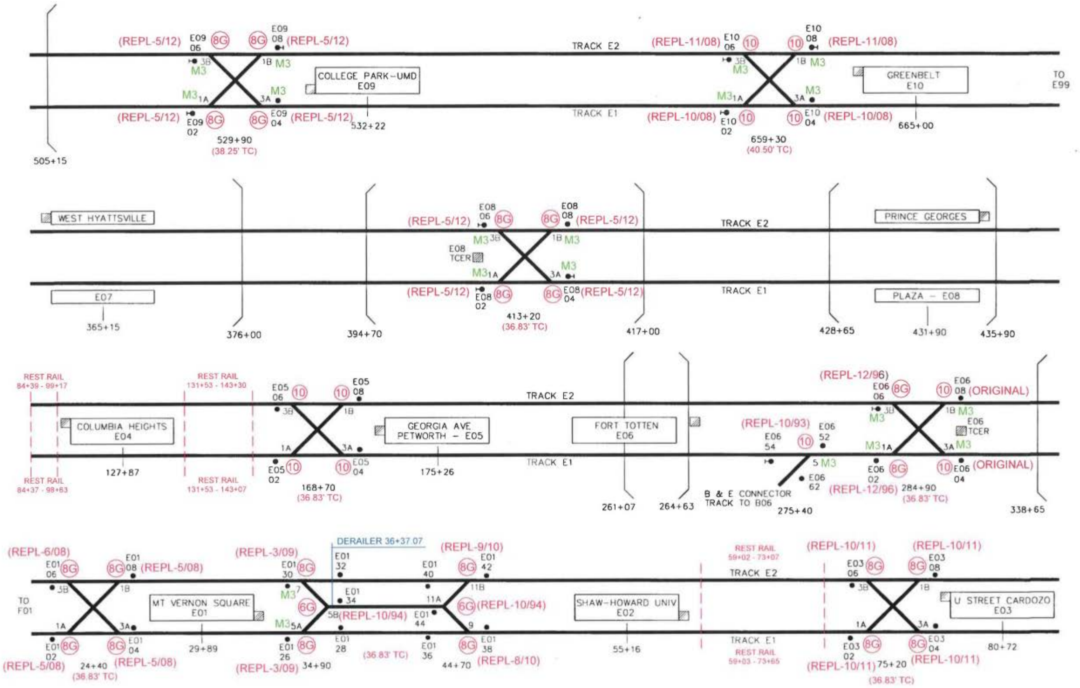
MAINLINE "C" (BLUE/ORANGE/YELLOW) LINE



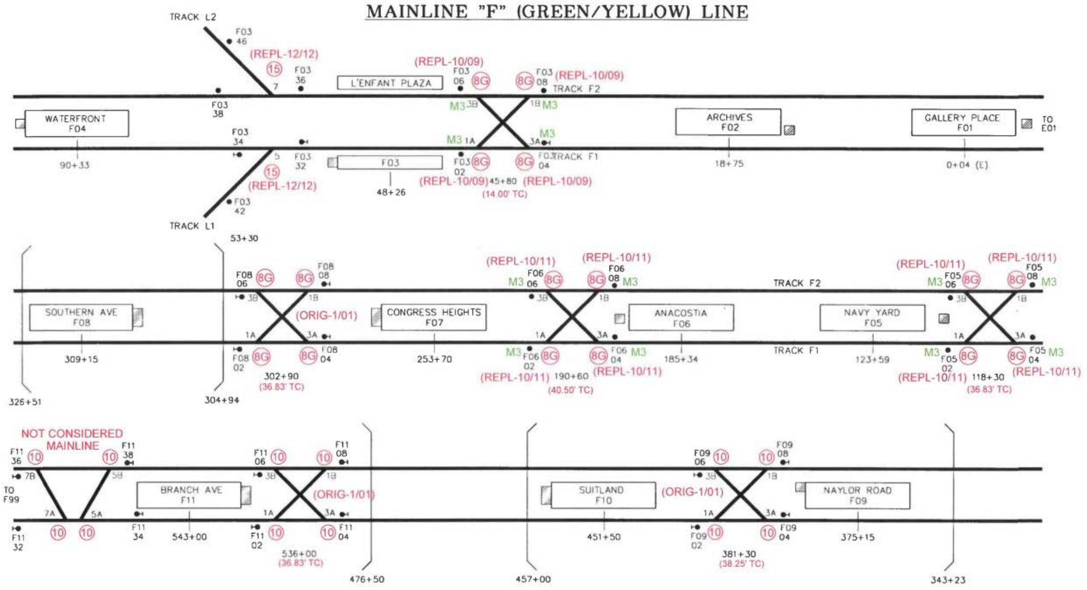
MAINLINE "D" (BLUE/ORANGE) LINE



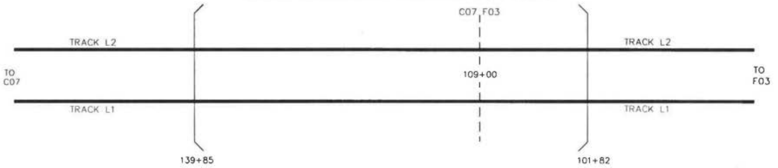
MAINLINE "E" (GREEN/YELLOW) LINE



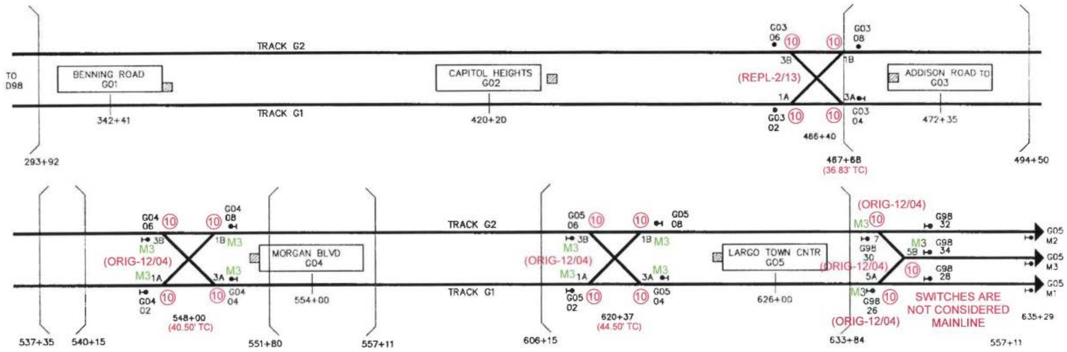
MAINLINE "F" (GREEN/YELLOW) LINE



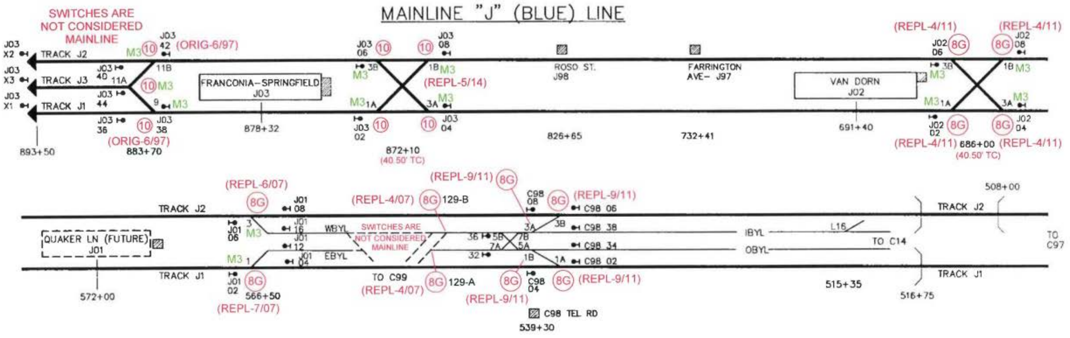
MAINLINE "L" (YELLOW) LINE



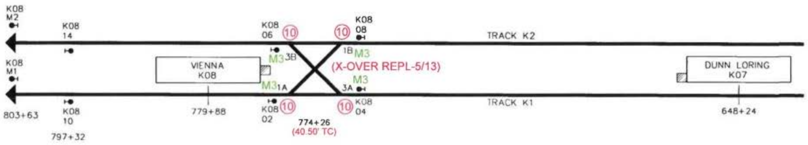
MAINLINE "G" (BLUE) LINE

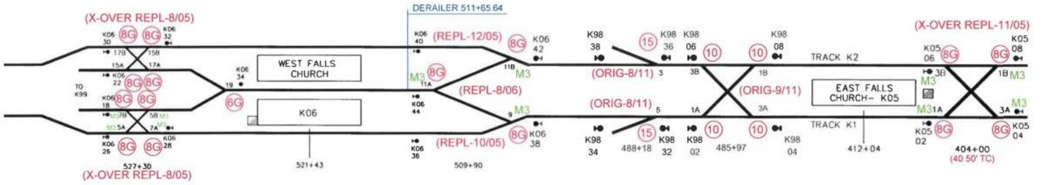


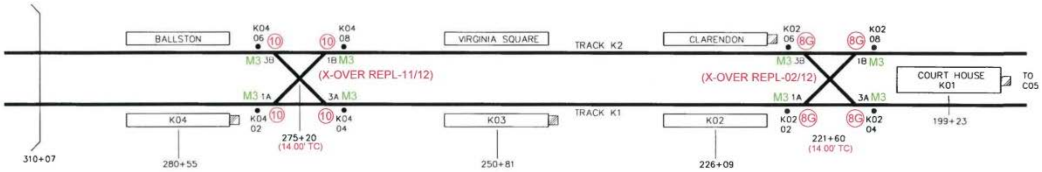
MAINLINE "J" (BLUE) LINE



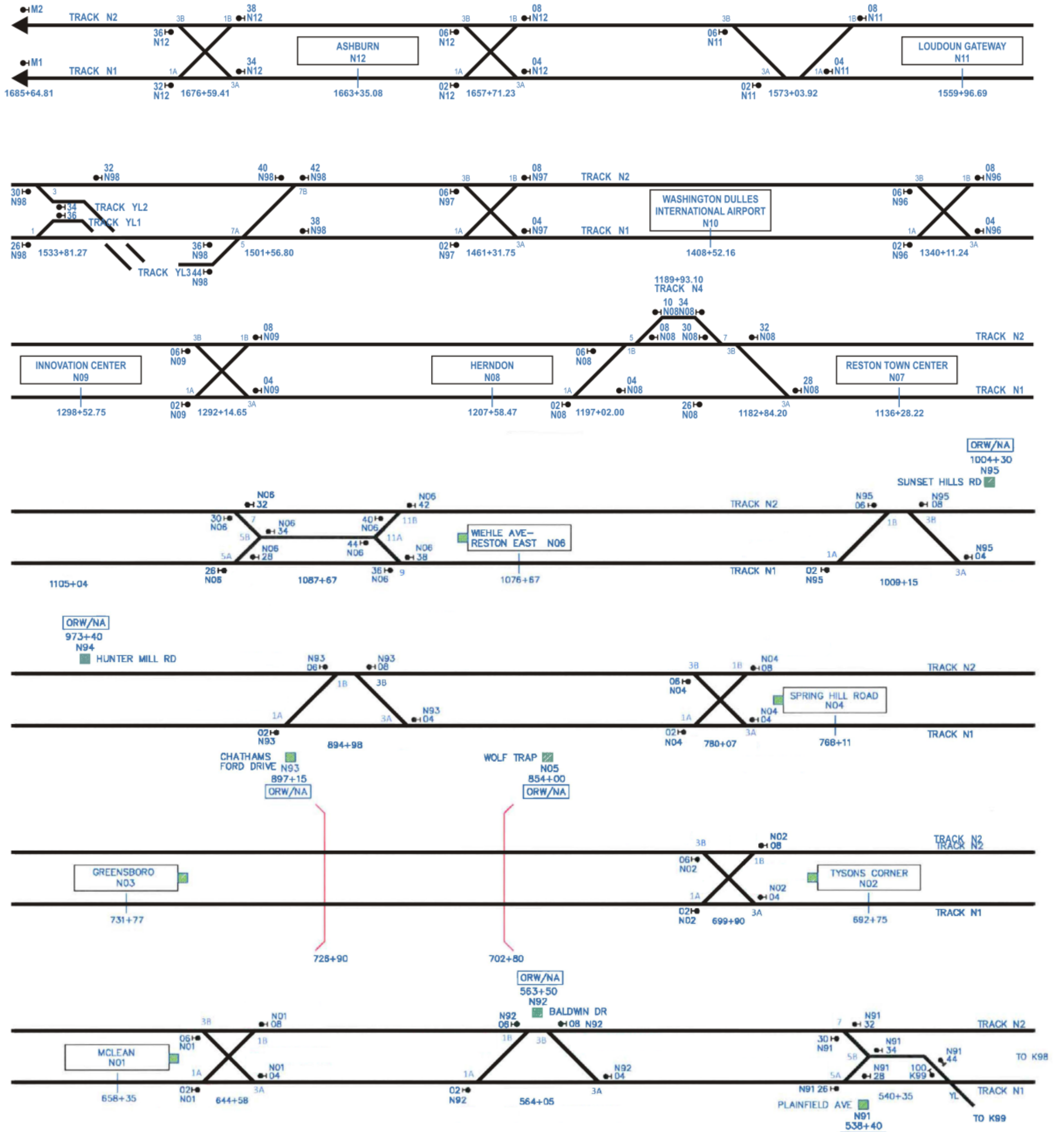
MAINLINE "K" (ORANGE) LINE







MAINLINE "N" (SILVER) LINE
PHASE 1 & 2



ORW/NA = OUTSIDE RIGHT OF WAY/NO DIRECT ACCESS TO WAYSIDE.

REVISED 11/27/12

Signal, Switch and Interlocking names are preliminary
Wolf Trap is a provisional future station

7 Appendix B – October 2014 Dwell Time Distribution Curves For Core Stations of the Red, Blue and Orange Lines, 7:30AM-8:30AM

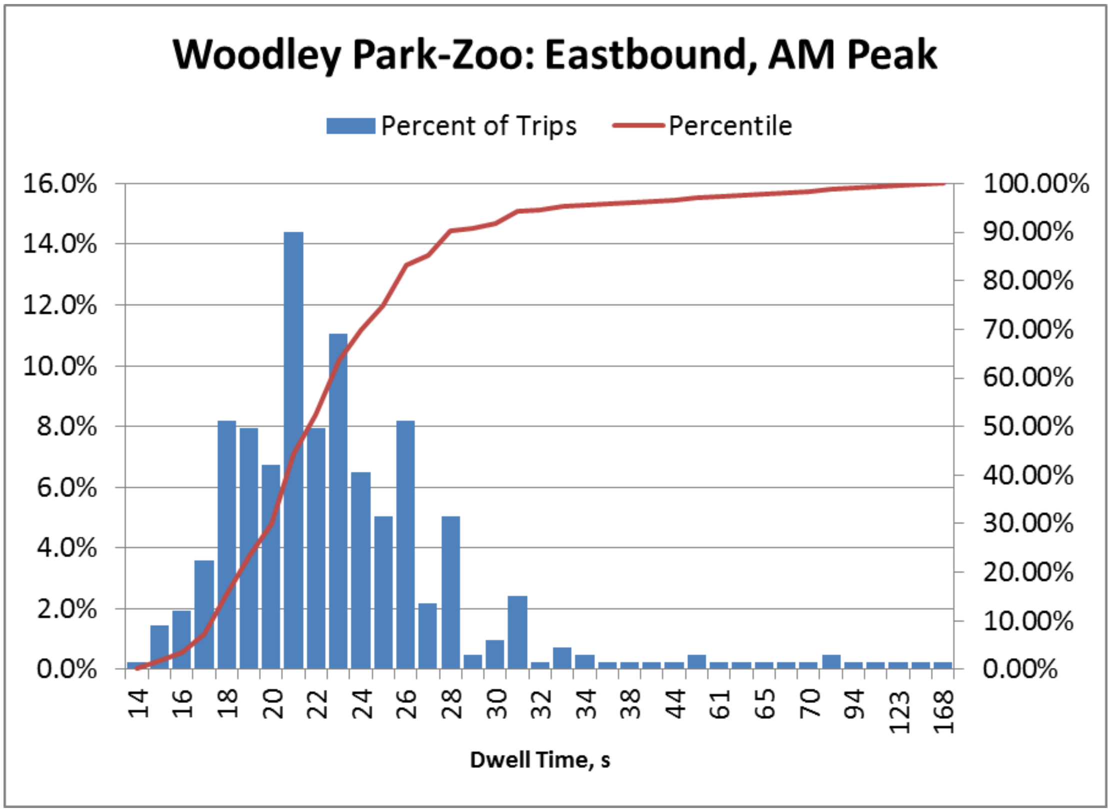


Figure 24 – Red Line, Woodley Park-Zoo Station AM Peak

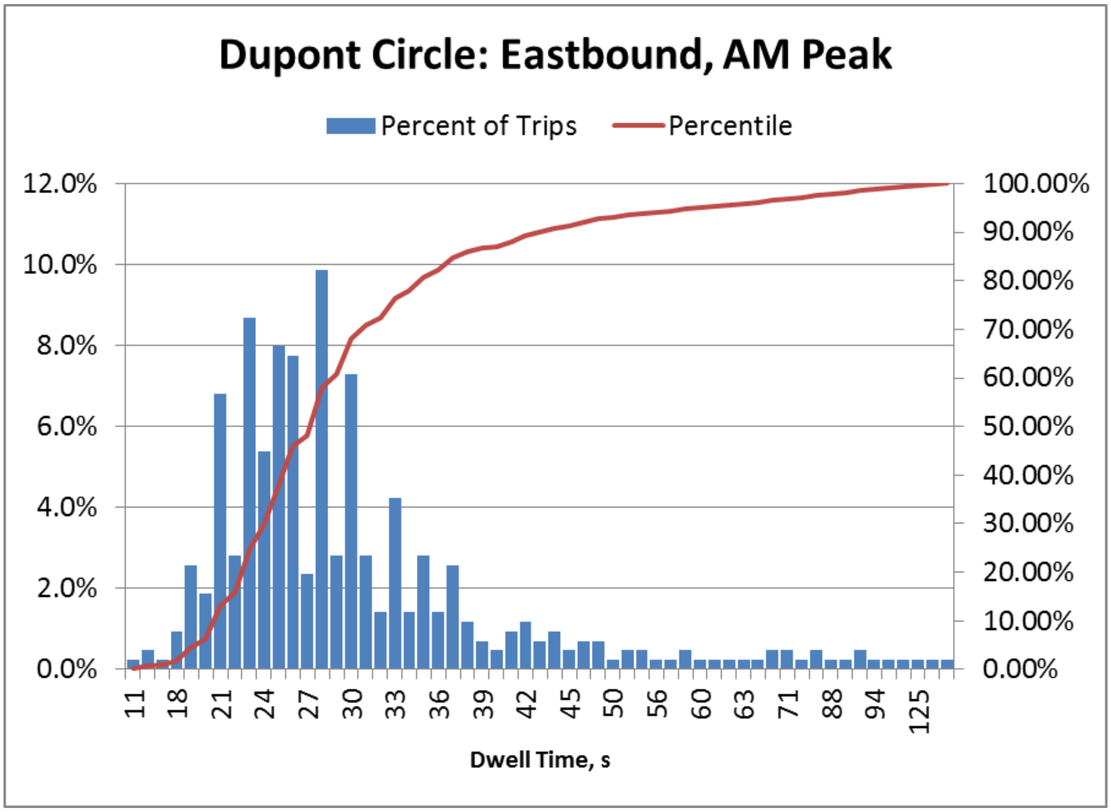


Figure 25 – Red Line, Dupont Circle Station AM Peak

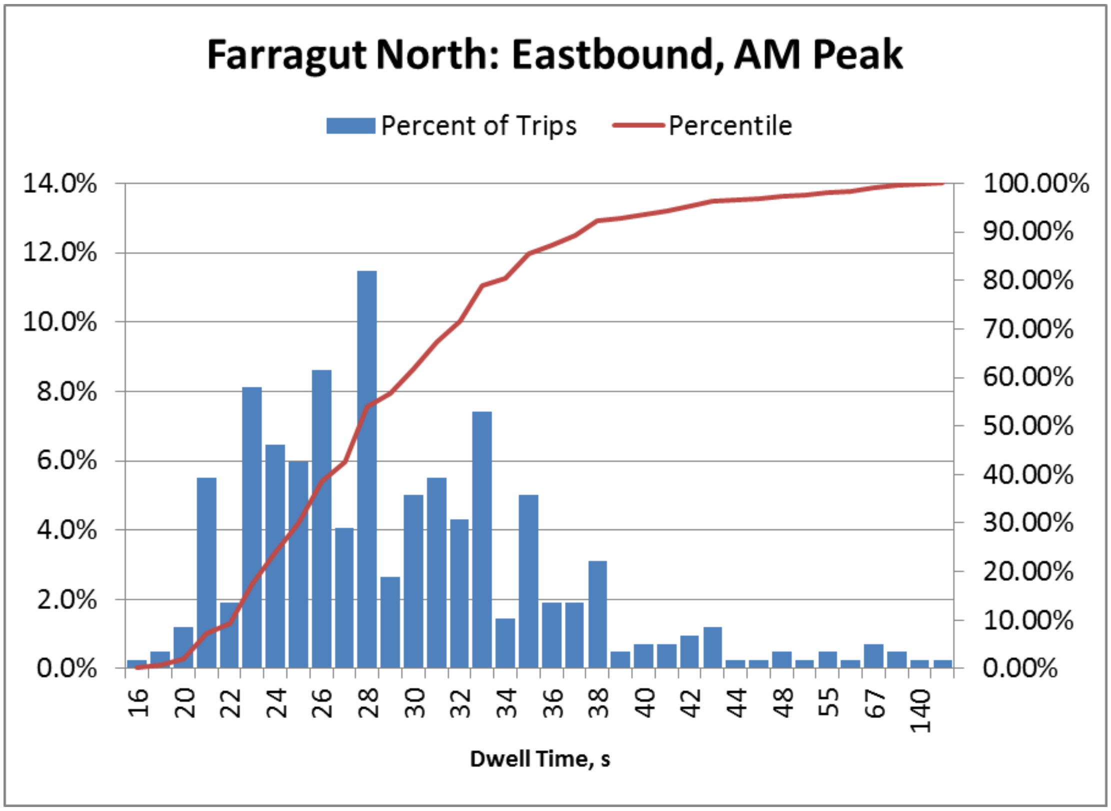


Figure 26 – Red Line, Farragut North Station AM Peak

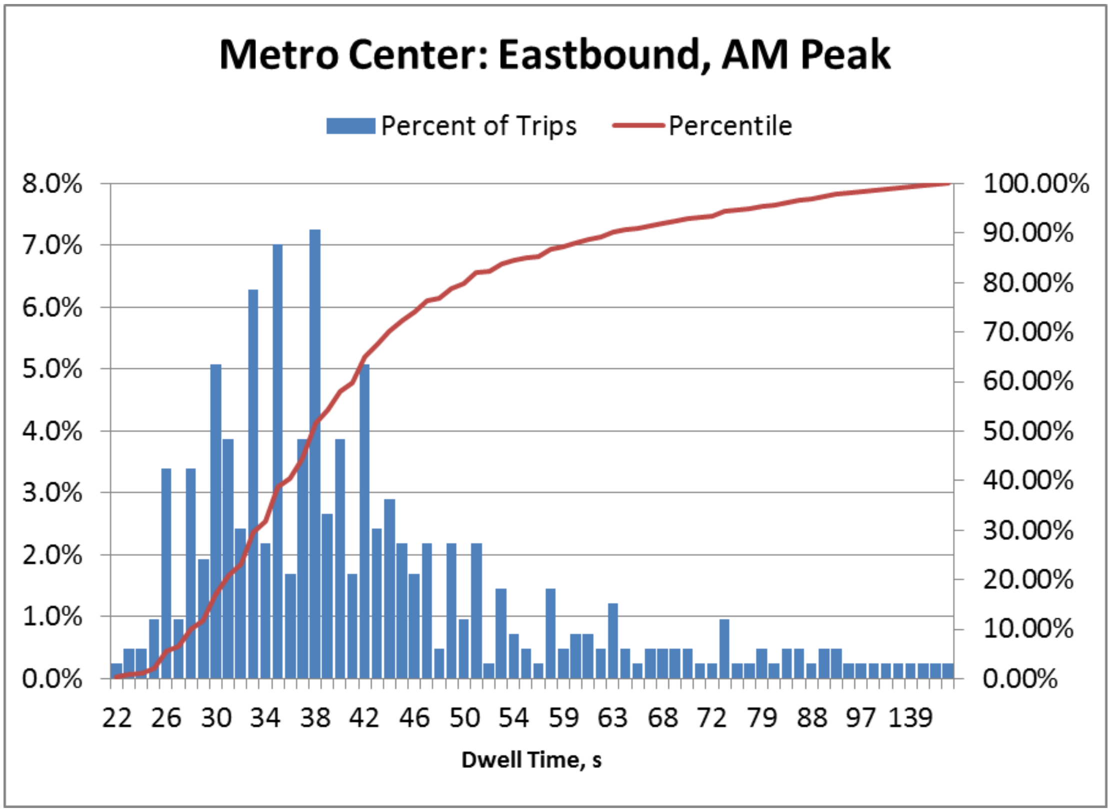


Figure 27 – Red Line, Metro Center Transfer Station AM Peak

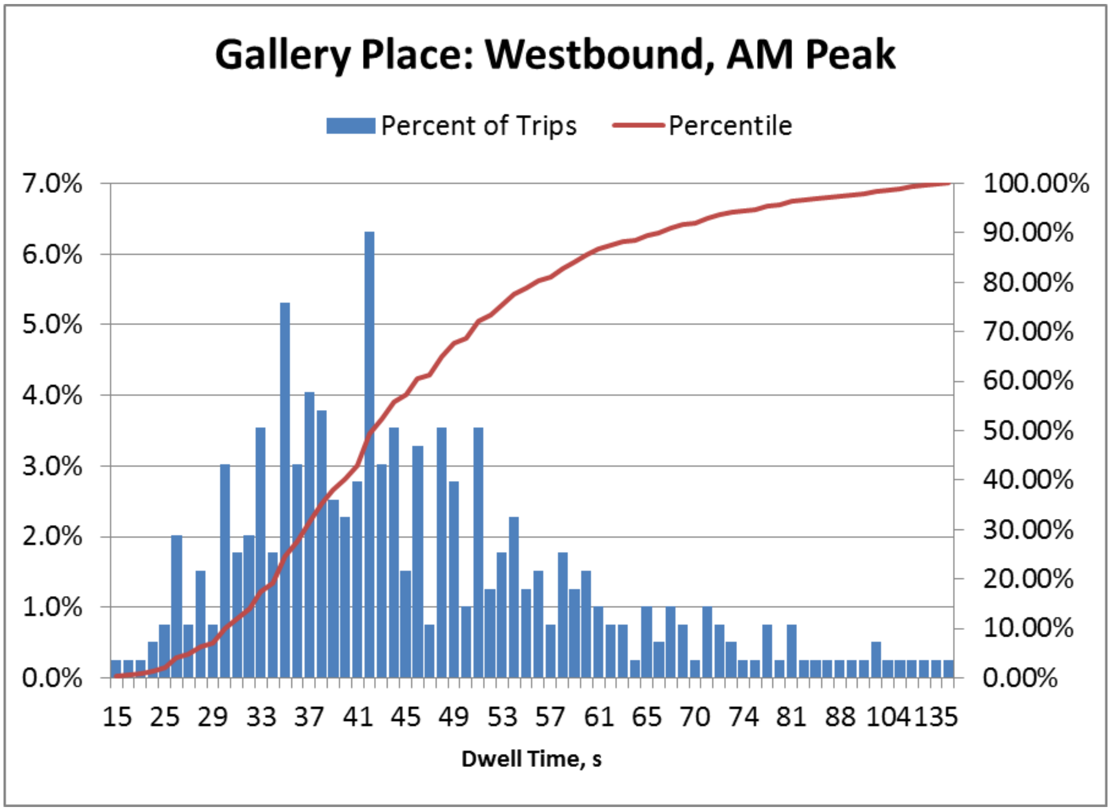


Figure 28 – Red Line, Gallery Place Transfer Station AM Peak

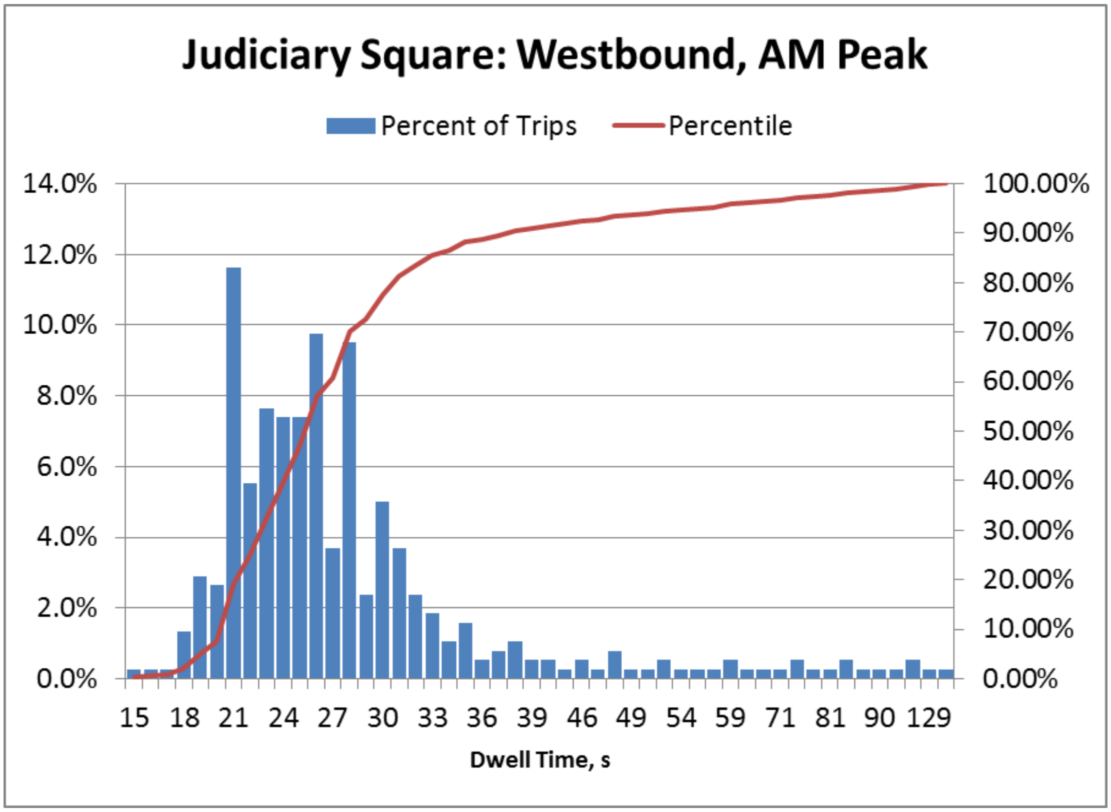


Figure 29 – Red Line, Judiciary Square Station AM Peak

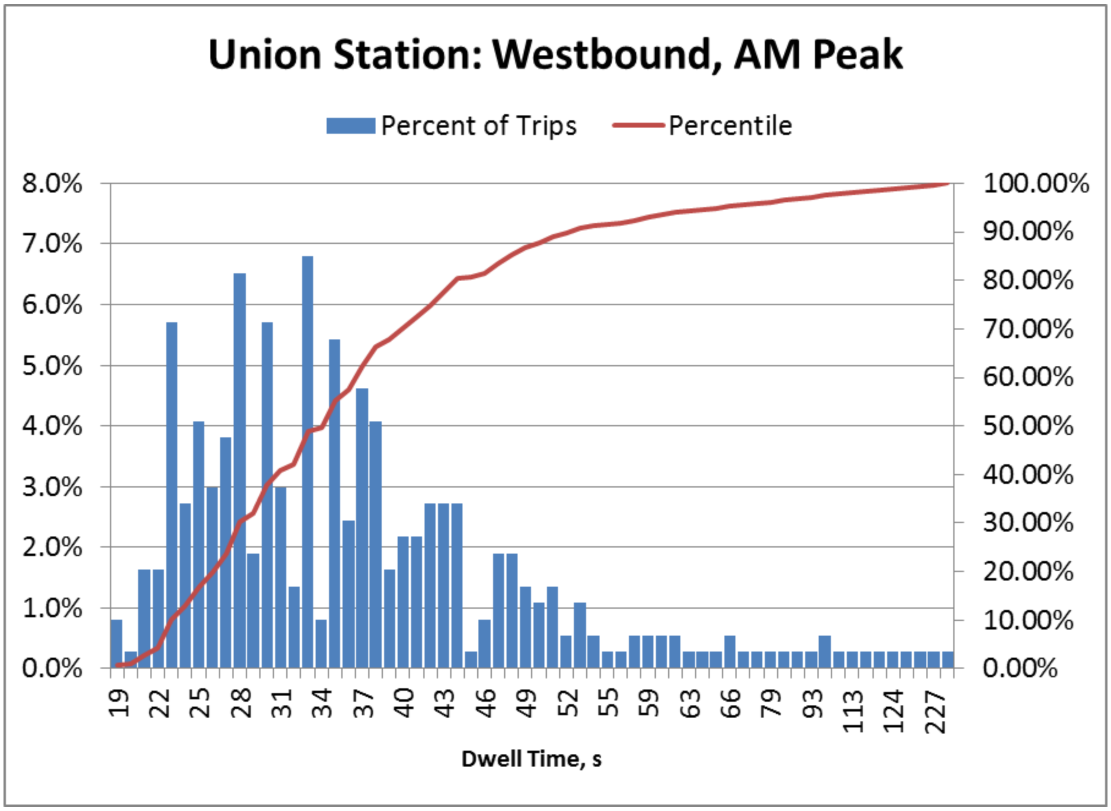


Figure 30 – Red Line, Union Station AM Peak

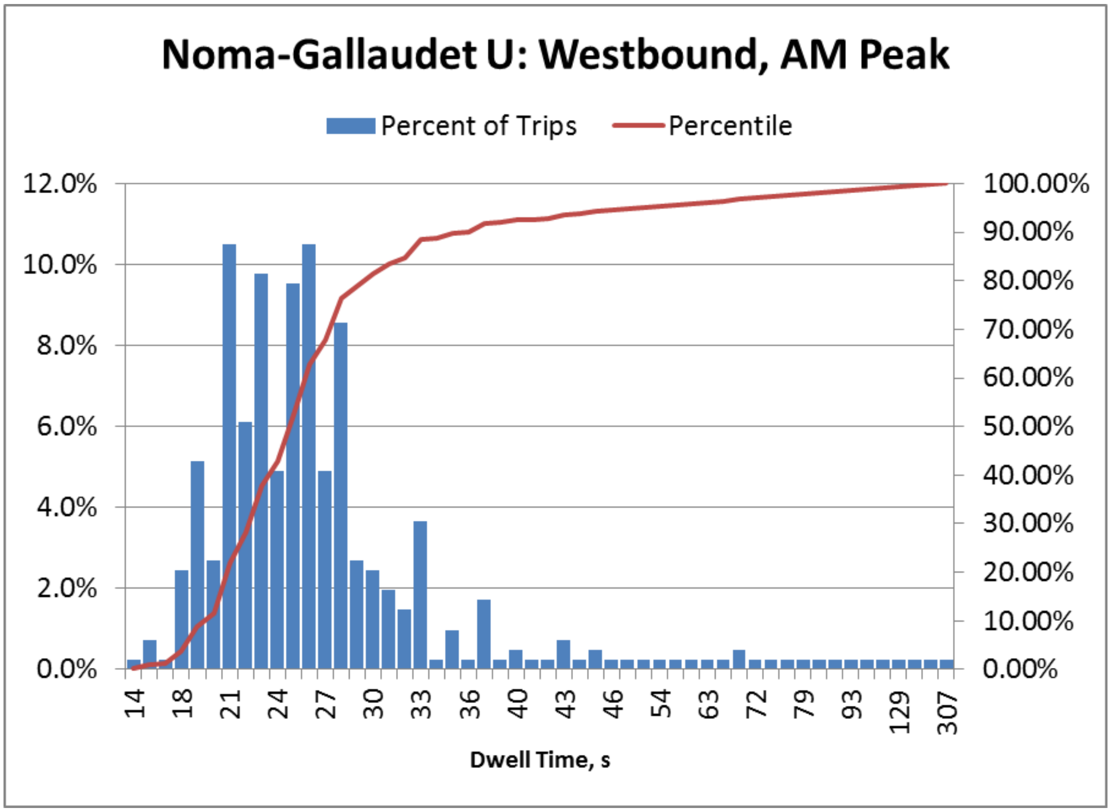


Figure 31 – Red Line, NoMa-Gallaudet U Station AM Peak

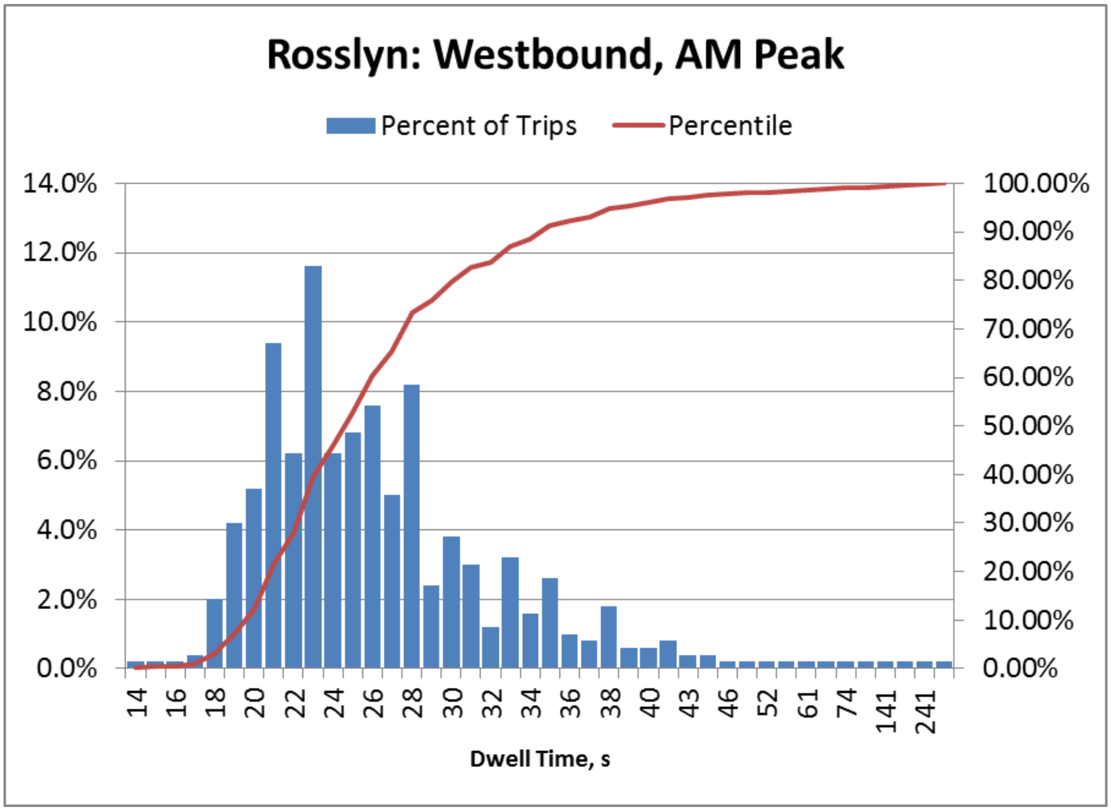


Figure 32 – Blue/Orange Line, Rosslyn Transfer Station AM Peak

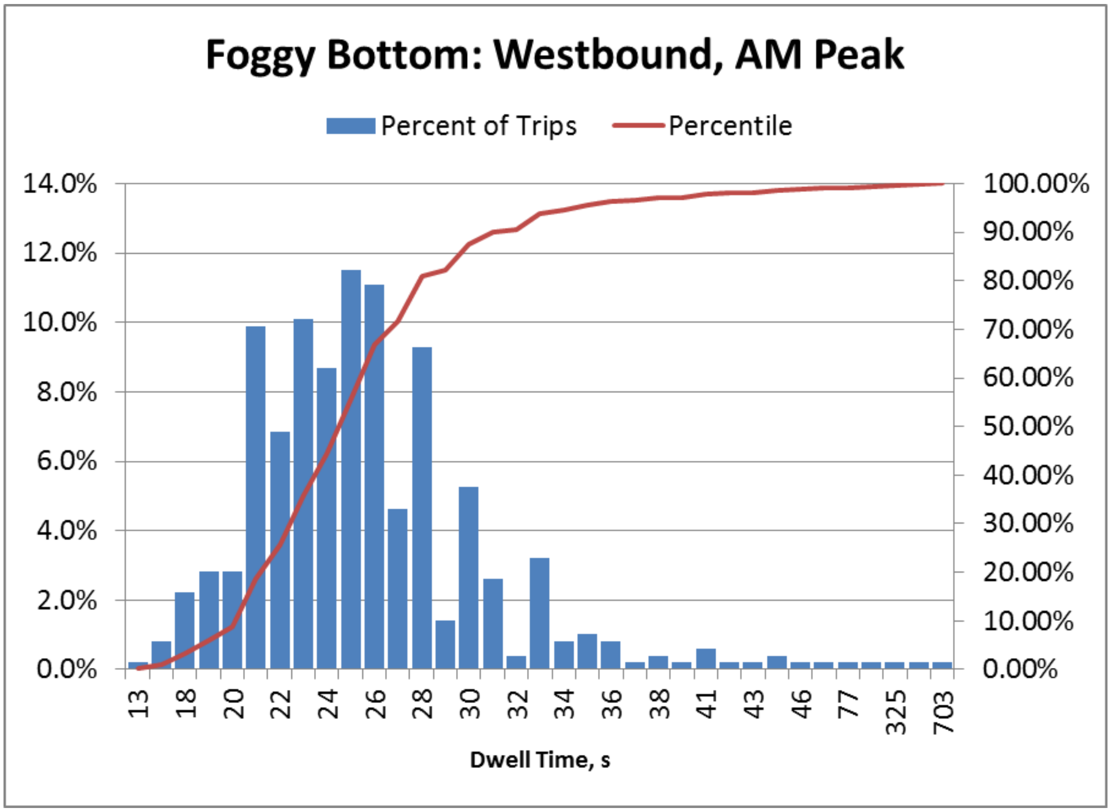


Figure 33 – Blue/Orange Line, Foggy Bottom Station AM Peak

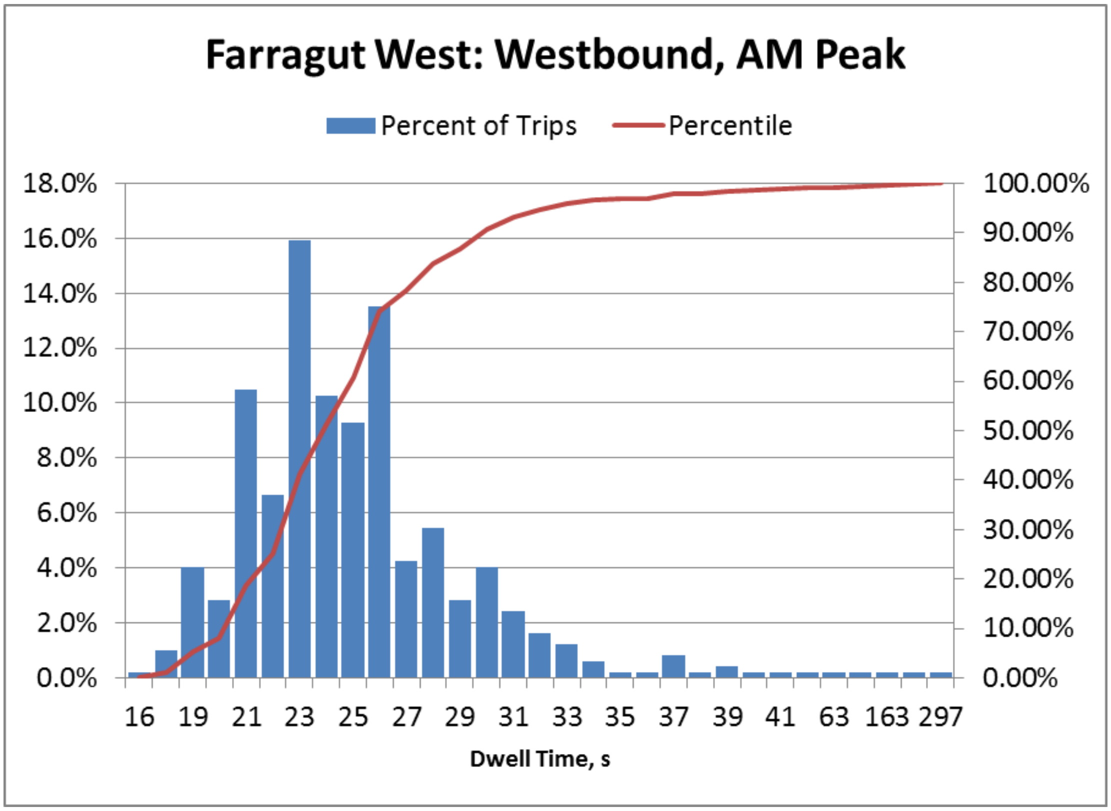


Figure 34 – Blue/Orange Line, Farragut West Station AM Peak

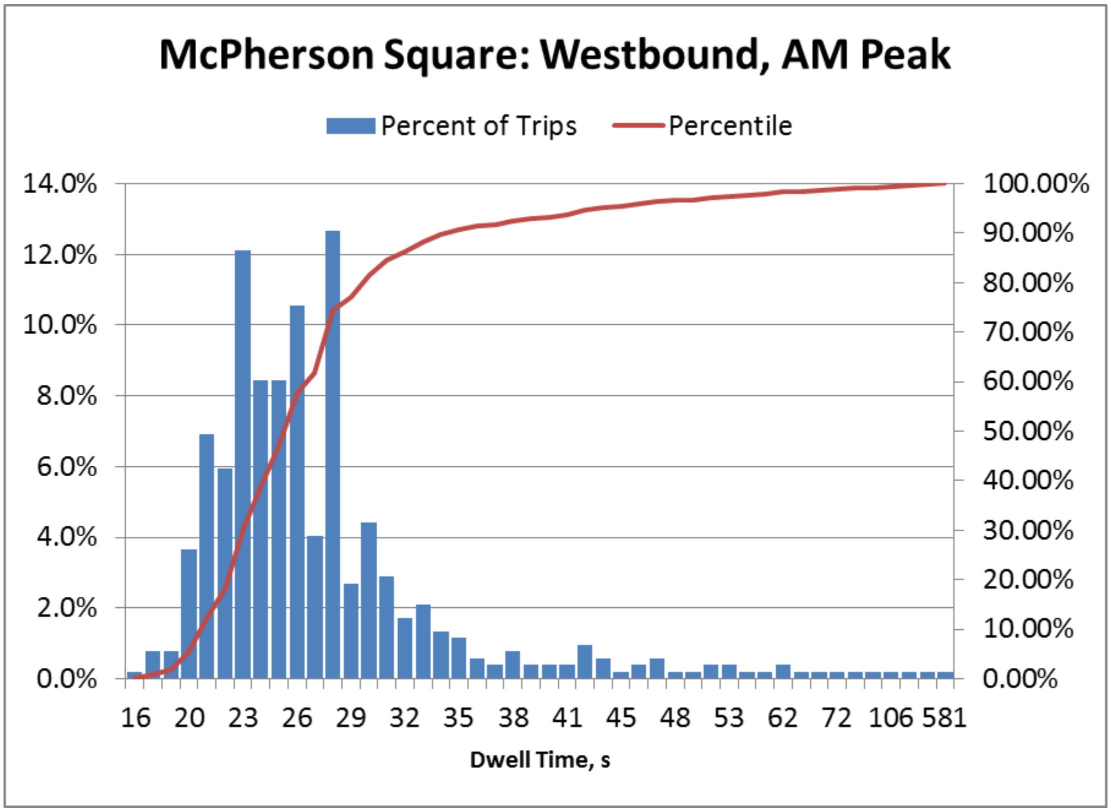


Figure 35 – Blue/Orange Line, McPherson Square AM Peak

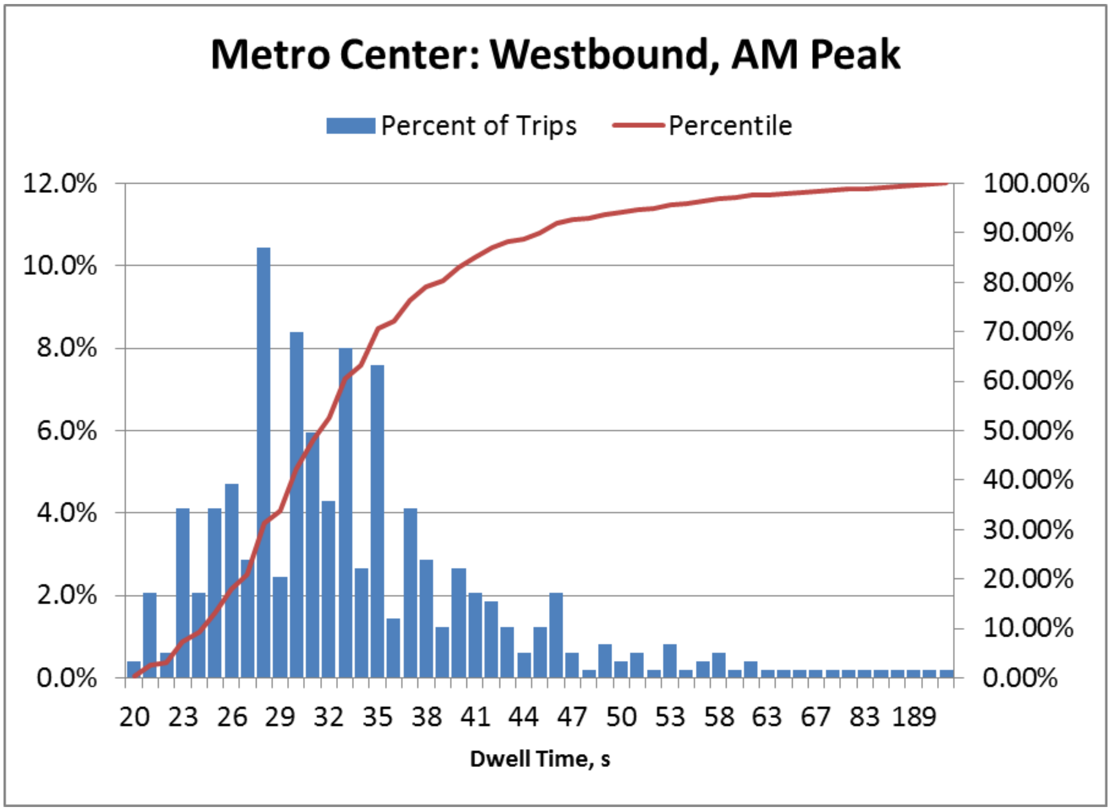


Figure 36 – Blue/Orange Line, Metro Center Transfer Station AM Peak

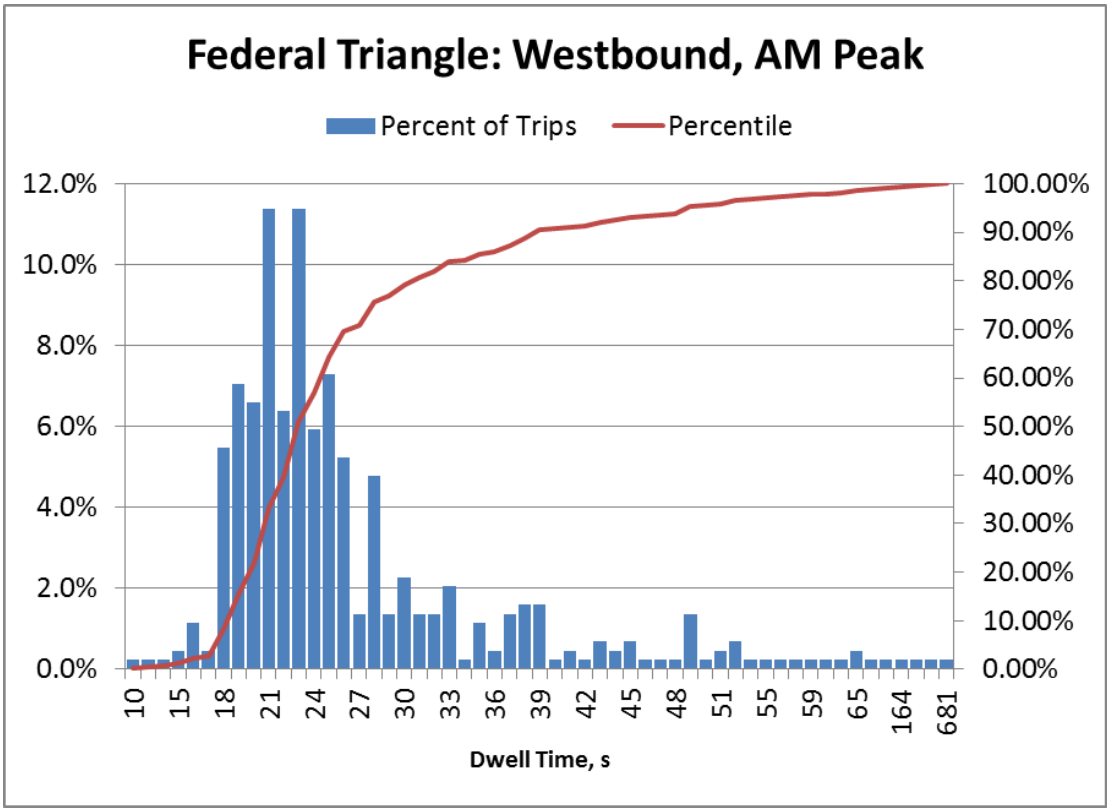


Figure 37 – Blue/Orange Line, Federal Triangle AM Peak

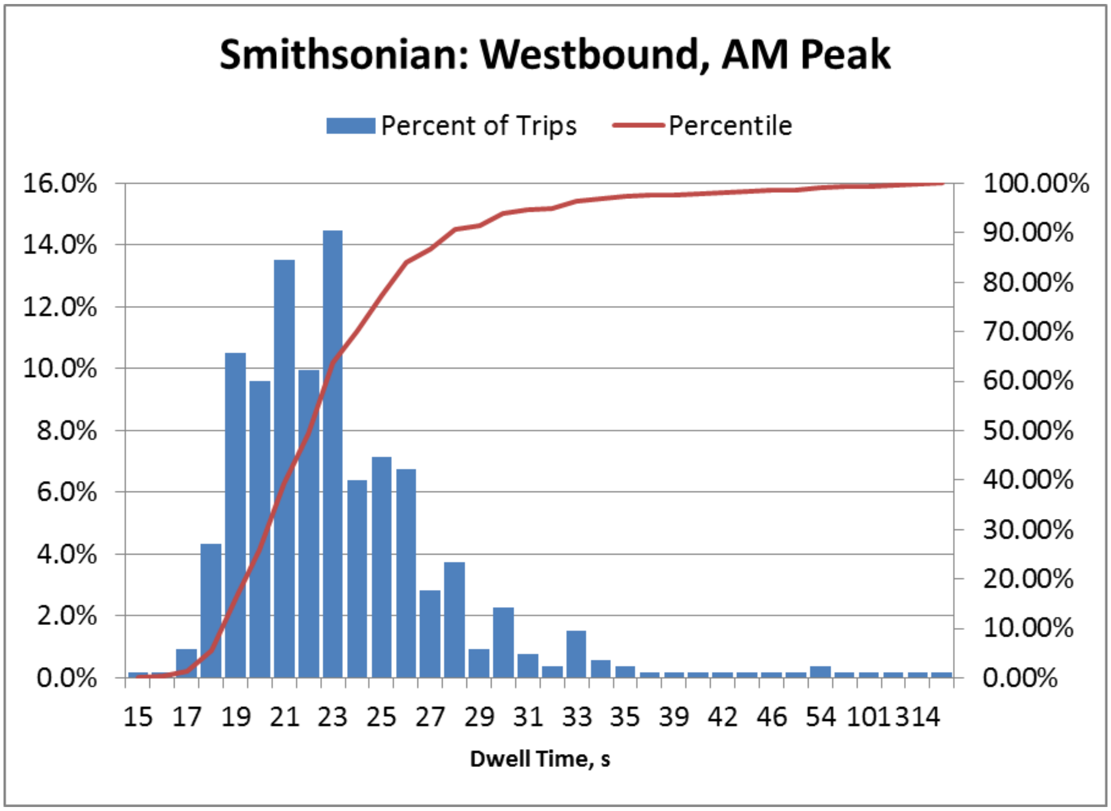


Figure 38 – Blue/Orange Line, Smithsonian Station AM Peak

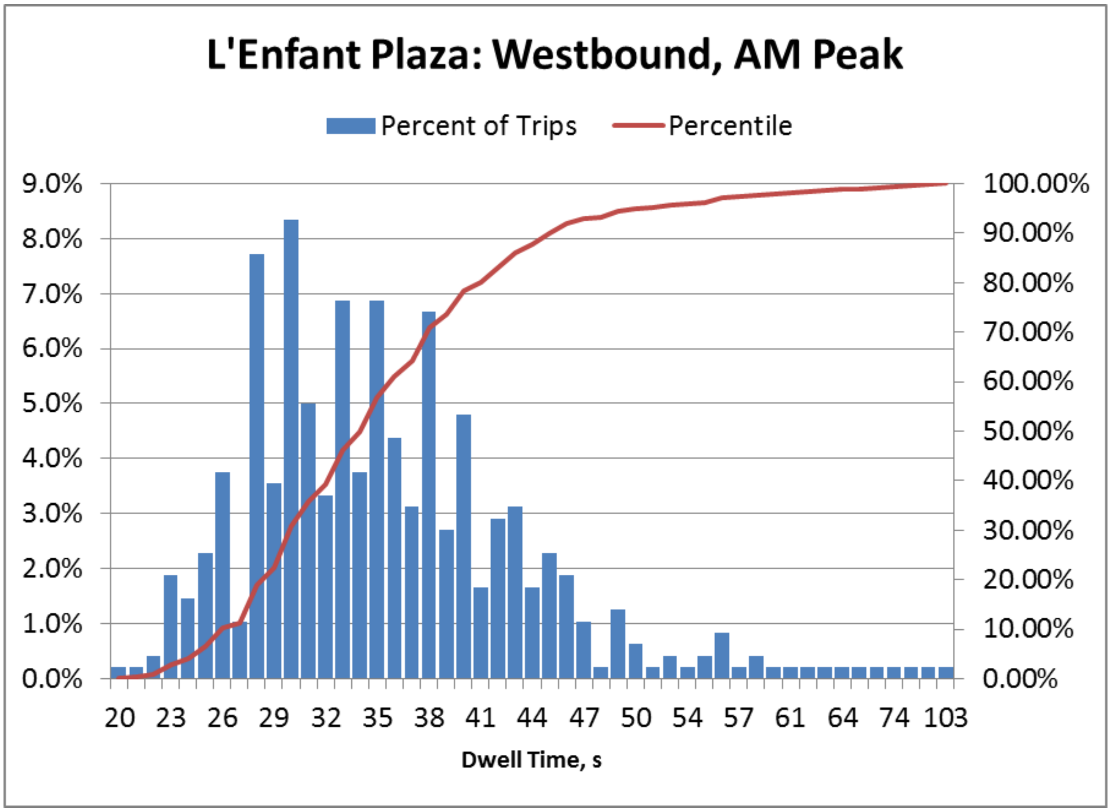


Figure 39 – Blue/Orange Line, L'Enfant Plaza Transfer Station AM Peak

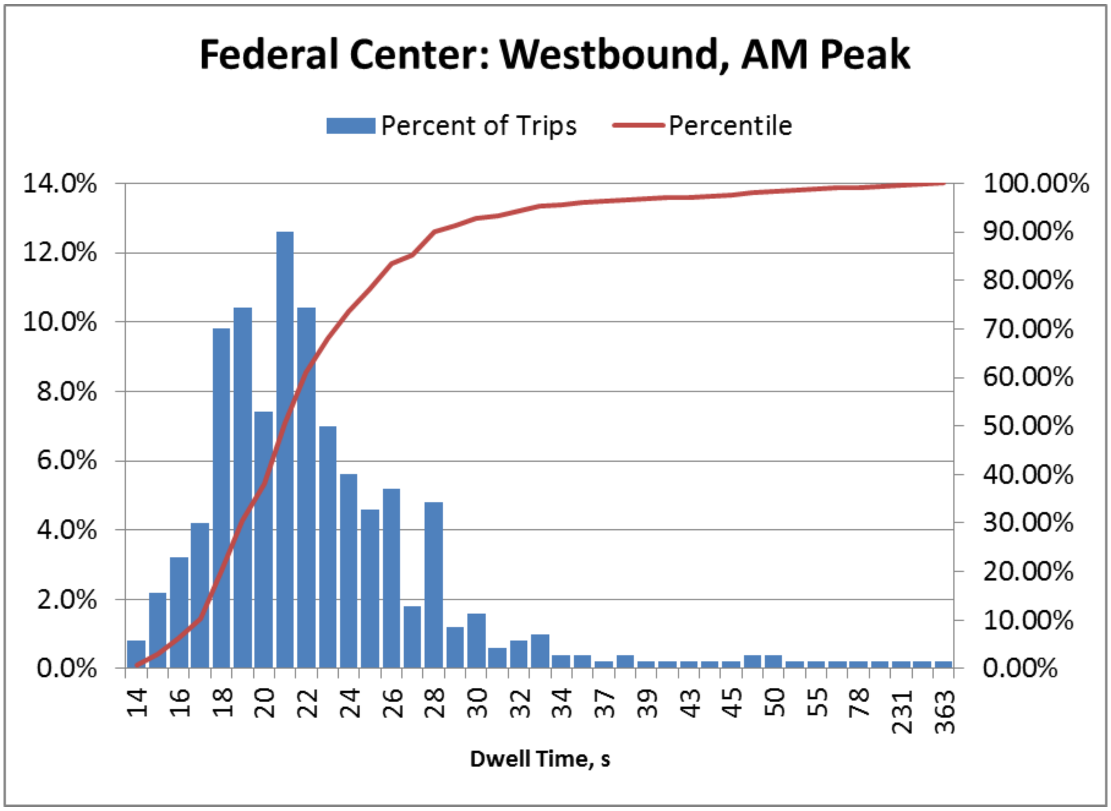


Figure 40 – Blue/Orange Line, Federal Center Station AM Peak

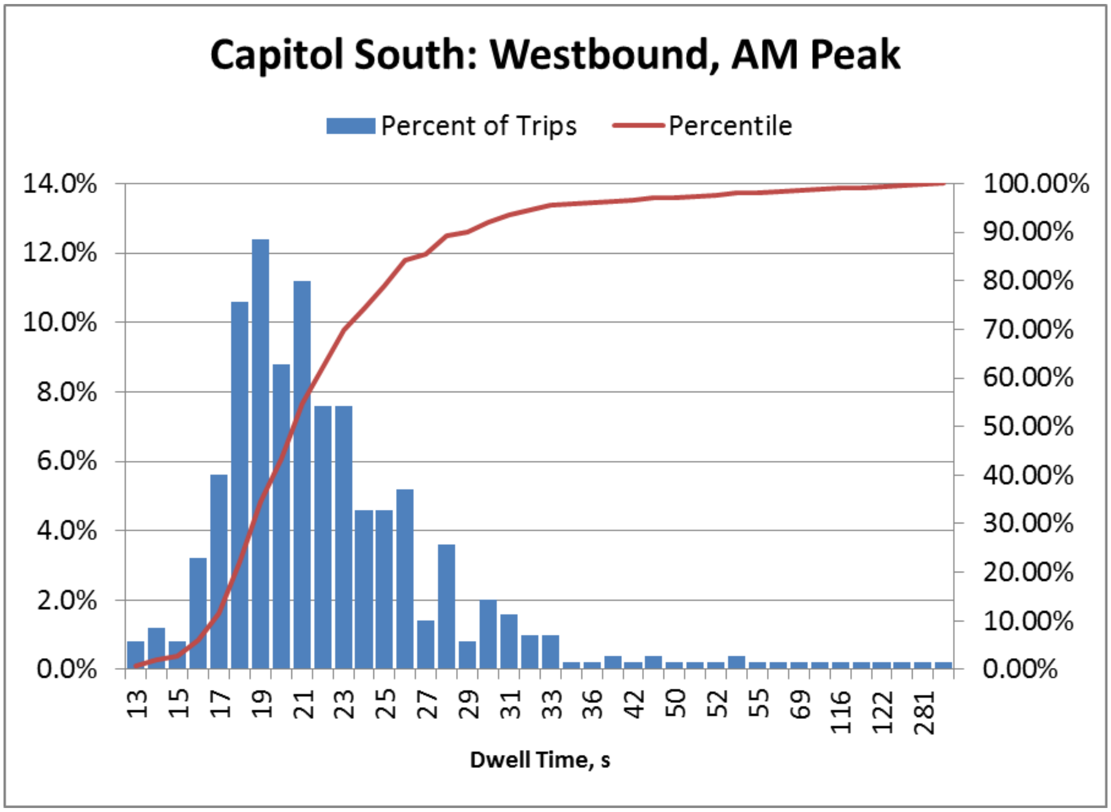


Figure 41 – Blue/Orange Line, Capitol South Station AM Peak

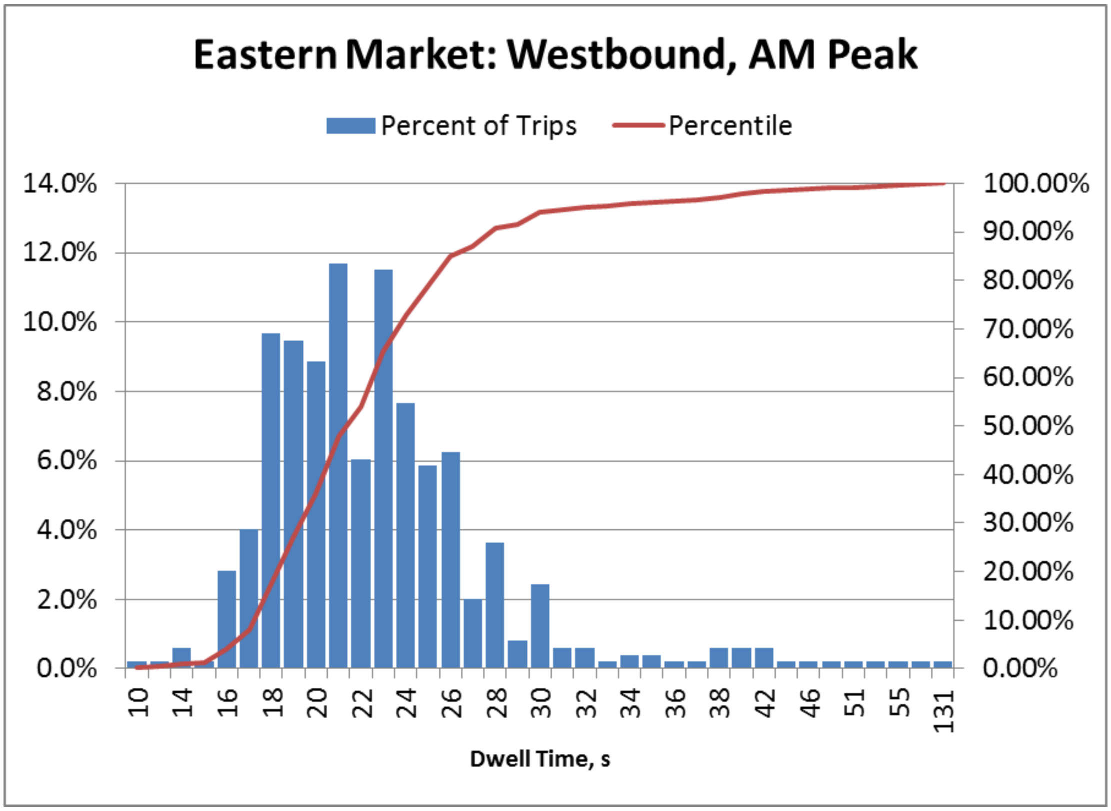


Figure 42 – Blue/Orange Line, Eastern Market Station AM Peak

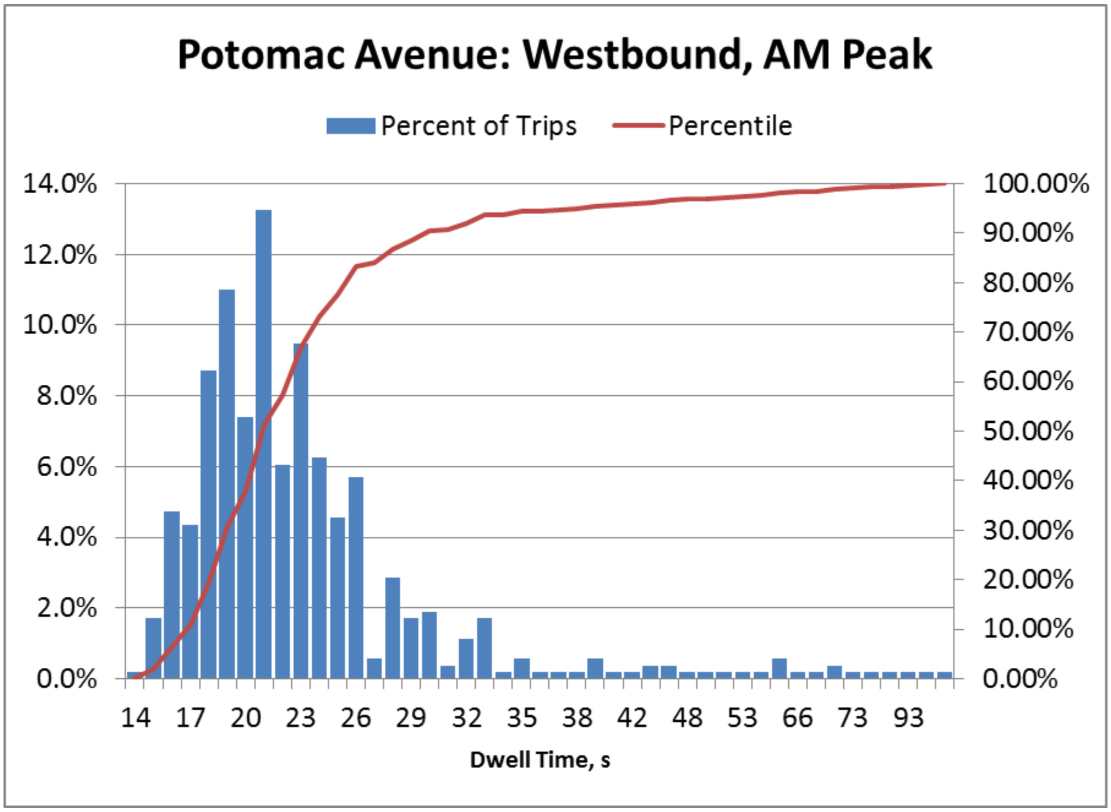


Figure 43 – Blue/Orange Line, Potomac Avenue AM Peak

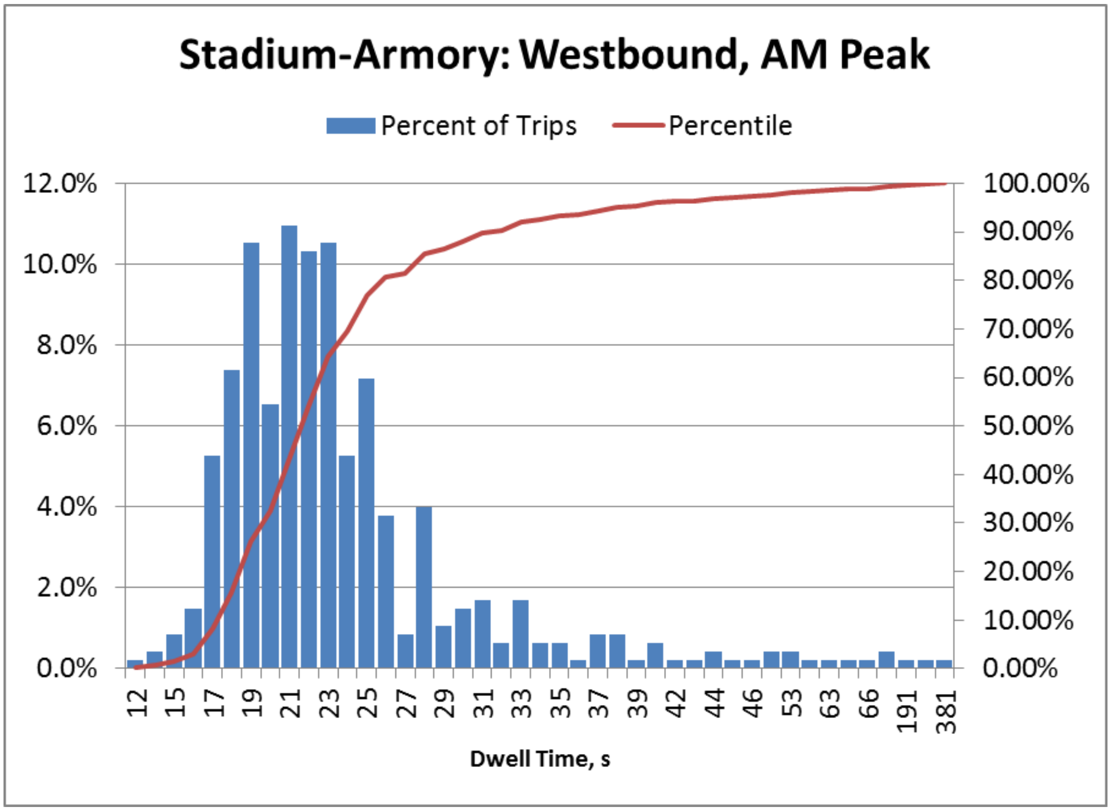


Figure 44 – Blue/Orange Line, Stadium-Armory Station AM Peak