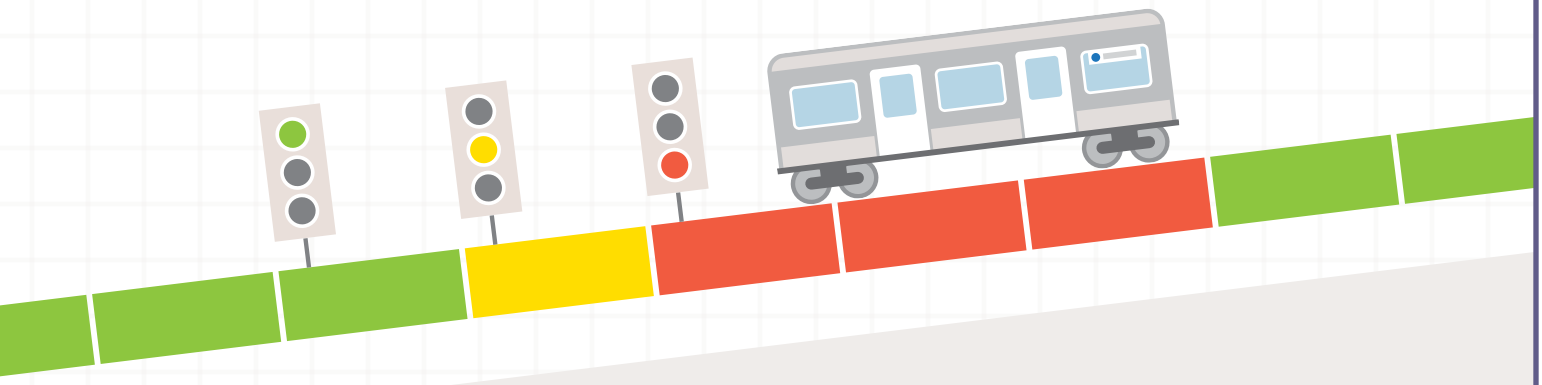
Regional Plan Association



Moving Forward

Accelerating the Transition to Communications-Based Train Control for New York City's Subways

May 2014

Acknowledgements

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June Marie Sobrito

Executive Summary

The New York City subway system has made strides in recent years in upgrading stations, subway cars and passengers' experience. But in one crucial area – signaling - the subway system remains antiquated, relying primarily on century-old technology to keep trains running. While New York is in the early stages of converting to communications-based train control, the modern telecommunications system that many of the world's metro systems rely on today, the pace of change has been slow. At the current rate, a full transformation wouldn't occur for more than 50 years, putting the city decades behind its peers around the globe.

What are the consequences of going too slowly?

More delays, increased safety risk and an inefficient use of resources. Because the network relies on old technology, repairs and replacement parts are costly. As the system ages, that burden will only increase.

What is holding New York back?

Resources, certainly. While CBTC will save money in the long run, it requires a substantial upfront investment in new systems and equipment. Future capital plans need to significantly increase funding beyond current levels. Converting to CBTC also could be done sooner with modifications to procurement rules and more flexibility to work on the tracks throughout the day. These are hard decisions that involve changes to longstanding procedures, but could speed up other projects in addition to signal work.

This report will explain what CBTC is and how it works. It will discuss the status of CBTC in New York City's subway system, and make recommendations to implement it more quickly and efficiently.

What is Communications-Based Train Control?

Today, the New York City subway relies on a central nervous system made up of 15,000 signal blocks, 3,500 mainline switches and 339,000 signal relays. These components, which have hardly changed since the subway opened in 1904, let train operators know when it is safe for them to move trains forward.

The type of signaling system used by New York's subway, called fixed-block wayside signals, divides the subway tracks into blocks of around 1,000 feet and creates a buffer of one or more additional trailing blocks to ensure safe separation of train traffic. The buffers limit the number of trains that can flow through the tracks at any one time.

The effects of these constraints have increased as subway ridership has grown. In the last 20 years, the number of passengers has climbed to its highest level since 1950, with more growth expected in the coming years. During peak periods, trains are forced to wait in stations while crowds of passengers exit and enter the cars, causing delays that ricochet through the system. The result is fewer trains running per hour. In off-peak hours, where ridership growth has been greater, it has become increasingly difficult to find adequate time to inspect, maintain and replace the signal blocks, switches, relays and automatic train stops without major effects on service. Dispatchers can only determine so much now about train location, and lack the precision and ability to centrally monitor and manage the entire system.

By contrast, CBTC combines the firepower of higher-speed computers and fiber-optic data communications to link tracks and vehicles into a seamless system. Computerized signal equipment installed along the tracks and on subway trains establishes precise knowledge about the location and speed of each vehicle, making it possible to centrally monitor and respond rapidly as conditions change.

Benefits for riders, operators, businesses and the public

The benefits of CBTC flow from the greater efficiency, reliability and flexibility that it provides. Because trains can safely run closer together, they can circulate with greater frequency, reducing bunching and uneven service. Theoretically, CBTC can accommodate 40 or more trains an hour, compared with at most 30 using traditional signal systems. Although running at full CBTC capacity would require other improvements to the subway network, such as straightening curved track and expanding stations, passengers would see substantially less waiting and crowding with CBTC.

Instantaneous communications would improve reliability, allowing New York City Transit to work around and respond quickly to both rare and commonplace events such as stalled trains, accidents, flooding and police actions. Customers also would experience more accurate and timely countdown clocks and other important information. While the upfront capital costs are high, the annual savings from reduced energy, maintenance and operations would substantially reduce the costs of running the system. Energy would be saved by smoothing rates of acceleration and deceleration, which also would make for a more comfortable ride. Since signal maintenance would be much less labor-intensive, the MTA would be able to maintain CBTC for far less than the $106 million annual cost for the current sig-

Nancy Borowick

nal system. Trains could be operated with a crew of one instead of two, or even without a driver. That would allow the MTA to reduce overall costs, shift labor to other operational or service needs or implement a combination of cost reductions and service improvements.

The benefits from full implementation of CBTC will flow well beyond those who ride the subways. A more cost-effective transit system will reduce pressure on the three main sources of MTA revenue—fares, bridge and tunnel tolls and taxes from both residents and businesses. It won't eliminate the need for additional revenue to maintain and expand the transit network, but it should be an essential part of a long-term financing strategy that includes both revenue increases and cost savings. Service improvements will allow the subways to comfortably absorb additional riders to support a growing economy for New York City and its suburbs. Without these improvements, New York will become less competitive with cities around the world that have more modern systems.

Lessons from other cities

CBTC is a proven technology that has been used on most subway systems around the world for many years. Some newer systems are completely operated with CBTC, while most older systems are in different stages of transition. CBTC is now the global standard, and a review of four noteworthy examples—London, Paris, San Francisco and Vancouver, as well as New York's experience to date—provide evidence of CBTC's benefits and some lessons for its future development.

- Full automation can dramatically increase the flexibility of the system, allowing operators to rapidly increase service or reroute trains in response to events.
- The largest capacity increases come not from running more trains, but from allowing more efficient utilization of existing trains that are more evenly spaced.
- CBTC systems rarely fail, and when they do the failures are localized. For this reason, some systems are finding that backup systems are unnecessary.
- The entire system doesn't need to be converted to CBTC to see benefits. Hybrid systems, networks with CBTC on trunk lines and conventional signals or street running on branches can still gain capacity, reliably and efficiency benefits.
- New signal technologies are easier to maintain and can save tens of millions of dollars on maintenance costs.
- CBTC dramatically changes how the system operates by centralizing the control of the network. Management must be prepared to adapt to the new operational possibilities that CBTC affords to fully realize its benefits.
- Labor needs to be brought into the discussion early. Implementation can take many years, often decades, and many current tasks will be phased out over time. This can provide an opportunity to create new roles for employees that increase their prestige - greater responsibility and skills – while improving service for passengers.
- Additional brick-and-mortar investments, like improvements in station circulation or correcting system bottlenecks, can magnify the benefits by eliminating limits on throughput that would otherwise be possible with CBTC.

Costs and challenges to implementation

Converting the entire subway system to CBTC is a major undertaking that will take many years to complete. It will cost more than building the first leg of the Second Avenue Subway or connecting the Long Island Rail Road to Grand Central Terminal, and comes with organizational hurdles that rival those enormous construction projects. Installing CBTC equipment throughout the system would cost an estimated $13.8 billion, or about $20 million for each mile of track. This doesn't include the costs of upgrading all of the interlockings – large junctions between lines - that aren't compatible with CBTC. Equipping the subway fleet would cost an additional $5.4 billion, or about $1 million for each car, for a total of $19.2 billion or almost $20 billion. As with signal and track maintenance, the conversion would need to take place in a 24-hour system that never shuts down.

Beyond the costs and complexities of construction, CBTC will require a new mindset for operating the system and challenging negotiations between management and labor. Technology creates opportunities to run the system in different and better ways, but requires more than simply adapting the system to the current operating environment.

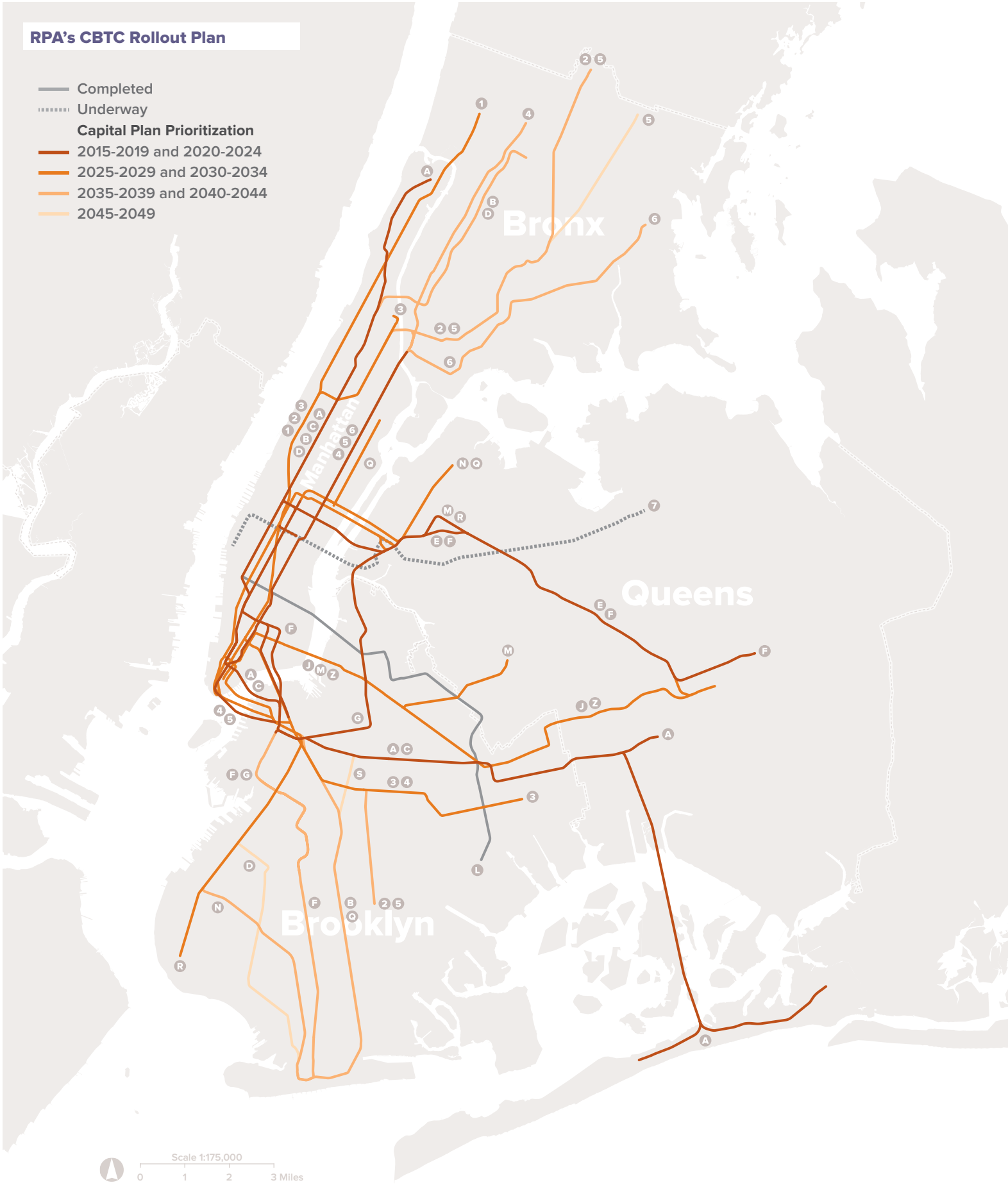
Labor must be a partner in this transformation. Under CBTC, train operators will no longer operate trains but will monitor them. CBTC, while not a requirement for one-person-train-operations, further eases the transition to it by offering another level of safety over fixed-block signaling. Transit agencies around the globe are making investments in technology that will allow them to increase their service and reliability with the same or smaller workforce than they have today. But technology doesn't have to result in a reduction of the unionized work force. Systems like the one in Paris have strong unions, but have reached consensus between labor and management on new practices to increase service to respond to growing passenger demand. Train operators and conductors in other systems have agreed to transition to roles at stations and control centers. New York will need to develop its own solutions, but the status quo will become increasingly untenable.

Transforming New York's Subways with CBTC

The process is already under way, but will take years to complete and must overcome a number of hurdles. In fact, only four miles of track per year have been converted since 1999. The MTA's Twenty Year Needs assessment envisions a pace of 16 miles per year. Assuming the initiative is fully funded, this would mean only half the system would be using CBTC by 2034. To keep pace with other regions and realize the full potential of CBTC, this effort needs to be both accelerated and expanded. Based on an extensive study of the subway's signal system, RPA is recommending the following measures:

Upgrade an average of 21 track-miles annually to CBTC during every five-year Capital Plan, completing the transition to moving-block technology in 35 years or less.

This program would cost an average of $393 million annually – more than $2 billion in each of the next seven five-year capital plans. When compared to the MTA's most recent Twenty Year Needs Assessment, RPA's proposal would almost double the investment in CBTC over the next two decades. To meet this goal the MTA will need to expand its Fast Track program and also explore extended overnight, weekend or other types of closures that might last weeks or months at a time. Lines should be prioritized based on their age, capacity and ridership growth potential, as illustrated in Chapter 5.


RPA's CBTC Rollout Plan
Completed
Underway
Capital Plan Prioritization
2015-2019 and 2020-2024
2025-2029 and 2030-2034
2035-2039 and 2040-2044
2045-2049
Bronx
Manhattan
Queens
Brooklyn
Scale 1:175,000
0 1 2 3 Miles

Accelerate the upgrades to rolling stock to operate in both moving-block and fixed-block environments. Without the operational flexibility of a larger CBTC-equipped fleet, the agency's options will be limited because of the interconnected configuration of the remaining lines that make up the subway. The full cut-over of the Canarsie line (L) to CBTC was delayed due to insufficient CBTC-equipped rolling stock, suspending most of the benefits of CBTC for years. The MTA most recent needs assessment states that it plans to retire its old and mid-life cars by 2027, making its entire fleet CBTC-ready or equipped. This schedule should be accelerated if possible. The agency also should take steps to overhaul its mid-life cars, which represent almost a third of its fleet. By extending the life of these cars, the agency will be able to increase the frequency of service throughout the system sooner, taking full advantage of the new capacity afforded by CBTC.

Replace old and damaged signals with CBTC, rather than replacing with old technology. The MTA should, whenever possible, replace fixed-block signals with CBTC when they reach the end of their useful life or are damaged. The MTA should conduct a systemwide survey so that the agency can prepare sites along the network for CBTC and possibly to install CBTC while workers have extended access, as the agency did during post-Sandy repairs.

Transform management practices to adapt to new approach to operations. CBTC is a transformative investment, but one that won't fulfill its potential if the subway is run as it always has been. Employees will need to adapt to maintain new equipment and managers must reconsider the 100-year-old approach they use to operate the subway.

The Federal Transit Administration's study of CBTC on the San Francisco Muni highlighted the importance of organizational reforms in tandem with the implementation of new train control technologies. It stated: "Transitioning from a fixed-block signaling based train control system to CBTC requires a dramatic shift in technological and business practices within the transit agency." The FTA also found that CBTC's "open architecture facilitates interoperability between equipment from different suppliers and maximizes the use of commercial off the shelf equipment."

Retrain and reposition workforce to take full advantage of technology investments and better serve customers. With fewer workers needed to operate the trains, the MTA should work with labor to shift conductors to customer-oriented services at stations. In Vancouver, for example, workers are cross-trained in many areas, from train systems to providing medical assistance. The MTA also could explore new roles for its train operators, such as monitoring and remotely operating trains in the railway control center – a similar approach to the one that has been taken in Paris. With a transition that will take at least three decades, there is an opportunity to negotiate a successful labor-management approach that can be implemented gradually across the agency.

Convert subway to driverless operations by 2040s. The MTA should begin to prepare the system for full automation in the 2040s once CBTC is installed. It will save the agency billions of dollars annually and allow it to increase service while keeping their operating costs in check. Full unattended train operations have been implemented around the world, even in older systems. Driverless metros more efficiently use existing fleets, are more energy efficient and offer greater flexibility.

Other actions that could enhance the service or cost-savings potential of CBTC go beyond its implementation. The following actions also should be considered:

- Eliminate the costly and unnecessary fixed-block back-up system envisioned for the system. Other systems have shown that CBTC can be reliably operated on its own.
- Enlarge stations, improve vertical circulation to address crowding and make adjustments to terminals and junctions where necessary. These changes will reduce dwell times and allow CBTC to run lines at full capacity.
- Eliminate major bottlenecks – inefficient terminals, at-grade junctions and sharp curves. The physical design and layout of the subway's track and stations limit the system's maximum attainable throughput.

These recommendations are explored in detail in subsequent chapters. In addition, a short video that can be viewed at www.rpa.org explores the difference between fixed- and moving-block technology.

Nancy Borowick

Introduction

The physical configuration and operation of the subway has changed little since the 1950's. While its trains might be modern, most of the subway's "hidden" infrastructure is not. One critical unseen component, its signals, still function much as they did when the first subway line opened over a century ago in 1904. The subway's signals are its central nervous system, controlling the "ebb and flow" of trains over the hundreds of miles of tracks that crisscross the city each day.

Signals govern how many trains can occupy one segment of track at one time, effectively setting the capacity[1] of the subway. Flexibility to reroute services in response to events is dictated by the sophistication of the signaling system, which controls how efficiently trains can be redirected around work zones and service disruptions, affecting the reliability and frequency of service. Redundancy and resiliency, more critical than ever due to the tragic events of September 11th 2001 and Super Storm Sandy in 2012, are also impacted by the type of signaling system in place.

Signals matter a lot. Yet, they are also the most underappreciated and inadequately funded part of the subway. Signals are really hidden, with components squirreled away inside hundreds of little rooms throughout the system and along the tracks. Straphangers and politicians don't see them nor understand their importance, but that must change as we enter an era of increasing subway congestion.

It wasn't until almost the turn of this century that subway ridership rebounded from the depths of recession of the 1970's, reaching levels not last seen since just after WWII, when fewer New Yorkers owned cars and many worked six days a week. The subway system is close to eclipsing its all-time high ridership of over two billion annual trips recorded in 1948, but will have to accommodate this record number of riders on fewer miles of track.[2] The projected population of the city and the surrounding region will generate more trips over the coming decades, but the system is clearly not ready for it. Capacity for growth will have to come from either more subway lines or from more capacity on the existing lines. While there are limited expansion projects underway, they are mostly targeted to provide relief to parts of Manhattan and the Bronx. To serve the future workers and residents of the entire city we will need to increase the capacity of the existing system, which means investing in modern signals and automatic train operation – running more trains and lowering costs. Capacity is not the only reason to make this investment. The urgent need for greater flexibility, replace aging/life-expired signals, redundancy and resiliency is just as important. Also, funding realities dictate that system efficiencies and cost savings must be found – all of which are possible through signal modernization. Our signal system is expensive to maintain and operate, has limited capacity and flexibility and is neither resilient nor redundant.

This report is intended to demystify signals and the benefits that would result from modernization. Chapter 1 explains how our signals work today and why they are limited in comparison to modern signals and automatic train operation. Chapter 2 details the anatomy of a modern signal system and automatic train operation (ATO) and the benefits of the technology. Chapter 3 overviews where CBTC has been implemented around the globe and includes four case studies that expand upon ATO/signaling investments in London, Paris, San Francisco and Vancouver. Chapter 4 covers past and current MTA investments in modern signaling and automatic train operation on the Canarsie (L) and Flushing (7) lines, discusses other signal-related improvements that have been made and the agency's publicly-stated plans to further upgrade the subway's signal system. Chapter 5 is RPA's screening analysis of signal age, subway capacity and a survey of what ridership growth subway lines might experience in order to determine CBTC phasing priorities. Finally, Chapter 6 proposes a long-term investment program for transforming the subway by modernizing signal and making other complementary investments. The plan also recommends several institutional reforms and cost savings strategies.

1 Capacity can also be determined by train car capacity, station capacity/circulation, terminal design and other physical bottlenecks that can constrain train throughput.

2 Many elevated lines, most in Manhattan, were torn down after WWII to improve the surface environment of the city – less noise and more light. Most were replaced by subway lines before being demolished, but some – like the 3rd and 2nd Avenue elevated lines – were not.

Albert Pego

Subway Signals, How They Work and Limits of the Existing System

Inaugurated in 1904, New York City's subway is one of the oldest, largest, and most complex urban rail systems in the world. It consists of 26 services running on over two dozen different lines[3], serving 468 stations that span 373 route kilometers (231 miles).[4] The system carries 5.4 million passengers every weekday and 1.6 billion riders annually (2012), more than the annual ridership of the Washington Metro, Chicago 'L', and Boston (subway portion of the "T") combined.[5] The subway is one of the primary means of transportation in New York City and must operate reliably for the city to function. The service outages during Hurricanes Sandy and Irene drove home this point when the city and its economy essentially came to a halt during these storms. As shown in Table 1, over 60 percent of the almost 1.4 million people traveling into the Manhattan Central Business District (CBD) during the AM peak (7-10am) do so directly via the subway. Many of those entering by commuter rail and buses from New Jersey also use the subway to reach their final destination.

To serve these people well, the subway system must be reliable and safe, and its signals are critical to its operation. They provide authority for train movements throughout the system and play an essential role in the subway's safe operation by indicating track conditions further ahead. When they fail, trains come to a standstill, leading to delays as services are either rerouted or suspended until the signaling system is restored.

The subway's current signal system is vast, consisting of 14,850 signal blocks, 3,538 mainline switches, 183 mainline interlockings (major junctions, large switching complexes), 10,104 automatic train stops[6], and 339,191 signal relays.[7] Over the past 40 to 50 years the MTA has replaced much of the oldest parts of the signaling system with newer equipment, but the basic principles of how the system operates remain the same[8].

The subway operates using a conventional fixed-block regime, meaning that its tracks are divided up into segments or blocks that average 1,000 feet in length. An insulator is placed between the rails on both ends of the track segment to create a block. An electrical current is then run through the block to a relay creating an electrical circuit. As long as the circuit is closed, meaning that the current is able to travel unimpeded from one end of the circuit through the relay to the other, the block is deemed open and not occupied by a train. As soon as a train enters a block its steel wheels break or "short" the circuit causing the relay to discharge and the block to register as being occupied. [9] The state of the blocks ahead dictates if or how fast a train may proceed along its route. An open circuit can also indicate a broken rail or a signal malfunction.

While fixed-block signals are a proven technology, they impose numerous operational constraints on the MTA and are expensive for the agency to maintain. One significant limitation of the technology is its lack of precision.

Table 1: Modal Share for Those Entering the Manhattan CBD in the AM Peak (7 – 10AM)

Mode	Total	%
Subway	847,370	61.94%
Commuter Rail	182,524	13.34%
Auto	181,215	13.25%
Bus	123,815	9.05%
Ferry	25,533	1.87%
Bike	6,161	0.45%
Tram	1,341	0.10%
Total	**1,367,959**	**100.00%**

Source: 2011 NYMTC Hub Bound table 14-b

"2011 Hub Bound Travel." . NYMTC. Web. 22 Oct 2013. <http://www.nymtc.org/files/hub_bound/2011_Hub_Bound_Travel_Data.pdf>.

Count from a "typical" fall workday. Most likely underestimates pedestrian and bikers because of the multitude of ways for them to enter the CBD.

The Pressure of Growing Ridership

Fixed-block signals do not allow the system to precisely determine the location of a train within a block, requiring one or more blocks [10] behind a train to be marked as "occupied" or red, followed by a yellow or "permissive" block to ensure safe separa-

3 Officially, the number of lines is 33, designating the Grand Central Shuttle as an additional line increases the number to 34. In addition, the MTA officially counts 24 distinct services. RPA's count includes the two diamond-express services on the #6 and #7 lines as distinct services.

4 These numbers do not include the Staten Island Railway (SIR), which was not considered for CBTC installation in the report. While the SIR operates under the auspices of the MTA, it is regarded as a distinct entity within the MTA and is not treated operationally as part of the subway. In fact, the SIR is a FRA-regulated railroad, unlike subway which is a considered an urban transit system under the FTA. Additionally, the SIR has a large amount of additional capacity under its current signaling regime. These circumstances do not preclude it from being upgraded to CBTC but this assessment should be done independently of the subway system and must also include an evaluation of the best use of the SIR right-of-way.

5 MTA.

6 These are articulated metal arms between the tracks that trigger a subway car's brake when they are in an upward position to prevent the train from entering a protected section of track.

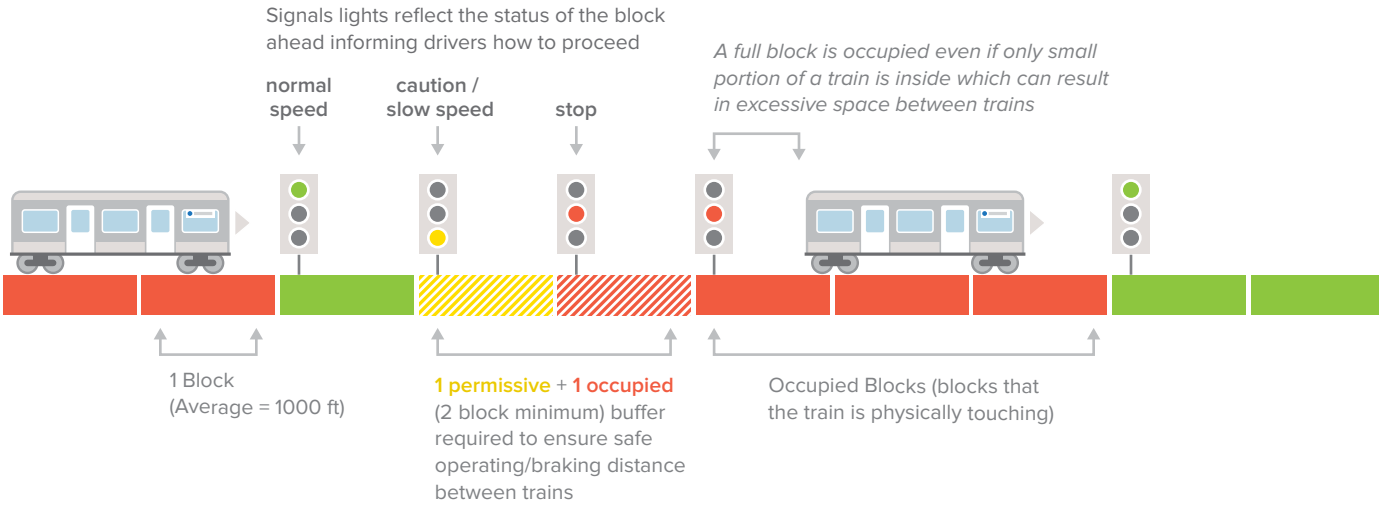
7 Metropolitan Transportation Authority. 2010-2014 Capital Plan. 2010. Print.

8 The only exception is the L subway line (Canarsie line) which has been upgraded to a modern CBTC system.

9 Relays are mechanical electromagnetic switches that rely on Newton's law of universal gravitation to operate. They contain an iron moveable armature and magnetic contact inside that, when charged, attracts the armature to the closed position. When it's discharged the armature opens usually with the assistance of a spring or weight. There are also solid-state relays that have no moving parts, but are more sensitive to electromagnetic natural events.

10 The number of trailing red blocks varies in order to maintain minimum safe distance based on the stopping distance of a train operating at maximum attainable speed which is determined on a location-by-location basis.

Figure 1: Diagram of a Conventional Fixed Block Signal System



tion distance between trains. As a train proceeds, the operator reacts to the trackside aspects, similar to a traffic light, that are either green for all clear, yellow for permissive/"proceed at a speed that is typically no faster than 10mph and be prepared to stop within a half distance of the next signal or obstruction ahead," or red for restrictive/"the train must come to a complete stop." A red or yellow signal indicates that another train either is currently or just was occupying the block in front of it[11]. The train might be completely stopped in the middle of the block or it could only be the last car or two of the train at the far end of the block. Either way, the entire block is indicated as occupied. Nor does it matter whether the train is moving fast or slowly. The block lengths are fixed and cannot be dynamically adjusted based on the braking performance and speed of trains – slower-moving trains require less space to come to a full stop than a train at a higher speed. This lack of precision and inflexibility of the fixed-block configuration results in an inefficient use of track space. One way to improve precision in a fixed block signaling system is to shorten the size of the blocks to more precisely locate trains. However, this solution is costly since it requires even more wayside equipment, can make a system less reliable (more circuits mean a greater chance of failure) and still cannot address all the aforementioned inefficiencies, like adjusting to train speeds. The MTA has taken this costly approach on some of its busiest lines. For example, the blocks around stations on the Lexington Avenue line in Manhattan have been broken up and signal timing has been introduced to allow trains to close on each other as they approach stations. Even with these improvements, the Lexington Avenue line is pushing the upper limits of what conventional signals are capable of as the subway gets more and more crowded – carrying over 1.8 million riders a day.[12]

Ridership on the subway has been growing steadily since 1982 when it hit a historical low point of 938 million annual riders. That same year also marked the beginning of the MTA's first Capital Plan, with over $100 billion spent since, $46.5 billion of which has been dedicated to rebuilding and improving the subway.[13] As shown in Figure 2, over 700 million more trips were taken in 2012 on the subway than in 1982, a 67 percent increase in ridership over that 30 year period. Even at the start of the great recession in 2008, subway ridership continued to increase. However it did register a 2 percent decline in 2009, but has since been increasing on average by 2 percent per annum. Ridership has now reached levels that have not been seen since 1950.

System Capacity

This higher ridership has come at a price, more crowded trains and congested stations have led to greater station dwell times and slower service. This has effectively reduced the capacity of the subways and resulted in ever greater delays. Nowhere is this more apparent than on the Lexington Avenue line where station crowding has reached levels that prevent the southbound express track from reaching its full throughput of 29 trains per hour (tph). At the Grand Central Station dwell times of a minute are commonly observed in the peak period, twice what would be required to achieve maximum throughput. These delays ripple throughout the southbound express track allowing only 26 tph to pass Grand Central in the peak, an approximately 10 percent reduction from the track's full throughput.[14] The delays also continue to accrue over the course of a train's run down the line, travel times from 125th Street to Bowling Green are 9 minutes longer during the very congested peak period than during the off-peak.[15]

Excessive station dwells can be caused by infrequent service and a station's physical constraints – inadequate platform capacity and vertical circulation elements, among others. The system

11 Except in the case of station time (ST) signals, which allows trains to close in at stations with a speed restriction, grade time (GT) signals, which enforces speed restrictions at grades or curves, or home signals, double-headed signals located at interlockings used to control merging and diverging traffic. All three signal types can have aspects that indicate red or yellow when a train is not occupying the blocks ahead.

12 The Lexington Avenue line (includes all riders on #4, 5 and 6) carries more riders daily than the Chicago 'L' and Washington D.C. Metro systems combined.

13 Permanent Citizens Advisory Committee to the MTA. "The Road Back: A Historic Review of the MTA Capital Program." May 2012. Web. 14 Oct 2013. <http://www.pcac.org/wp-content/uploads/2013/01/The-Road-Back-Final.pdf>.

14 Metropolitan Transportation Authority. Second Avenue Subway Supplemental Draft Environmental Statement. 2003. Web. <http://www.mta.info/capconstr/sas/documents/sdeis/chapter5b.pdf>.

15 Metropolitan Transportation Authority. Second Avenue Subway Final Design Application. 2004. Web. <http://www.fta.dot.gov/documents/SAS_make_the_case.pdf>

is also plagued by other bottlenecks such as tight curves and inefficient terminals and junctions. Combined, these physical attributes constrain the upper limit capacity of the system and make it less reliable.

All parts of the New York City subway are not equal. Many metros predominately operate single lines that host just one service along their entire length. This is not the case in New York. Our subway is similar to a tree, with many branches connecting to a trunk. The subway's trunk lines, mostly in Manhattan, are straining under the pressure of multiple services. Whereas, the branch lines on the outer edges of the system are more lightly used. However, there are some lines in the system that have untapped capacity under the current fixed-block system.

Table 2 lists the maximum and scheduled capacity for the lines that serve the central business district of Manhattan, at locations within the core or major entry points. It shows that the untapped capacity amounts to only 20 trains on six lines, mostly on the Jamaica line (J, M, Z) and the 7th Avenue/Broadway local (#1), and to a lesser extent on the Canarsie line (L). Under the MTA's existing loading guidelines this would equate to only an additional 17,000 riders during the peak period. Eight of the thirteen lines are operating at maximum capacity.

The interwoven configuration of the various lines can also place limits on some of this available excess capacity or, conversely, understate the underutilization of some lines. For example, the A train south of 59th Street runs exclusively on its own express tracks to Canal Street in Lower Manhattan. Yet, its capacity is limited to 16 tph (current service) per track because it must share the express track along Central Park West north of Columbus Circle with the D (10 tph) until they both diverge again at 145th Street, and later with the C (7 tph) on a segment of track south of Canal Street, including the Fulton Street Tunnel, to Downtown Brooklyn before finally returning to an exclusive set of express tracks for its run to the Rockaways. This places limitations on how much additional service can be added unless headways can be further lowered.

In addition, growing ridership will continue to put pressure on the system, especially at major subway hubs that typically connect multiple services and other locations in the system where trains reach their heaviest loads. The MTA surveys these locations, called peak-load points, several times a year to understand how effectively they are able to deliver scheduled service, most of which are at or near the last station before trains enter the CBD. As subway ridership grows, these locations are likely to take on the features of the Lexington Avenue line, creating capacity limitations and more crowding. This is discussed in greater detail in Chapter 5.

Other Considerations

The capacity constraints imposed by fixed blocks are significant but are not the only operational limitations caused by the existing signal system. Our current system does not allow for bi-directional running and dynamic routing of trains – without this flexibility the system cannot respond as effectively to incidents or schedule frequent service around work windows.

Bi-directional running would allow for trains to run in both directions on a single section of track, which would be helpful for rerouting around work zones during overnight periods. Typically, this is not allowed on most portions of a fixed block system as the signal aspects and block schemes were designed to only handle trains travelling in one direction.[16] As a result, the signal system is unable to properly indicate block availability to trains travelling in the "incorrect" direction.

Dynamic routing of trains allows for trains to adjust their route and reach the same destination (or a new one if required) after having begun their run. In a fixed block system a train's route is set once it begins its run at the origin station of the

Figure 2: Annual Subway Ridership, 1982-2012

(billions of trips)

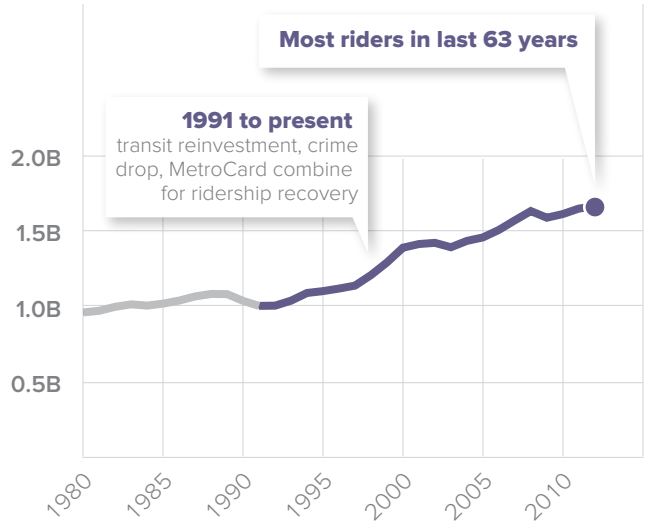


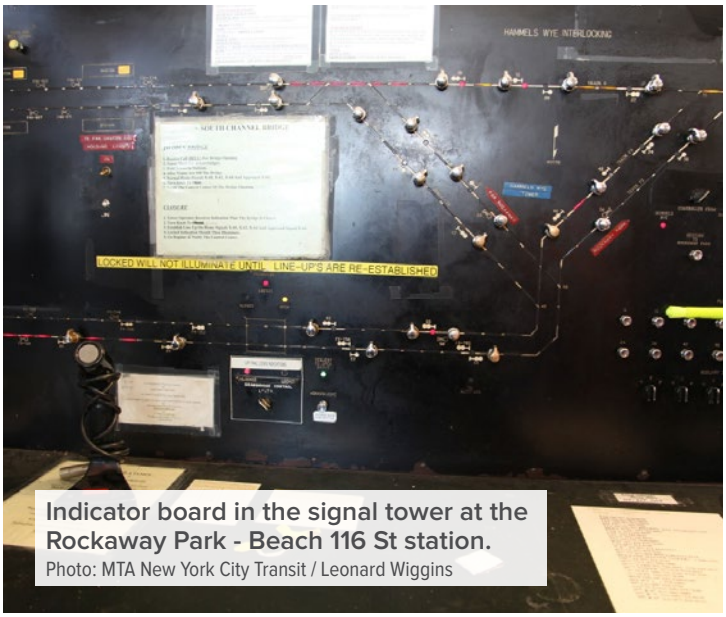
Table 2: Subway Line Capacities: Maximum Throughput vs. Scheduled Service

Line		Max Capacity (tph)	Max Scheduled (tph)	Excess (tph)
1	(66th St./Bway)	24	18	6
2 3	(Times Sq)	23	23	0
4 5	(125th st)	29	29	0
6	(59th St./Lex)	24	24	0
7	(Grand Central)	27	27	0
J Z M	(Williamsburg)	25	19	6
L*	(1st Ave.)	22	19	3
E F	(Qns Blvd)	30	30	0
R	(Whitehall St.)	10	10	0
N Q	(Qboro Plz)	15	15	0
C	(59th St.)	8	7	1
B	(59th St.)	12	10	2
A	(59th St.)	18	18	0
D	(59th St.)	12	10	2
Total				**20**

Source: RPA Analysis and MTA

* CBTC will allow for up to 28tph on the L after improvments to the line's power system and yards are made.

16 Some portions of the New York Subway, such as the center express tracks on the Pelham line, are signaled for bi-directional operation. However, they are operated in a manner that only allows for trains to head in the peak direction when express trains are in operation. Other portions of the subway such as tunnels that may necessitate long stretches of track to be shut down for repairs may be signaled for bi-directional operation. These segments of track operate more like a uni-directional track that allows for changes in direction at pre-determined times; they do not allow for true bi-directionality.



Indicator board in the signal tower at the Rockaway Park - Beach 116 St station.
Photo: MTA New York City Transit / Leonard Wiggins

route. Under the current system the routes and timing of all trains are set weeks or months in advance with the goal of maximizing capacity while avoiding conflicts.[17] If the need for a train to be re-routed arises, for example switching a local train to the express track to bypass a disabled train, the original routes and timings must be manually adjusted by dispatchers. They must try to minimize any conflicts to prevent delays from propagating throughout the system. This is an inefficient approach; in most cases dispatchers receive information on incidents after they already occur and only then can they react. It is difficult for even the most experienced dispatchers to foresee potential delays and adjust train schedules and routes accordingly. Unfortunately, there is only so much that can be done to make this operation more efficient as fixed block systems do not allow for the determining of the precise location of trains and centralized automated control of train traffic nor can they dynamically predict conflicts or automatically select the "best" re-routing solution. The MTA has started to address this problem by overlaying a system called Automatic Train Supervision (ATS) on the existing signal system on the A division (IRT) of the subway. ATS actively tracks trains throughout the A division and displays this information in a centralized location, the Railroad Control Center (RCC), allowing dispatchers to monitor the system in real time. ATS also allows for the RCC to control the A division interlockings from a single location letting dispatchers identify and correct conflicts on the fly without having to manually call multiple interlocking towers.

Despite the operational flexibilities provided by ATS, the subway's maximum capacity is still limited by its fixed block nature as well other track-geometry, station and terminal constraints. This, in particular, is a growing problem as ridership continues to increase in the off-peak and overnight periods. In fact, this is where the majority of the increase has materialized in recent years.

17 D'Ariano, Andrea. "Improving Real-Time Train Dispatching: Models, Algorithms and Applications." The Netherlands TRAIL Research School, n.d. Web. 22 Oct 2013. <http://www.nextgenerationinfrastructures.eu/images/Thesis_dAriano.pdf>.

Struggling to Operate a 24/7 Subway

Unlike most metro systems, the New York City subway never closes. The signal system must function 24 hours a day, 7 days a week, 365 days a year. As shown in Table 3, from 2007-2011 the system has seen average weekday off-peak and overnight ridership increase by 7.4 percent while peak ridership has increased by 2.2 percent.[18] These additional off-peak riders account for almost three-quarters of the ridership gain over this period. Unfortunately, many of these off-peak trips coincide with the work windows in which the MTA conducts most of its maintenance on the underground lines from midnight to 5am and 10am to 3pm on surface lines, making it hard for the agency to provide frequent and reliable service to satisfy growing demand while still ensuring that there is sufficient time to repair and maintain the subway. This is the reality of a 24/7 system.

The recent rise in off-peak ridership has not been accompanied by a similar increase in service frequency. Despite the 7.4 percent increase in average weekday off-peak ridership from 2007-2011 there has only been a 3.2 percent increase in off-peak train frequency over the same time period.[19] Off-peak passengers are confronted with infrequent service and increasingly more crowded trains, yet relieving these conditions is complicated by the need to maintain the system. In certain corridors, the need to accommodate maintenance and capital work during off-peak hours limits the maximum number of trains that can be operated to less than the peak period maximum. On multiple track lines, for instance, all scheduled off-peak service must be able to operate on a single track in each direction, which reduces capacity, especially once non-standard merging and diverging movements across interlockings are taken into account.

The MTA is struggling to meet this demand while simultaneously finding time to repair its track structures and wayside equipment. One strategy it has recently explored to balance these two goals is the FASTRACK maintenance program. FASTRACK completely suspends service over a section of the system from 10pm to 5am Monday through Friday. This gives track workers seven uninterrupted hours for four straight nights to perform track maintenance and repairs without having to constantly break down and set up their equipment to allow trains to pass.

While FASTRACK can be a major inconvenience to those using the affected lines on weeknights, it increases the efficiency of maintenance operations for the system as a whole. This is shown by a recent FASTRACK closure on the Broadway BMT line in Manhattan which allowed for 98,725 pounds of scrap to be removed, 33 sections of rails to be replaced, and 18 switches to be serviced plus other miscellaneous tasks in just one week instead of over the course of many weeks or months.[20] FASTRACK also allows the MTA to perform maintenance

18 MTA.

19 The percent change in off-peak train frequency was calculated using NYMTC inbound/outbound Hub-Bound Counts for a typical fall workday. These counts include all subway lines except for the three shuttles and G train. However, these lines account for a relatively small portion of the trains traveling on throughout the system on a given day.

20 "Second Performance Completed On the Great White Way." Metropolitan Transportation Authority. Web. 22 Oct 2013. <http://web.mta.info/nyct/service/fastrack/NQR_04_19.html>.

Table 3: Average Weekday Ridership Change, 2007-2011

	7-10am peak	4-7pm peak	Total Peak	10am-4pm mid day	7pm-7am night	Total Off Peak	Daily Total
2007	1,263,230	1,280,336	2,543,567	1,390,426	1,108,271	2,498,696	**5,042,263**
2011	1,275,015	1,324,878	2,599,893	1,491,548	1,192,854	2,684,402	**5,284,295**
Difference	11,784	44,542	56,326	101,122	84,584	185,706	**242,032**
Percent Change	**0.9%**	**3.5%**	**2.2%**	**7.3%**	**7.6%**	**7.4%**	**4.8%**

Source: MTA

Table 4: Average Weekend Ridership Change, 2007-2011

	Morning	Evening	Mid Day	Late Night	Weekend Total
2007	569,738	1,124,450	1,944,690	1,489,894	**5,128,772**
2011	607,287	1,194,919	2,056,844	1,638,000	**5,497,050**
Difference	37,549	70,469	112,154	148,106	**368,278**
Percent Change	**6.6%**	**6.3%**	**5.8%**	**9.9%**	**7.2%**

Source: MTA

that would have otherwise taken place during the weekends – another time period in which the MTA has experienced a large increase in demand. As shown in Table 4, average weekend ridership has increased by 7.2 percent from 2007-2011 compared to 4.8 percent on an average weekday. Again, much of this increase has been concentrated over the night, a time when the MTA tries to do most of its maintenance.

The MTA has tried to reduce the passenger delays caused by FASTRACK by confining the program to lines that are paralleled closely by other services (e.g. the West Side IRT and IND), allowing riders to still use the subway to get near their destination. However, as the program achieves its maintenance goals at these locations it will necessarily have to move to lines in the outer boroughs which are relatively isolated and which will require alternative surface transit services.

Despite the disruptive nature to some passengers FASTRACK allows the MTA to optimize its maintenance programs, freeing up some off-peak capacity on non-FASTRACK lines and reducing the amount of passenger delays across the system as a whole. While this allows for more frequent service, rising operating costs will place limits on the amount of service that the MTA can afford to provide.

Aging and Vulnerable Signals = Rising Costs

Rising costs can be attributed to equipment and labor. Older mechanical equipment requires more labor intensive maintenance and operations, including drivers, conductors and trackside signal maintainers. The subway today is a very manual/hands-on operation.

All of the signal aspects, switches, brake stops, relays and other components of the system are operated using electro-mechanical equipment. Because much of the signaling system was installed during the first decades of the 20th century much of this equipment must be custom ordered or salvaged from old parts to maintain compatibility with other system components. Even the parts of the system that have been modernized still use mechanical parts that require labor and time intensive maintenance. Some components (e.g. cylindrical relays) are out of production, requiring the agency to invest in the resources to rebuild them itself. Difficulty obtaining replacement equipment magnifies the delays and outages associated with catastrophic events such as the 2005 relay room fire that shut down the A and C services in Manhattan or the flooding from Hurricane Sandy since NYCT is unable to maintain an adequate inventory of spare parts to prepare for such events. These events have also revealed the tremendous amount of damage that can be done to electro-mechanical signal equipment when exposed to the elements. More than a year after Hurricane Sandy, the MTA is still replacing damaged signals throughout the system and has had to close down the Montague tunnel, running the R service in two segments for over a year to repair and water-proof signal equipment and other damaged tunnel infrastructure. As more frequent extreme weather events continue to test the resiliency and redundancy of the subway and its infrastructure, conventional technology has proven to be vulnerable to flooding – especially when exposed to salt water.

The bulk of the cost to maintain this antiquated system is labor. Currently, it costs $168,000 per track mile per year for signal maintenance, inspection, and repairs. Of this $168,000, $161,000 is spent on labor and only $7,000 is spent on materials.[21] This massive disparity between materials and labor costs occurs because every piece of a fixed-block signal system must be repaired, maintained, or replaced by hand, a very labor-intensive process. To reach the signal equipment workers must walk the tracks to the location of the equipment in question and then begin their work, many times with active train lines only yards away. Sometimes, this work is simply greasing an aging switch or testing a relay, but the age of the system requires tasks like these to be performed frequently. Additionally, much of this work is done during overnight periods and the weekends, qualifying many workers for overtime pay.[22] All of these factors add significant cost, resulting in a subway system that's labor intensive and expensive to keep up.

Running trains in a fixed block system is also labor-intensive. The subway requires a train operator to drive the train and interpret signals, and a conductor for almost every revenue service

21 MTA.

22 DiNapoli, Thomas P. "Metropolitan Transportation Authority Management and Control of Employee Overtime Costs." Office of the New York State Comptroller. 2009. Web. 14 Oct 2013. <http://osc.state.ny.us/audits/allaudits/093010/09s88.pdf>

train, per the MTA's existing labor agreement, to operate the doors, make announcements, and other necessary tasks.

Table 5: Number and Wages of Subway Operators and Conductors, 2013

Train Position	Full-Time Employees (2013)	Average Wage (2013)
Operator	3,008	$81,342
Conductor	2,245	$63,890

Source: MTA.

Train drivers and conductors are skilled workers with an average annual salary for a train driver of $81,342 and $63,890 for a conductor.[23] However, these salary levels do not include the long-term liabilities of healthcare and defined pension benefits that all NYCT employees receive. Healthcare, pension, Other Post-Employment Benefits (OPEB), and other fringe benefit costs have risen a combined 54 percent over the past half decade and now consume just under 40 percent of the NYCT 's labor costs.[24] NYCT projects its pension, healthcare, OPEB, and other fringe costs to increase an additional 23 percent by 2016, consuming an even greater share of the operating budget and putting considerable pressure on the MTA to raise sufficient funds to operate and maintain existing service levels. [25, 26]

Work rules and crew size have been a major point of contention between the MTA and the unions representing transit workers. The MTA began planning in the 1980's to transform the system to one person train operations (OPTO) from the two man crews we have today, but the unions have made the retention of two-man crews a priority in labor negotiations. Unlike New York, nearly every other comparable metro system in the world, including Chicago, London, Paris, and Singapore, operates with either one driver or none at all.

Under OPTO rules, the conductor position which is responsible for opening/closing the doors, making announcements, and checking the platform would be eliminated. Instead, the train operator would assume these responsibilities, in most instances with the aid of closed-circuit television (CCTV) cameras to monitor blind spots. The MTA currently operates all shuttle trains and the G train under OPTO rules. However, past efforts to expand OPTO to the L and other services were challenged in arbitration by the Transport Workers Union (TWU) in 2005. The arbitrator ruled that converting the L to OPTO would violate a 1994 labor agreement between the two organizations. This agreement set criteria that stated OPTO could only be implemented on services that run trains less than 300 feet long (or about four cars), have low passenger volumes, and only during non-peak periods.[27] Unless the MTA and union reach a new agreement the agency will be unable to implement OPTO across more than a handful of places in its system.

The subway's fixed-block system has performed well over a century, but its capacity limitations, lack of flexibility and rising costs are becoming a liability. As time goes on, the effort and cost to operate and maintain the aging signal system will continue to increase and at some point will become unsustainable.

A solution to these problems that plague the agency can be found in modern automated train technologies, specifically automatic train operation and communications based train control.

A Call to Action: The Moving-Block Solution

On August 28, 1991 a Lexington Avenue line train operator under the influence of alcohol fell asleep at the controls as his Woodlawn express 4 train was approaching the 14th Street Union Square station. The express had been scheduled to be switched to the local track because of maintenance, requiring the train to pass over a switch with a restricted speed limit of 10 mph. Instead, the train entered the switch at up to five times that speed causing the subway cars to derail, resulting in five deaths and 215 injuries. This derailment occurred despite the fact that the train triggered the train stop as it approached the switch which engaged the train's emergency brakes. However, because the train was traveling at such a high speed it still failed to stop before entering the switch. [28] This incident motivated the agency to seriously explore modern signaling technologies for the first time, culminating in a 1994 business case for automatic train operations and communications based train control.

Automatic train operation (ATO) has existed since the 1960s, with some of the earliest examples found in the United States – the Washington D.C. Metro (1976) and San Francisco's Bay Area Rapid Transit (BART) system (1972). The first automatic heavy rail line in the United States was actually the Times Square shuttle which was automated from 1960-1964 using a technology similar to one used later by BART.[29] The earlier systems were capable of automated operation but they still relied on a fixed block signal system to track trains throughout the network. These systems operated in the same manner as the one in the New York City Subway but are overlaid with two additional technologies, Automatic Train Supervision (ATS) and Automatic Train Protection (ATP). ATS is a wayside system which controls train routing and scheduling by tracking individual trains using additional wayside equipment throughout the metro and adjusting switches or interlockings to properly route the trains. The system also allows for a centralized control center to monitor the location of all trains in the system.[30] ATP is the system which prevents trains from operating in an unsafe manner, using speed codes transmitted through the tracks to control train speed. These codes are set based on block occupancy and interlocking status so that trains are slowed or stopped as they

23 Citizens Budget Commission. "MTA - TWU Wage Negotiations: A "Fair Increase" Will Not Increase Fares." January 2012, Web. 14 Oct 2013.

24 Metropolitan Transportation Authority. MTA 2013 Adopted Budget February Financial Plan 2013 – 2016. 2013. Web. < http://www.mta.info/mta/budget/pdf/Adopted_Budget_Feb_Financial_Plan2013-16.pdf>

25 Metropolitan Transportation Authority. MTA 2013 Adopted Budget February Financial Plan 2013 – 2016. 2013. Web. < http://www.mta.info/mta/budget/pdf/Adopted_Budget_Feb_Financial_Plan2013-16.pdf>

26 Numbers include all NYCT employees such as bus operators.

27 Ramirez, Anthony. "Train Conductors Must Stay, Arbitrator Says." New York Times 11 February 2006. Web. 22 Oct. 2013. <http://query.nytimes.com/gst/fullpage.html?res=9D02E1DA153EF932A25751C0A9609C8B63&smid=pl-share>.

28 McFadden, Robert. "Catastrophe Under Union Square; Crash on the Lexington IRT: Motorman's Run to Disaster." *New York Times* 01 September 1991. Web. 22 Oct. 2013. <http://www.nytimes.com/1991/09/01/nyregion/catastrophe-under-union-square-crash-lexington-irt-motorman-s-run-disaster.html?pagewanted=all&src=pm>.

29 An unrelated fire in the GCT station of the line consumed the automated train and the service was never restarted.

30 NYCT has just completed the installation of ATS on the A-Division (IRT) of the subway.

Photo: Jackson Whitmore

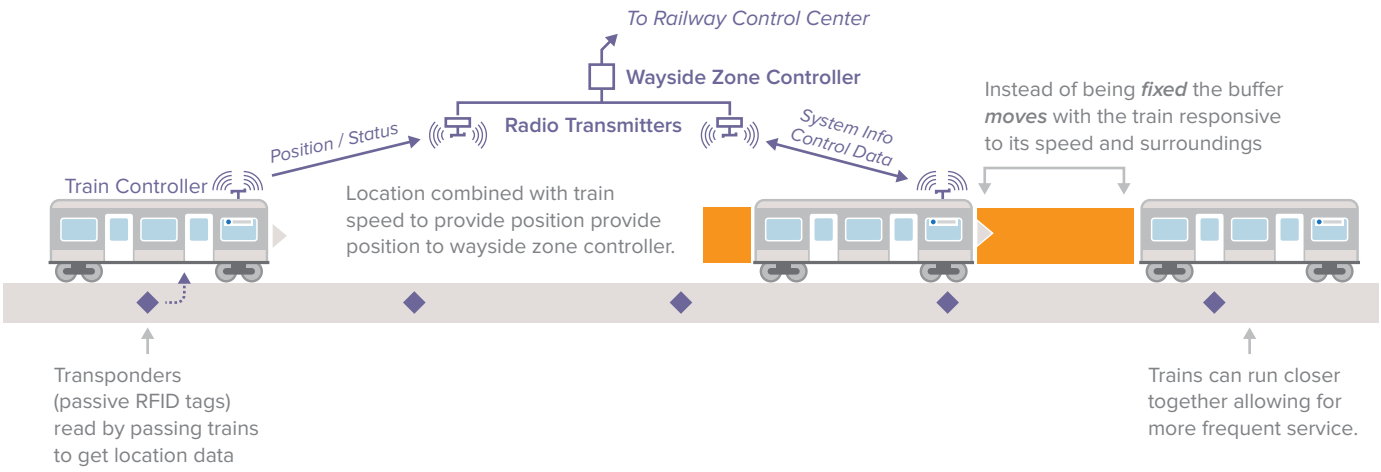
approach occupied blocks or interlockings that are not yet set. [31] Combined together, these two systems enable the signal system to track, schedule, and route trains through the network while simultaneously ensuring that the trains are properly spaced. While these earlier ATO overlays provided some operational efficiencies, they were hamstrung by the fact that they still used fixed blocks and therefore did not overcome the inefficiencies that are inherent to such signal systems.

Since these early systems, a more advanced technology for ATO has been developed. Higher-speed computers, fiber-optic data communications, and more efficient algorithms have led to new signal technologies which completely replace fixed blocks. These systems are referred to as communications-based train control (CBTC). CBTC can completely replace or significantly reduce the number of fixed track circuits and expand the purview of the signaling to include the vehicles as well. It's a paradigm shift that addresses many of the constraints that inhibit the subway system we have today as well as the safety issues present in the first generation ATO systems. CBTC will be discussed more fully in Chapter 2.

31 National Transportation Safety Board. Collision of Two Washington Metropolitan Area Transit Authority Metrorail Trains Near Fort Totten Station. 2010. Web. <http://www.ntsb.gov/doclib/reports/2010/RAR1002.pdf>.

What Is Moving Block and What Are the Benefits?

Figure 3: Diagram of a Moving Block (CBTC) Signal System



The reliability and capacity of our current signaling system will be strained as it continues to age and the city and region grow. Over a quarter of the signaling system is not in a state of good repair (SOGR), with some parts being over 80 years old[32]. This aging system will need to absorb many of the workers commuting to 900,000 additional jobs that the city is projected to add between 2010 and 2030, an 18 percent increase from 4.6 million to 5.5 million.[33]

The subway must be able to reliably serve us and future generations, this fact is undisputable. A modern, moving-block, signaling system is part of an essential set of long-term investments that's critical to accomplishing this goal. It unchains trains from their fixed blocks and instead surrounds them in a protective buffer that moves with the train, shrinking and expanding based on the train's speed and the surrounding environment.

Moving Block = CBTC

Communications-Based Train Control (CBTC) is a moving-block signaling system that consists of computerized signal equipment installed along the trackside and on subway trains – all controlled by millions of lines of complex software. "Communications-Based..." refers to the constant two-way communication between the trains and the trackside equipment, which enables the system to precisely track the trains and maintain a safe separation distance based on the performance of the vehicle and its operating speed. CBTC equipment consists of several major components: on the trackside there are transponders, radios[34] and zone controllers and onboard the trains there are radios, vehicle controllers and speed sensors. All these subsystems have redundant components. The most dramatic change between moving block and fixed block systems is the inclusion of the vehicle as part of the signaling system. Under CBTC train cars are equally as critical as trackside equipment.

The Cars

CBTC equipped trains can operate automatically, with a driver's role typically limited to monitoring the health of the vehicle, operating the doors and visually inspecting the tracks ahead for obstructions[35]. Several pieces of equipment must be installed on the cars to accomplish this. The first is a set of components to precisely measure the speed and location of the train. The second is a radio which receives information from the wayside about the location and track conditions ahead of the train including the status of any remaining fixed-block signals, the position of switches and any trains ahead. It also transmits information to

32 Metropolitan Transportation Authority. MTA Twenty-Year Capital Needs Assessment 2015-2034. 2013. Print.

33 NYMTC 2040 Social Economic Demographic Projections

34 The "radio" is just one method to achieve the continuous two-way communication between vehicle and trackside that is fundamental to the nature of CBTC. There are, and have been, other methods implemented to achieve this continuous communication in other CBTC applications, such as inductive loop communication. The move to radio implementation was driven by the higher maintenance costs associated with continuous wire-based implementations.

35 CBTC-equipped trains can operate in two modes, automatically in Automatic Train Operation, (or ATO) and manually in Automatic Train Protection Mode, or ATPM, under the direction of the CBTC signal system. To maintain the train operators' skills NYCT mandates at least one off-peak trip a day be completed in manual mode.

the wayside on the train's location, speed and other telemetry. The third component is an onboard computer that functions as the "brain" of the car and uses the information received from the first two components and an onboard database of the line (grades, curves, platform locations, speed restrictions, wayside equipment locations, etc.) to safely determine how far and how fast it can go. The onboard computer is able to interpret this information and make decisions at a much faster rate and more accurately than a human operator ever could, eliminating human error, one of the most common causes of train accidents[36].

The Tracks, Wayside

The wayside is the space along or adjacent (relay rooms) to the tracks where CBTC components must be installed. There are three wayside components – transponders, radios and zone controllers. Each is critical to the operation of CBTC and its ability to communicate with the cars and the control center.

Transponders are installed every 500 feet or so along the track and act as beacons, similar to a milepost, marking a fixed geographic location in the system. They are passive devices and are only activated when a CBTC-equipped train runs over it, requiring no power or communication hook-ups.

To communicate with the cars, wayside radios must also to be installed. The radios are placed in cases along the track approximately every 2,000 feet. Each radio case has to be powered and serially connected together using a fiber optic communications cable. The radio network communicates the location of each train to a central rail control center and the zone controller, ensuring that the central control knows exactly where each train is and every train knows exactly where it is in the system.

Zone controllers are the final piece of wayside equipment, typically installed in relay rooms to interface with legacy fixed-block signals and interlocking equipment. They pool the status of the fixed-block signals and switches/interlockings and communicate this information to each train in its "zone" of responsibility. The zone controller and the trains are in constant communication, with each zone controller essentially having a map of all the trains in its territory. It also communicates with the central rail control center and can enforce temporary speed restrictions on trains in its zone, such as those required for work zones to ensure the safety of the workers along the tracks.

As the subway transitions to the new generation of interlockings – solid-state devices rather than relays – the zone controllers would no longer have to be placed in relay rooms. Instead, it would be possible to relocate the zone controllers to a central facility or other better suited locations. This could expedite troubleshooting problems with this critical piece of hardware and remove it from the harsher environment (heat and steel dust) of the subway tunnels and future Sandy-like events. The current migration to solid state interlockings has the added benefit of removing more electromechanical equipment, which requires more frequent maintenance and active inspections. Zone controllers are also capable of directly controlling the interlockings, which would further eliminate equipment and streamline operations.[37]

The Control Center

CBTC centralizes the monitoring and operation of metros and requires a control facility to manage the system. In some metros there are operations control centers for every line and in others a singular operating theater for the entire network. The New York City Transit's Rail Control Center was built to consolidate monitoring and interlocking control as part of the ATS project for the entire subway system. Today, only a third of the network is controlled from this facility. This theater is where the information from each CBTC sub-system would feed into to be analyzed, collected, and stored for later service analysis or real-time transmission to the public over the internet. Dispatchers would monitor the health of the system and trains from behind their desks, and while the system would typically operate itself based on a pre-determined schedule and correcting for incidents as required, the dispatchers could override it if required.

Benefits of a CBTC System

CBTC is transformative. It will make the subway safer, increase its capacity and provide greater flexibility and resiliency. CBTC will improve customer information and can significantly reduce costs. Most importantly, CBTC will create a more reliable and efficient subway system.

Safe and Redundant

All mainline tracks and subway cars are in a state of good repair, reducing the likelihood of derailments or vehicle mechanical failures. And while the fixed-block signaling system is outmoded and in some places very old, the train stops are designed to spring to the upright position if a track circuit is broken from a loss of

36 Federal Railroad Administration. Office of Safety Analysis. Table 3.01.

37 Interviews with Siemens and Thales technical staff during the course of the study (CY2012-2013) helped to further inform RPA staff on the functional details of the technology.

power or other malfunction. So even though a failure can cause massive delays, they rarely result in a serious accident or injuries. However, the system is not considered completely fail-safe[38] and serious accidents have occurred like the Union Square incident, previously detailed in Chapter 1, which was a major driving force behind the MTA's adoption of CBTC.

If CBTC had been installed at the time, the Union Square tragedy could have been avoided because the system would have been in control of the train, stopping a driver from disobeying speed restrictions in the first place and thus preventing it from attaining a velocity that would allow it to blow through the train stops.

CBTC automatically brakes a train that attempts to exceed the maximum allowed speed that the system has determined is safe for the conditions in which it operates at any given point in time.

CBTC is designed to fail safely in the event of a system malfunction. Any loss of communication between the train and the signal system over a certain time period, typically a few seconds or less, results in the train immediately applying its brakes and coming to a halt.

CBTC hardware and software are also designed to be fully redundant to minimize the possibility of failures affecting the system. The network architecture of CBTC allows for greater flexibility in the location of equipment, increasing opportunities for redundancy. Critical systems can be distributed throughout the operation, greatly reducing the impact of natural disasters or targeted attacks. Every "mission-critical" piece of software or hardware is dually or triply redundant, meaning that were a transponder or section of code to fail, there is an equivalent one ready to take its place.[39] This allows the CBTC system to continue to function normally with no interruption in service or degradation of performance while the failed component is replaced or repaired. Because CBTC systems are actively redundant these transitions occur automatically without the need for human intervention, although the system will still inform maintenance crews of the failure so that it can be remedied. This approach to system design means that even though CBTC systems are designed to be fail-safe, they rarely actually reach the point of failure.

More and Better Use of Capacity

CBTC uses existing track space more efficiently than fixed block regimes, reducing the distance between trains and allowing them to safely run closer together. Conversely, it also actively manages the spacing of trains to curtail bunching and uneven headways (frequency of train service)[40]. When trains bunch headways become irregular and the leading trains in the bunch can become overcrowded. CBTC adjusts train speeds to maintain regular headways and more efficiently spread loads across all trains. These improvements will not only deliver more trains per hour,

Table 6: Maximum Possible Throughput vs. Achieved Throughput by Service

	Trains Per Hour			Headways (in minutes)		
Line	Max	Scheduled (peak)	Diff +/-	Max	Scheduled (peak)	Diff +/-
1	24	18	6	2.5	3.3	0.8
2 3	23	23	0	2.6	2.6	0.0
6	24	24	0	2.5	2.5	0.0
4 5 (LEX)	29	29	0	2.1	2.1	0.0
7	27	27	0	2.2	2.2	0.0
J Z M	25	19	6	2.4	3.2	0.8
L	22	19	3	2.7	3.2	0.4
E F (QBL)	30	30	0	2.0	2.0	0.0
R	10	10	0	6.0	6.0	0.0
N Q	15	15	0	4.0	4.0	0.0
A	18	18	0	3.3	3.3	0.0
B	12	10	2	5.0	6.0	1.0
C	8	7	1	7.5	8.6	1.1
D	12	10	2	5.0	6.0	1.0

Source: MTA

the standard way of measuring capacity, but will also ensure that the capacity now in place is fully utilized.

How CBTC will impact the capacity of the subway is complicated by the system's interconnected nature with services running over multiple physical lines. As discussed in Chapter 1, there are parts of the subway that are congested or limited by their existing fixed-blocked signals that would benefit from additional throughput, but there are others – typically branches in the outer boroughs or parts of the IND – that already have untapped capacity under the existing fixed-block system. Yet, all lines will benefit from the even train spacing, which enables a more reliable service and a greater use of train capacity.

Under ideal conditions CBTC can deliver headways of 90 seconds or less, which equates to 40 or more trains per hour, far greater than the typical throughput of 20-25 trains per hour on the subway today. It has increased capacity on some metros by up to 20 percent when installed across an entire line as seen in implementations on the Milan, Singapore, and Paris metros.[41,42] However, it is unlikely that the New York City subway will see train frequencies much lower than 120 seconds because of physical limitations that constrain throughput. These include sharply curved track geometry, limited vertical circulation and platform capacity at stations, inefficient terminals and other physical bottlenecks, such as the at-grade crossing of the IRT services at Nostrand junction, that restrict train speeds. Today, only three lines, the Lexington Avenue (4,5), Flushing (7) and Queens Blvd (E, F) lines, approach two minute headways and most typically fail to deliver this level of service due to extensive dwell times caused by overcrowding at stations. This is equivalent to 30 trains per hour, which is considered the upper limit of conventional train control systems with no dwell time constraints.[43]

38 "Oversight: Williamsburg Bridge Collision (II)." Council of the City of New York: Committee on Transportation. Web. <http://www.laguardiawagnerarchive.lagcc.cuny.edu/FILES_DOC/Microfilms/05/011/0000/00017/050183/05.011.0000.00017.050183.9.pdf>.

39 Software redundancy is typically more complex than articulated in this description but generally involves two sections of code that give the same outputs for the same inputs but have been written in a different manner to reduce the possibility of a bug manifesting itself in both sections of code.

40 ATS does this to a lesser extent. It can be programmed to manage for a wait assessment by holding trains at stations.

41 Briginshaw, David. "CBTC extends its reach." *International Railway Journal*. 4 Feb 2013: n. page. Web. 22 Oct. 2013. <http://www.railjournal.com/index.php/signalling/cbtc-extends-its-reach.html>.

42 "Facts and figures on Line 1." . Siemens, n.d. Web. <http://www.siemens.com/press/pool/de/feature/2012/infrastructure-cities/mobility-logistics/2012-04-metro-paris/factsheet-driverless-metro-paris-en.pdf>.

43 TRB – Rail Transit Capacity, Chapter 2, pgs. 5-11

Figure 4: CBTC = Greater Operational Flexibility, Including Bi-Directional Running on All Tracks

Table 6, shows the maximum trains and headways possible under the existing fixed-block system for subway services entering the Central Business District, including all but the G and the shuttle services.

It clearly indicates that the 2/3, 6, 4/5, R, N/Q , A and E/F (QBL) are at their maximum capacity, as defined by services with a possible headway decrease of 30 seconds or less, and would benefit from the shorter headways. The 1, 2 and 3 in particular have maximum headways of less than 120 seconds and could see substantial increases in service if its capacity were made equal to the 4, 5, and 6.

Chapter 5 will further explore subway passenger capacity and existing peak-load points, evaluating where the needs are the greatest and where CBTC would have the most impact.

Greater Flexibility

As demand for frequent subway service throughout the day increases, the necessity for greater flexibility becomes even more critical. New York is the city that never sleeps. Nor does the 24-hour a day subway, yet like every mechanical system it requires frequent maintenance. While CBTC itself can obviate the need for some of this maintenance, tracks and structures will always need to be inspected and maintained, requiring a wide berth around work zones and restrictive speed limits to ensure the safety of track workers. Trains travelling through work zones may go no faster than 10mph, 8mph less than the average speed of the subway as a whole and much less than the average speed of the express lines.[44] Because the fixed-blocked signaling system is designed to be safe at the maximum attainable speed it significantly loses capacity if restricted to very low speeds. This limits the throughput of the line, curtailing the frequency and reliability of the subway. CBTC can operate efficiently at any speed, more precisely define work zones and offers options, like bi-directional running, that could allow services to route around these work areas or give them a wider berth.

Today, dispatchers must verbally communicate orders to reroute trains, and there are also constraints on how trains can move on the tracks based on the fixed directionality of the existing signaling system. Most of the subway system is unidirectional.[45] CBTC allows trains to safely run in both directions on all tracks. It also removes the requirement for dispatchers to verbally communicate their rerouting orders to train operators[46] and towers during incidents or scheduled track work. Instead, this is done automatically (and almost instantaneously) by the system, with service (trains and interlockings) adjusting in unison throughout the line in response to an incident, high-demand event or scheduled work. CBTC also makes it possible to more rapidly restore normal service after nonrecurring incidents. It accomplishes this by adjusting train speeds and hold times at stations along the line to keep trains separated and prevent the bunching that typically occurs.

Resiliency: Adapting to Climate Change

As the city and region continue to grow, expanding along its shorelines, so does the threat of flooding caused by storms and sea-level rise due to global climate change. It is predicted that extreme storm events will increase in frequency and severity over the coming decades exacerbating the 2.5 foot rise in sea levels predicted for New York City by the 2050s.[47] The subway system must adapt to meet this threat. Flooding events are particularly problematic as mechanical and electrical components of the current system are vulnerable to salt water. This was clearly evident in fall of 2012 when the 9.4 feet storm surge of Superstorm Sandy combined with the high tide, created a 14-foot wall of water that washed over parts of Manhattan and Brooklyn disabling the Coney Island Yard, the world's largest, and flooding seven of the ten East River subway tunnels severely damaging some of them.[48,49,50] In the worst example, the Montague Street Tunnel, one of the last tunnels to be cleared of corrosive salt

44 "Joint Track Safety Force Final Report." . NYCT & TWU Local 100. Web. <http://www.twulocal100.org/sites/twulocal100.org/files/track_safety_task_force_final_0.pdf>.

45 Exceptions are the third express center tracks on some lines and some other critical segments of the subway.

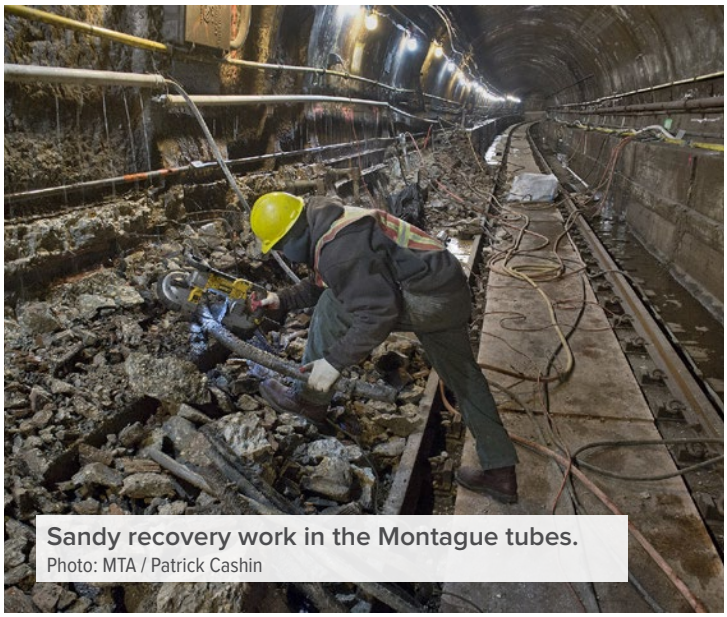
46 Dispatchers still will communicate orders with train operators and conductors as long as the subway is crewed.

47 New York City Panel on Climate Change. Climate Risk Information 2013. 213. Web. <http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf>.

48 Flegenheimer, Matt. "Flooded Tunnels May Keep City's Subway Network Closed for Several Days." New York Times 30 October 2012, n. pg. Web. 22 Oct. 2013. <http://www.nytimes.com/2012/10/31/nyregion/subways-may-be-shut-for-several-days-after-hurricane-sandy.html?smid=pl-share>.

49 New York City Panel on Climate Change. Climate Risk Information 2013. 213. Web. <http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf>.

50 "Sandy's Effects Still Evident at Coney Island Rail Yard." Metropolitan Transportation Authority. Web. <http://new.mta.info/news/2013/01/14/sandys-effects-still-evident-coney-island-rail-yard>.



Sandy recovery work in the Montague tubes.
Photo: MTA / Patrick Cashin

water, has experienced a 120 percent increase in signal related delays. This directly led to the decision to close the tunnel for 14 months to repair all of the damage, likely just one of several closures that will be required over the coming years.

CBTC will not harden the subway against all these threats, but it will allow the system to recover more rapidly from flooding with fewer long-term repercussions. Much of the vital CBTC signaling equipment is modular and can be removed prior to a storm. Some components, like transponders, are completely waterproof, consisting of a circuit board concealed in silicon within a plastic casing. Other CBTC components, like radio boxes, are not and must be removed prior to storms. However, their modular nature makes this process straightforward and restoration relatively quick. All the CBTC trackside components are connected using fiber optic cabling for communications which, unlike the copper cabling used by the fixed-block system, is constructed of a material (glass) that's immune to the effects of salt water corrosion.

Transponders have already proven to be robust in the face of flooding, operating normally after being submerged in salt water for five days when the 14th Street tunnel, which carries the Canarsie line, was flooded during Superstorm Sandy. This is in contrast with many fixed block signal components which had to be completely replaced, repaired, or extensively cleaned to remove salt residue.

Conserving Energy

The skill and experience of subway train drivers varies considerably. Riders experience this variability on a daily basis. Some train rides are smooth, requiring minimal bracing, while others end with a jolt and riders frantically grabbing the closest handrail to steady themselves. This uneven operation is not only unsettling, but also energy inefficient, reduces capacity and is costly. Sharp acceleration consumes energy, while braking hard increases the wear-and-tear on the equipment and generates excess heat. Many of the MTA's newer subway cars do have regenerative braking, which can capture the energy generated during braking. Unfortunately, the energy cannot be fed back into the system or stored, so almost all of it is wasted.

Under CBTC, the variability in how trains operate during each of their runs and with different drivers would almost completely disappear. The train operator would no longer be in charge of "driving" the vehicle, just monitoring. Since track geometry and most track speed restrictions of each line are fixed and do not change, aside from adjustments to ensure separation during incidents or congestion, the train would operate in almost the same manner every time it made its run. CBTC also minimizes the use of hard braking except for emergency situations. Instead, it uses coasting, constant speed adjustment and light braking to maintain its required separation distances and smoother running. This will also save energy.

Better Customer Information Systems and Analytics

CBTC's benefits extend beyond the realm of subway operations which are typically invisible to the average customer – who want their trains to arrive on time and aren't concerned about how this is accomplished. CBTC at its core is a software-driven solution, making it possible to more easily construct interfaces to other software systems and giving the MTA the ability to share real-time subway data with its customers. CBTC would allow the MTA to improve countdown clocks by showing the location of trains along the line in real-time and with greater accuracy than is possible today, letting customers plan their trips with even more precision. Train location data could also be shared with software developers to be used in creative ways to develop innovative applications. For example, an application could use the subway's real-time location to track a friend's train and make it easier to time the meeting location.

CBTC will also enable more detailed service announcements regarding delays and train re-routes. Since CBTC systems maintain a constant state of their "health" it could be possible for the system to indicate to customers the exact reason for a delay, if related to a malfunction of CBTC, and offer an estimated recovery time.

The enormous amount of data generated by a CBTC system would not only be used to inform customers. It would be invaluable for planning and for analytical uses as well. Currently, the ATS systems installed on the A division allows for the MTA to analyze a time series of train movements. CBTC would take this even further and allow planners to constantly monitor the performance of the system and adjust schedules or the CBTC's algorithms to improve performance in real time. Access to this information would also allow for more effective future planning. Weight sensors present on the subway cars could be used to create approximate crowding measures which could be combined with train movement data from the CBTC system to adjust headways to reduce crowding at trouble points. Again, as with the customer information benefits of CBTC the possibilities of how to use the data to plan and manage the subway are extensive.

Lower Costs

CBTC can generate significant operating and maintenance cost savings. Fixed-block signaling systems require an active maintenance regime that is labor intensive. In 2012, over 90 percent ($105.6 million) of the MTA signal maintenance costs were ascribed to labor.[51] Groups of signal maintainers must walk the

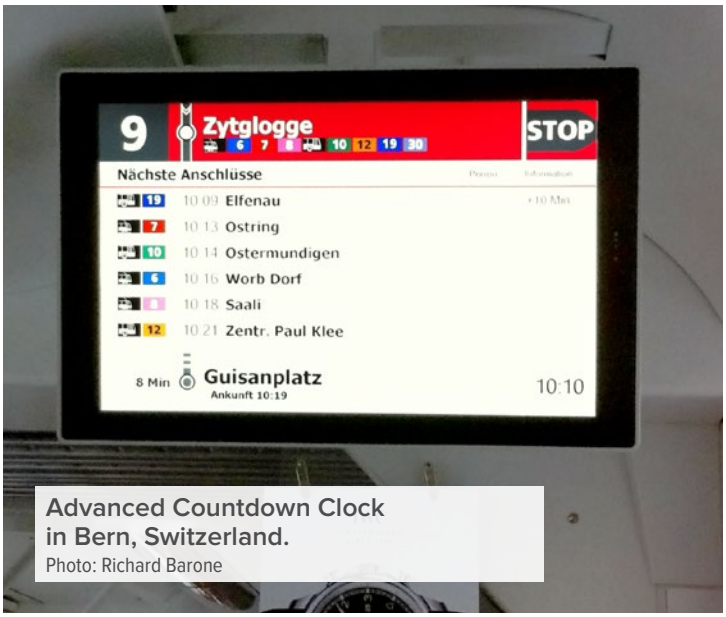
51 MTA

system daily to inspect, visually evaluate and test hundreds of mechanical components (such as relays, motors, circuit controllers, transformers, etc.) to ensure they are in working order. Fixed-block signaling systems have little redundancy and no centralized diagnostics. When a component fails, train service on the affected line(s) grinds to a halt with no warning. Conversely, CBTC signaling systems are designed with complete redundancy and their components are centrally monitored. Maintenance forces at central monitoring stations are alerted when a component's health status is less than optimal. Should a CBTC component fail, the redundant system automatically takes over. This provides time to diagnose the failing component and replace it. CBTC eliminates the need for costly and frequent inspections and greatly reduces the quantity of Auxiliary Wayside System (AWS) signals (which still require maintenance). However, CBTC-equipped rolling stock can offset some of these savings, due to higher capital expense to equip vehicles and increased maintenance costs for the additional onboard components.

Currently, almost all of the subway's trains are operated by a two-man crew, an operator who drives the train and a conductor who operates the doors and makes announcements. New York City is one of only a few systems left in the world that has not adopted one-person-train-operations (OPTO) or unattended (driverless) operations. OPTO can be implemented without CBTC, but the added safety and the control of modern signaling further obviates the need for a second crewmember. Under CBTC the driver's role will be reduced to monitoring the train, not actively operating it except at stations when they will control the dwell time. Thus, it's logical that they should also operate the doors. If the subway transitions to OPTO it could save the MTA millions in wages and benefits. However, the agency might also decide to redeploy these workers at stations to assist customers, a strategy used by many other systems when transitioning to automation.

Further out it might be possible to fully automate the subway, a change analogous to when human operators were removed from elevators. This has already happened at several metros – some older than our subway. However, while the current CBTC system being deployed by the MTA does automate the operation of the trains, other investments would need to be made to support this type of full driverless automation. The CBTC radios do not have the bandwidth (only 1mbps) for remote passenger announcements, a requirement for full driverless operation. This is not an oversight, but the industry standard that separates mission critical train control from other services. Real-time train announcements may be possible through the MTA's existing VHF radio system or planned cellular network installations. It would also be essential to install an intrusion detection system or passenger screen doors – both improve safety and provide other benefits. If trains were transitioned to completely driverless automation the savings could be significant. Table 7 details the annual labor costs for operators and conductors which are just over $100,000 per worker or 15% of the subway's operating budget.

Although the subway's fixed-block signaling systems were designed to last for 50 years, the originally installed components, which were installed over different eras by various vendors, become obsolete in far shorter a time period. The resulting (and



Advanced Countdown Clock in Bern, Switzerland.
Photo: Richard Barone

Table 7: Total Wages for Subway Operators and Conductors (2013)

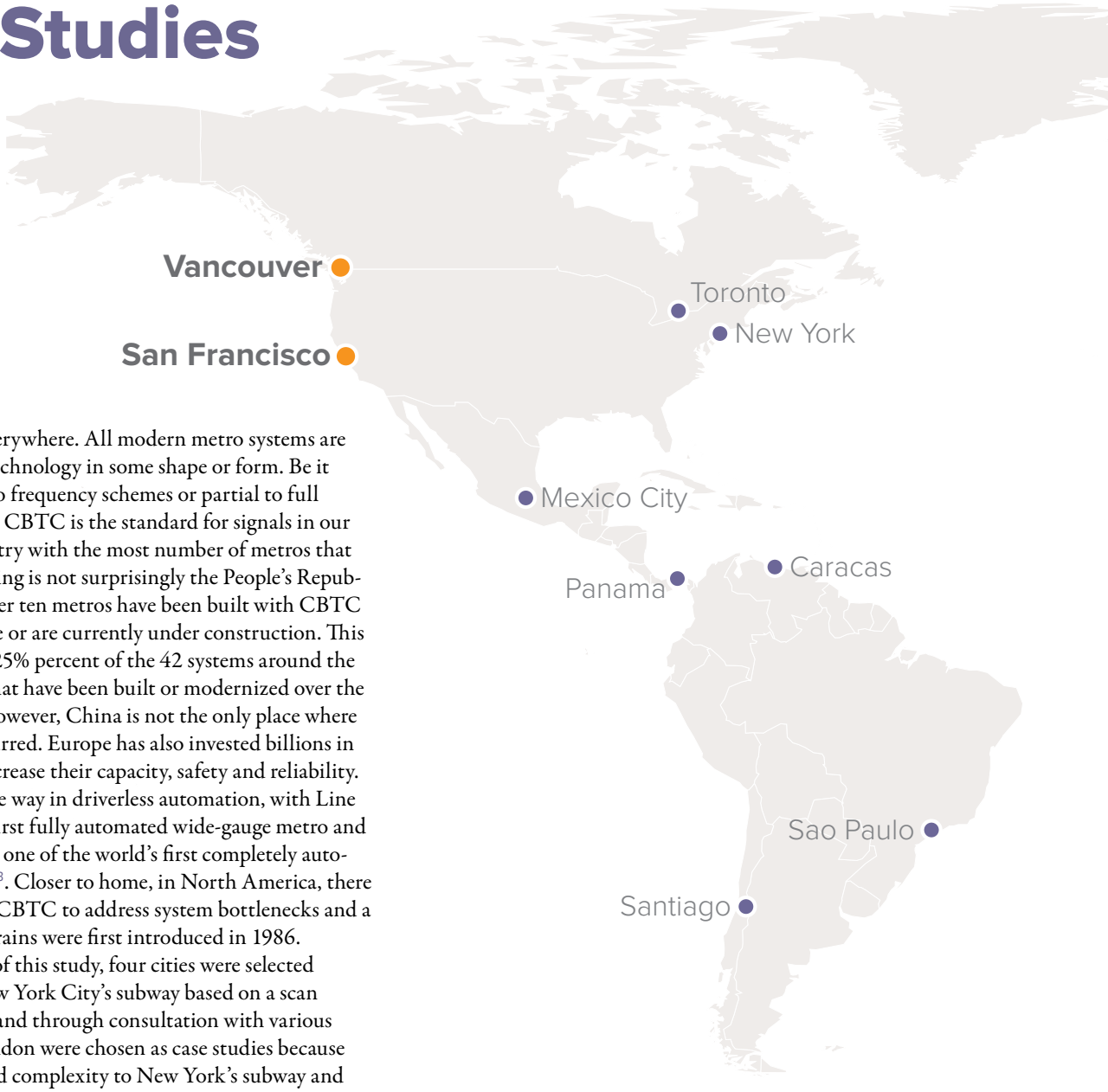
Number of Operator/Conductor Positions	5,253
Total Compensation (Salary+Benefits)	$527,945,452.15
Average Compensation per Worker	$100,503.61

Source: MTA

anticipated) obsolescence requires the MTA to purchase and store vast amounts of spare components and parts. Once the supply of spare components and parts are depleted, the agency's only option is to remanufacture replacements from salvaged components retrieved from the field after a failure, a process which is extremely labor intensive. Most times, it requires three or more salvaged components to create a remanufactured one. Eventually, it becomes impossible for the MTA to create the replacement parts – a serious problem that places the operational integrity of the subway at risk. This problem is ameliorated by CBTC. Its components are designed to last for 25 years and can be upgraded at a much lower cost. Fixed-block signaling systems require signal maintainers to enter the tracks to retrieve and replace components. CBTC signaling systems require circuit boards (and similar type components) to be swapped out in signal rooms, eliminating the need for workers to enter the tracks. In addition, CBTC software is reusable (requiring reconfiguration with the new hardware) and does not need to be completely redeveloped with each hardware upgrade. Fixed-block signaling systems are location specific, whereas, CBTC signaling systems can be consolidated to further reduce the amount of components and number of locations.

CBTC's improvements in safety, reliability and operational flexibility have made it the signal solution of choice for newly built metros around the world and, moreover, many older systems have begun to replace their original fixed block systems with CBTC to realize the benefits and savings offered by CBTC. Chapter 3 will take a look at three systems around the globe that took this approach and one that was built from the ground up to operate solely with CBTC.

National and International Case Studies



CBTC systems are everywhere. All modern metro systems are using moving-block technology in some shape or form. Be it inductive loop or radio frequency schemes or partial to full driverless automation, CBTC is the standard for signals in our modern era. The country with the most number of metros that rely on modern signaling is not surprisingly the People's Republic of China, where over ten metros have been built with CBTC during the past decade or are currently under construction. This represents just under 25% percent of the 42 systems around the world (see Figure 5) that have been built or modernized over the past two decades.[52] However, China is not the only place where investments have occurred. Europe has also invested billions in its older systems to increase their capacity, safety and reliability. Europe has also led the way in driverless automation, with Line 14 in Paris being the first fully automated wide-gauge metro and Copenhagen building one of the world's first completely automated metro systems[53]. Closer to home, in North America, there are examples of using CBTC to address system bottlenecks and a city where driverless trains were first introduced in 1986.

For the purposes of this study, four cities were selected for comparison to New York City's subway based on a scan of available literature and through consultation with various experts. Paris and London were chosen as case studies because of their similar age and complexity to New York's subway and also because both operators are aggressively modernizing their metros. San Francisco's Muni was selected because it installed CBTC to smooth the operation of a part of their system that was congested after the merging of several lines, a problem that our subway faces, and was the only city with a publically available cost-benefit analysis of its CBTC installation. Finally, Vancouver has the oldest continuously operated CBTC system, serving as a case study on the reliability of CBTC over the course of several decades. Table 8 lists some comparative statistics for the four selected systems.

52 Regional Plan Association analysis of existing CBTC installations. Current as of May 2013.
53 Fischer, Elisabeth. "Justifying automation." railway-technology.com. (2011): n. page. Web. 22 Oct. 2013. <http://www.railway-technology.com/features/feature127703/>.

Figure 5: CBTC Systems, a World View

All Installations Are Partial or Complete

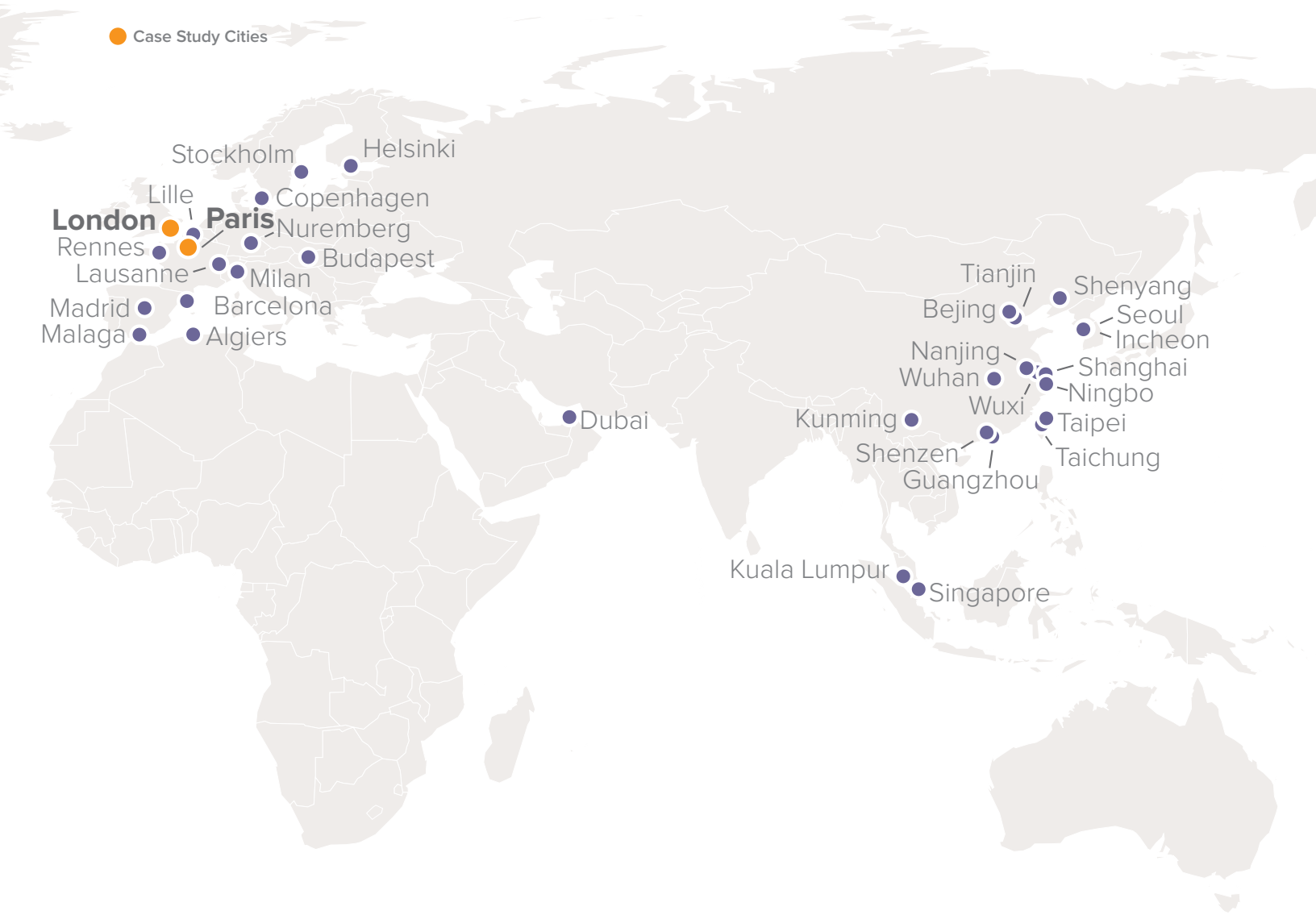


Table 8: Comparative Statistics of Cities Selected for Study

Metro System	CBTC Status	System Opening	System Lines	System Stations	System Length (miles)	System Length (km)
London Underground	Underway	1863	11	270	250	402
Paris Metro	Partial	1900	16	245	136	218.4
San Francisco MUNI Metro Subway*	Complete	1980	6	9	6	9.3
Vancouver SkyTrain	Complete	1986	3	47	43	68.4

Source: Regional Plan Association.

*All San Francisco Muni Metro numbers are for the subway portion of the system

The London Underground
A 150-Year Old Modern Metro

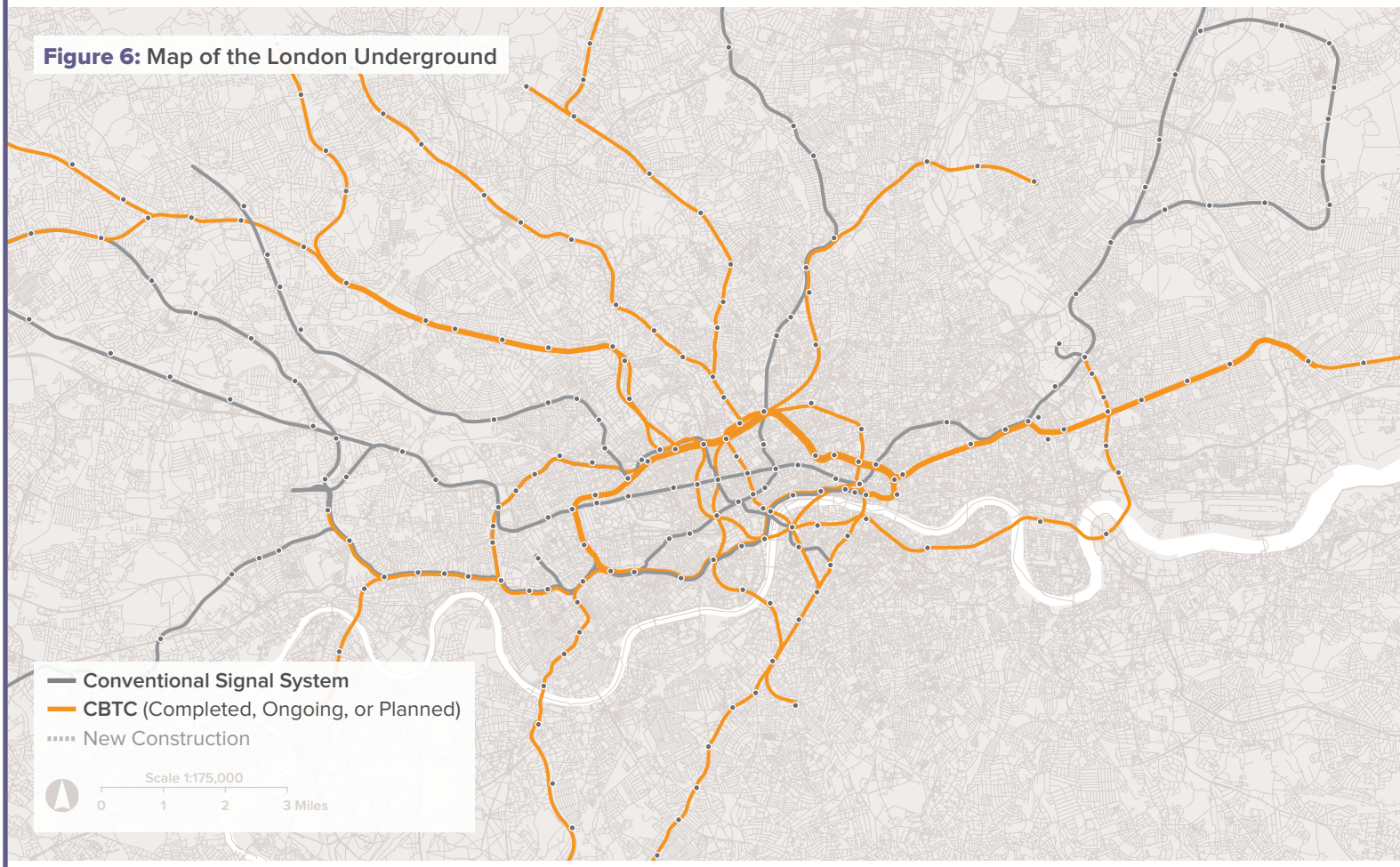
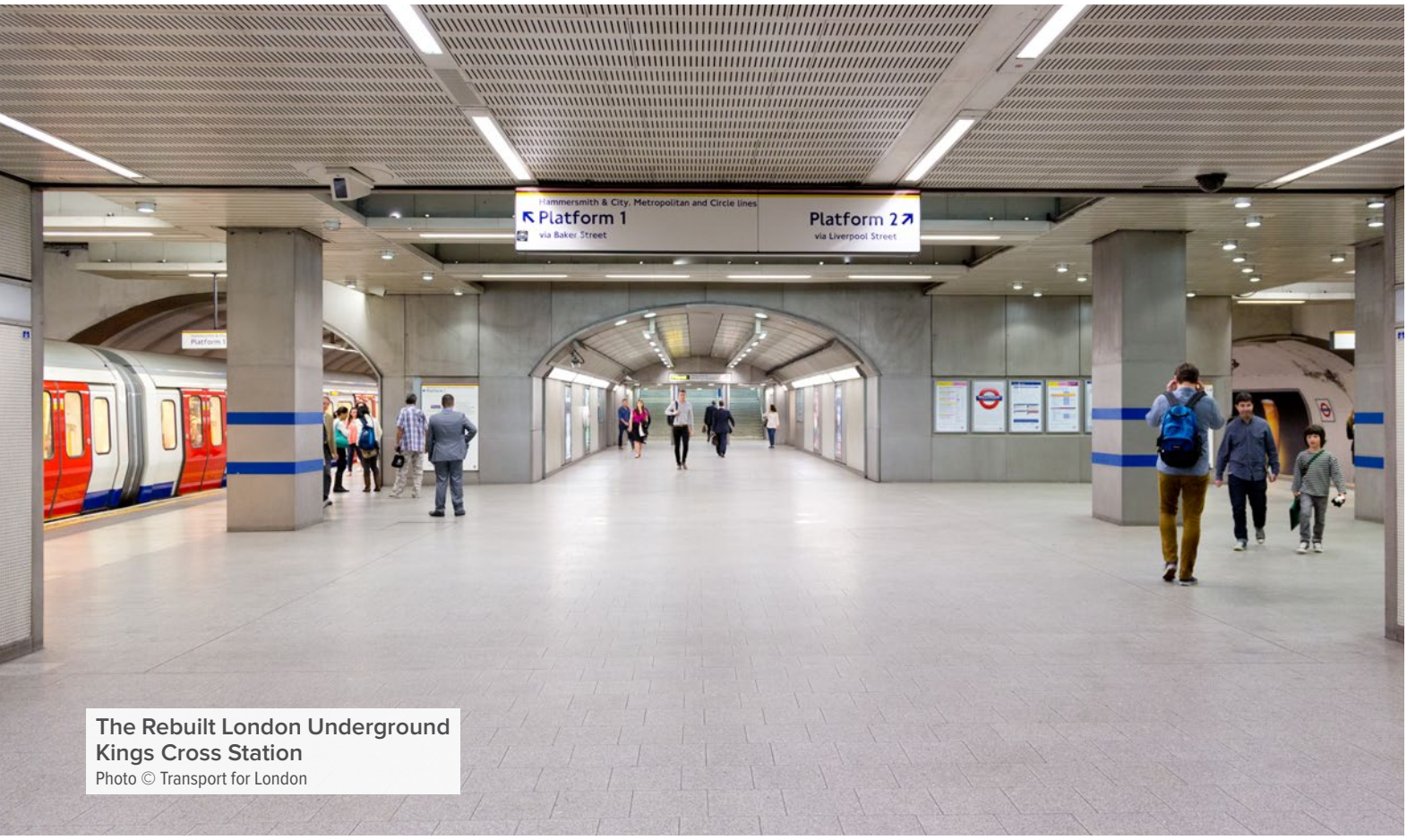


Figure 6: Map of the London Underground

The London Underground (the Tube), the world's first underground railway system, opened in 1863. Yet, the Tube today does not appear rundown or outdated. Its willingness to experiment – including the deployment of simplified signage, the latest in signaling technologies, creative funding methods involving the private sector and governance reforms – have resulted in a system that feels more modern than most metros of its era.

Over the past two decades the London Underground's governance and institutional structures have been upended, moving from public to private operation and then back again to the public sector. The Underground was initially part of a national agency – London Transport. Then its operations and infrastructure were broken up and contracted to the private sector under a public-private partnership in 2003 and between 2009 and 2013 it was returned mostly to public control, this time becoming part of Transport for London, an agency under the direct authority of the Mayor of London. While many have questioned the wisdom of the privatization scheme, there is no doubt that this institutional shake-up helped spur a remarkable transformation of the London Underground from an underinvested railway to a modern industry leader. Significant investments have addressed most infrastructure repair backlogs and system expansion is well underway after decades of disinvestment. Ridership has grown from 400 million annually in the 1980's to over 1.2 billion today, straining the tube's reliability and capacity. In response, the London Underground has undertaken an ambitious Tube Improvement Plan to increase the capacity of the entire system by over 30 percent.[54] The centerpiece of the program is an accelerated roll-out of CBTC to increase the system's throughput, i.e. the rate that trains operate on each line. The program calls for simultaneously installing CBTC on several lines and then on one line every five years, completing all 11 lines by the 2030's. Four lines are currently underway and two more are in early planning stages. Combined they account for almost 70 percent

54 The program also includes longer-trains and other station improvements to increase carrying capacity.



The Rebuilt London Underground Kings Cross Station
Photo © Transport for London

of the Tube system. The initial phase of the program – the first four lines[55] – is estimated to cost $6.9 billion or £4.5 billion, with the remaining lines after 2022 projected to cost twice that amount, for a total of $13.8 billion (£9 billion).

CBTC was first introduced as part of the privatization scheme and is already operational on the Jubilee, Victoria and Waterloo & City lines. The contracts between the London Underground and private infrastructure operators mandated performance targets that could only be reached through the introduction of modern signaling and automatic train operations (ATO)[56]. One of the negative consequences of the privatization scheme, which included three different operating companies granted rights over specific lines, was that each operator used a different vendor and technologies that were incompatible, making maintenance more costly and complex.

London's reasons for investing in CBTC are straightforward: to improve reliability and increase the capacity of the Tube. Unlike New York, its decision was not motivated by safety –there have been no major accidents attributed to signals since 1974[57]. Options to further reduce the size of signal blocks were dismissed early due to the higher maintenance costs and reliability issues – smaller blocks increase the likelihood of metal filings bridging the insulation joints that separate the blocks (track circuits). In fact, London has decided to remove the track circuits/blocks once CBTC is installed. Their reasoning is twofold, maintaining both systems is expensive and they see little benefit in keeping a full backup system or simplifying it to the point where it would have little utility if CBTC did fail. They regularly inspect each line and do not rely on the track circuits to detect breaks, which they see as an imperfect method of detection. Preemptive action through the use of rail inspection vehicles and track workers is preferred, detecting flaws before failure – saving the costs of derailments and associated operational delays.

Operational savings will primarily be found through a reduction in track maintenance costs (labor and materials). The Tube was completely converted to OPTO in the 1980's and its CBTC installation will still retain a driver onboard to monitor the train and operate the doors. It's estimated that the average cost per track-km for maintaining the Tube will be reduced by as much as 18 percent, from $107k (£65k) per track-km to $87k (£53k) per track-km. Up to this point, investments in CBTC have reaped huge benefits for Underground riders; the Victoria line has seen an increase in throughput form 27TPH to 33TPH – a 22 percent increase in capacity – and the Jubilee line now runs a third more trains in the peak and has seen a 22 percent reduction in travel times since its CBTC upgrade. Reliability has also increased on both lines, lost customer hours (a time and geographic weighted measure of reliability) have declined by 40 percent between 2007/2008 and 2011/2012 and it appears that the Underground will likely reach its goal of a further 30 percent improvement by 2015. While these results show the

55 This figure includes upgrades to signals, depots and other infrastructure and the procurement of 191 trains.

56 The Victoria line, constructed in the 1968, was one of the first lines in the world with automatic trains operations. Nevertheless, until this past decade the overwhelming majority of the Tube was still operated manually with little or no automation.

57 This incident was caused by inadequate signal protection at the Northern line's terminus at Moorgate, which allowed a train to overrun the platform and travel an additional 66 feet until it slammed into a solid wall at the end of the tunnel. There were 42 fatalities and 74 injuries, more details are available at (http://www.railwaysarchive.co.uk/documents/DoE_Moorgate1975.pdf), the 1975 accident report prepared by the Department of Environment.

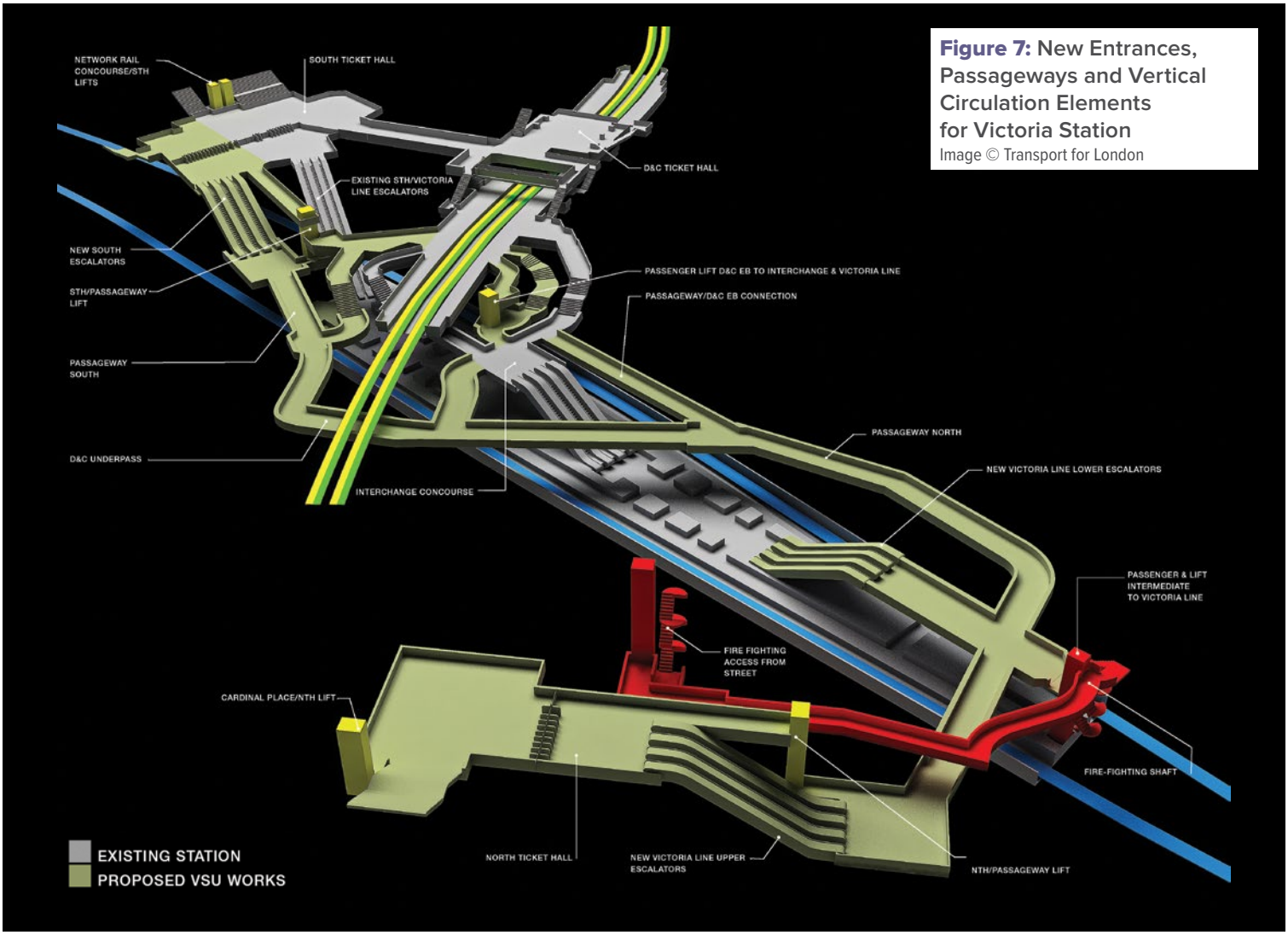


Figure 7: New Entrances, Passageways and Vertical Circulation Elements for Victoria Station
Image © Transport for London

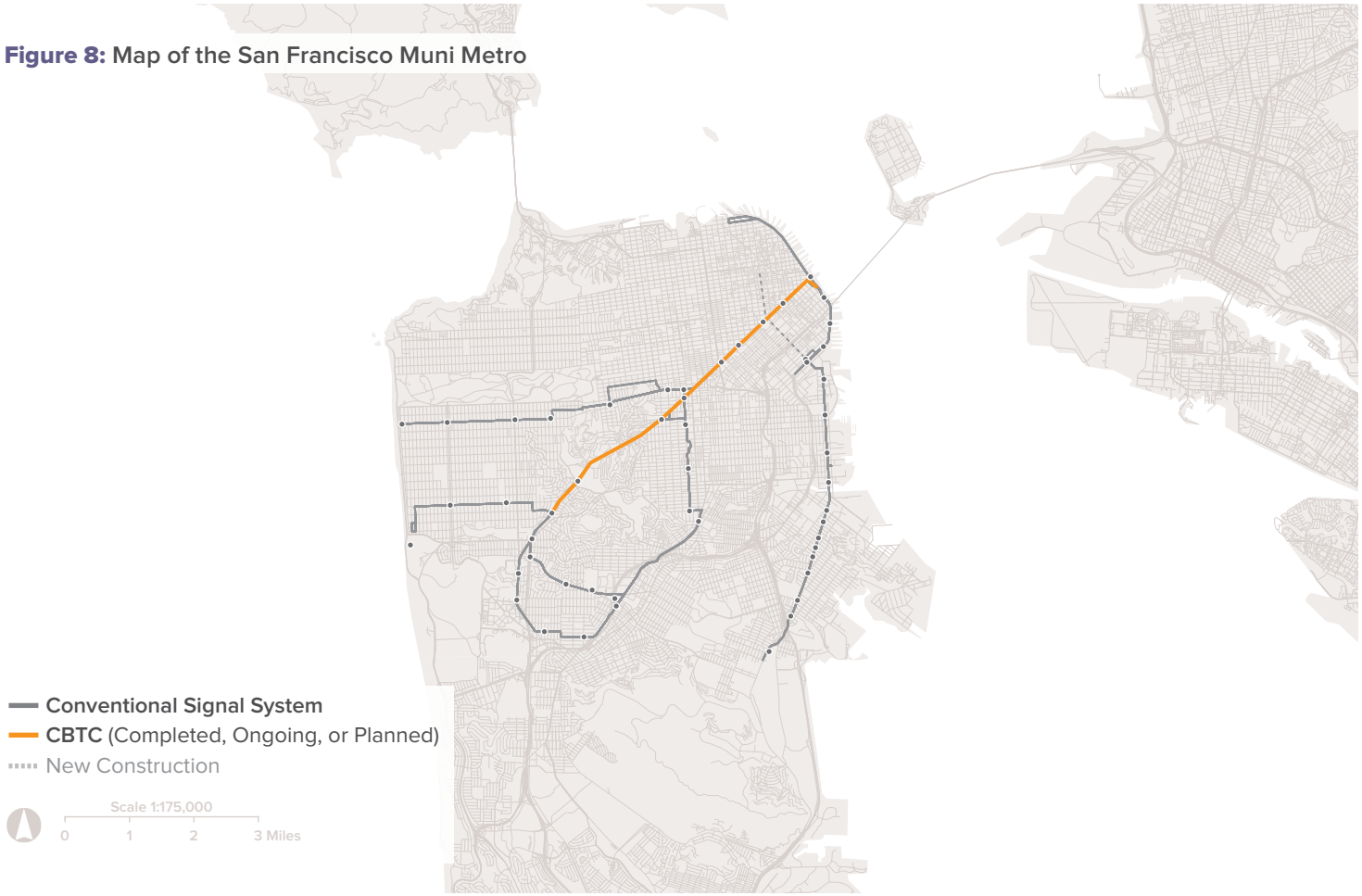
real capacity and travel benefits that CBTC can deliver, severe passenger congestion at Tube stations highlights the importance of complementary investments in circulation improvements that could also be needed as passenger demand increases.

Congestion at London's Tube stations is a serious problem; currently ten stations must be closed for limited periods during peak congestion to prevent dangerous levels of overcrowding. At Victoria station, one of the more severely crowded stations, the London Underground is spending over $1.2 billion (over £800 million) to build a new north ticket hall/entrance, enlarge the existing south ticket hall/entrance, install nine new escalators and several elevators – predominately to relieve the crowding but also to improve intermodal connections between the Tube and national rail lines at the Victoria Rail Terminal.

Like New York's subway system, London's is a legacy system that has had to address decades of disinvestment and loss of ridership, followed by ridership growth and the congestion that accompanies it. Unlike New York, it has chosen an ambitious investment program to modernize signals and make physical station circulation improvements, steps that will not only save money but bring direct benefits to its riders.

San Francisco Muni Metro
A Domestic Comparison

Figure 8: Map of the San Francisco Muni Metro



The modern incarnation of San Francisco's original streetcar system, the San Francisco Municipal Railway (Muni), operates historic street cars, buses, trolley buses, and a light rail system referred to as the Muni Metro (the railway). The majority of the railway operates above ground in mixed-traffic conditions on local streets. There are also two tunnel segments of the railway, the 2.3 mi (3.7 km) Twin Peaks Tunnel and the 3.5 mi (5.6 km) Market Street Tunnel, collectively referred to as the Muni Metro Subway (the subway). Subway capacity constraints, reliability, and safety issues prompted Muni to adopt a CBTC moving-block signal system for both tunnels in the mid-1980's, the first-ever retrofit of a fixed block system in the U.S.

Prior to the implementation of CBTC, the subway was operated in a cumbersome manner with inbound trains from different lines being coupled together at the West and Duboce Portals in an attempt to maximize tunnel capacity by creating larger train consists. While the subway's fixed-block signaling system was designed for a theoretical maximum of forty trains per hour, a maximum of only 26 trains per peak hour was attainable. This was a consequence of the tunnel's physical limitations and a terminal station which could only achieve two to three minute turnaround times.[58] Moreover, the coupling of trains at the entrance portals was an unreliable solution because of unpredictable arrival times resulting from mixed-traffic operation and failed couplings. Coupling required schedule changes for all coupled lines if there were any service outages or delays. It was also labor intensive, with a full time staff of four needed to monitor the light rail vehicles (LRVs) via radio, assist in the coupling operations, and supervise turnarounds at the terminal station. [59]

Outside of these capacity and reliability issues, the Muni's original signal system in the subway also had design flaws which

58 Rojas, David, and Eric Phillips. United States. Federal Transit Administration. Communications-Based Train Control (CBTC) Before/After Cost Effectiveness Study. 2011. p. 5 Web.
59 Ibid. p. 10-11.

San Francisco MUNI, The Embarcadero and Brannan Street
Photo: AgentAkit (flickr)

led to safety issues. The system used three speed codes transmitted through the tracks to enforce speeds within the tunnel. However, the lowest of these codes was 10mph (16 kph). This meant an operator might be instructed to operate at 10mph (16 kph) even if a train occupied the block directly in front of his train. At certain blind curves in the tunnel this created the possibility for rear-end collisions. A succession of these types of collisions in the 1980's combined with operational inefficiencies led Muni to pursue a signal system that would prevent such accidents.

Because the Muni was not upgrading any signals on the on-street portion of its network, they needed a CBTC solution that was capable of quickly switching between moving and fixed block operation at the subway's entrance portals. As a result, the CBTC system adopted by Muni is capable of operating in four modes: automatic mode, cab signaling mode, cut-out mode, and street mode. [60] LRVs operate in "street mode" when running in mixed-traffic on the surface streets under line of sight rules with the driver in full control of the vehicle – except for a top speed restriction of 30 mph (48 kph) enforced by onboard hardware.[61] As LRVs approach one of the subway's portals the driver enters a unique ID number into the CBTC system determining the train's route. Once the route is set, the train switches over to "cab signaling mode," in which the driver still controls the train under the supervision of the centralized vehicle control center (VCC) that can issue and enforce speed restrictions through the onboard CBTC equipment. Finally, the operator switches his train into "automatic mode" giving full control of the train's movement and routing to the VCC. The train doors are opened by the VCC but must be closed by the operator to ensure that the operator is staying alert during the run.[62] This final switch occurs at the first station after the train has entered the subway. The final mode, "cut-out mode," engages if there is a communication error between the carside and wayside systems during any part of this process. In this mode, trains are not under control of the VCC but are constantly monitored by it using the CBTC system's inductive loops to allow for proper routing of other trains. Trains that enter this mode as a result of a failed check-in will try to check-in again at one of six or so "recovery points" positioned after each portal entrance. [63] In the event of a complete failure of the CBTC equipment on the train, trains continue to operate under line of sight rules in cut-out mode and are routed and tracked by the VCC using axle counters. [64]

After a multi-year evaluation, a CBTC solution was chosen rather than an upgrade of the existing fixed block system, which would have required extensive physical modification of the track circuits and control systems causing extensive service interruptions. CBTC could instead be overlaid on the existing signal system, tested during the night when the Muni wasn't scheduled to run, and then cut-over without any serious service outages. [65] The initial CBTC installation included a very basic fixed block system which interfaced with the CBTC system. This system was included to ease fears that the CBTC system would turn out to be unreliable. However, these fears proved unfounded as the wayside components of the system have only failed a handful of times and the fixed block system is currently being removed. [66]

When the Muni subway was cut over to CBTC the number of trains utilizing the subway increased by approximately 30 percent, the number of vehicles passing through the tunnel declined from 70 to 50 vehicles per hour. Since Muni no longer coupled

60 Ibid. p. 7-8.

61 Line of sight rules dictate that a train must be operated at a speed at which it can come to a stop within half the distance of the operator's line of sight. This allows enough space for a train to break to avoid obstacles on the track and also to prevent two trains heading towards each other to come to a stop before a collision occurs.

62 SFMTA. Once a train doors open there is only 5 seconds of dwell time enforced by the system. If a train operator wishes to leave immediately after that limit they are free to do so and the system will compensate. However, if the operator does not leave after 45 seconds the VCC issues a message to a dispatcher who will contact the operator via radio to find out the cause for delay.

63 SFMTA

64 Line number and run numbers are communicated via radio in the event of a complete CBTC failure. This information is then entered manually into the VCC by a dispatcher at which point the VCC will automatically set the route for the train.

65 Rojas, David, and Eric Phillips. United States. Federal Transit Administration. Communications-Based Train Control (CBTC) Before/After Cost Effectiveness Study. 2011. p. 5 Web.

66 In the event that a station controller or other vital piece of the CBTC wayside components fail, Muni operates the subway portion of the railway using flag signals and clamping switches by hand. A vital wayside component of the system is considered to have failed if 3 seconds go by without communications between it and the VCC.

trains, the trains passing through the subway were comprised of one or two vehicles instead of three or four. Despite the decrease in vehicular throughput ridership has remained stable indicating the old fixed block signals and coupling system were inefficiently allocating passenger space. [67] Similar to what was experienced in Paris, the new CBTC system enabled Muni to provide the level of service required to meet the demand of its riders with fewer vehicles allowing Muni to run a more efficient operation and reduce operating costs. These significant benefits were realized even though the Muni did not deploy CBTC across its entire rail network or even an entire line. All of the benefits accrued by the agency came from optimizing operations on a 5.8 mi (9.3km) segment of the system while leaving the rest of the system operating as it had been before. This indicates that on large networks that require CBTC to be installed in phases, the installing agency will still realize benefits from the day the first phase is completed even if it doesn't cover an entire line or service.

Muni initially planned to replace their entire fleet of older LRVs with new CBTC-compatible LRVs. However, it decided instead to upgrade many of the existing LRVs with CBTC equipment to allow them to operate with either signal system. These cars were first placed in service in 1979 and were entirely manual with no CBTC-compliant equipment, requiring upgrades to their wiring, communications and onboard "fly-by wire" subsystems to operate in the new environment. [68] The use of the modified LRVs also required a more extensive modification of the CBTC system's software. It had originally been designed for use with only the Breda LRVs but had to be re-programmed and tested to handle every possible permutation of Breda and Boeing LRV trains to ensure that the braking profiles computed by the system were safe. [69]

Muni also recognized, like London and Vancouver, that physical bottlenecks needed to be addressed to fully realize the benefits CBTC. The Muni-Metro Turnback (MMT) was a capital investment comprised of a new segment of track at the subway terminus to facilitate reverse train movements and connect to the new Ferry Portal. This improvement was necessary to take advantage of the increased throughput provided by the CBTC system by decreasing the long turnaround times at the Embarcadero Terminal. The MMT also served as the initial test track for CBTC equipment, allowing the Muni to work out many software glitches before cutting the subway over to the new system completely. [70]

To take full advantage of the benefits of CBTC, Muni had to first overcome a few political and operational roadblocks. Due to political pressure to demonstrate the new system, Muni was forced to open the system despite the fact that it was still being re-programmed to accept the older LRVs that were retrofitted with CBTC equipment. This meant Muni had to operate a mixed fleet, meaning some cars were outfitted to work with the fixed block system and others with CBTC, which prevented the CBTC system from dynamically managing the entire active fleet. Eventually, the CBTC system performed at the same level as the old system when all non-CBTC rolling stock was removed from service.[71]

Secondly, Muni had to deal with the inevitable operational issues that result from switching to a new signal system because of a reluctance to change internal cultural and business practices to conform to CBTC. It wasn't until the operating protocols were updated and the managers began to gain experience with the new system that the service improved to allow 35 tph with CBTC, overtaking the service levels of the fixed block signals.

Once the CBTC fleet was fully up and running Muni began to experience the operational benefits and savings of its new signaling system. The FTA completed a cost-benefit analysis (CBA) of the Muni's CBTC installation that quantified the capital, operating, and maintenance benefits of the new signaling system. Over the lifetime of the CBTC system, assumed to be 30 years by the FTA, the operational and maintenance savings resulting from the installation of CBTC over upgrading the existing fixed block system are projected to be $446.7 million (2010 dollars) or just under $15 million annually.[72] These annual savings work out to approx. 8 percent of the Muni's annual operating budget.[73] The lion's share of these savings, $425.8 million, are operational in nature and result from Muni being able to provide the same level of service to its customers while utilizing fewer vehicles.

The complex environment of the Muni Metro made it an ideal candidate to be the first fixed block signaling system to be upgraded to CBTC in the United States. CBTC will give Muni space to grow, allowing the railway to increase its capacity as needed from the current throughput of 35 trains per hour to a maximum sustained level of 48 trains per hour. By allowing the VCC to dynamically control dwell times and subway speeds, CBTC provides a solution to the bunching and irregular train arrival times resulting from the unpredictability of surface running which had long been a major issue for passengers using the subway. In addition, the new system allows for sections of track to be bypassed and lines to be scheduled independently of one another relative to demand, which had not been possible before due to coupling.[74] The system is even capable of allowing bi-directional running which can be used during track outages to allow trains to run as shuttles.[75] All of this was achieved by just converting a small section of the network to CBTC, demonstrating that a hybrid network of CBTC and non-CBTC track segments can still deliver significant operational and capacity benefits.

67 Rojas, David, and Eric Phillips. United States. Federal Transit Administration. Communications-Based Train Control (CBTC) Before/After Cost Effectiveness Study. 2011. p. 15 Web.
68 "Light Rail Vehicle/Rapid Transit Car." Boeing. Web. 22 Oct 2013. <http://www.boeing.com/boeing/history/boeing/lightrail.page>.
69 SFMTA
70 Rojas, David, and Eric Phillips. United States. Federal Transit Administration. Communications-Based Train Control (CBTC) Before/After Cost Effectiveness Study. 2011. p. 8 Web.
71 SFMTA
72 Rojas, David, and Eric Phillips. United States. Federal Transit Administration. Communications-Based Train Control (CBTC) Before/After Cost Effectiveness Study. 2011. p. 45 Web.
73 Federal Transit Administration. National Transit Database.
74 Ibid. p. 21.
75 SFMTA

Paris Metro
The Future Is Here, Now

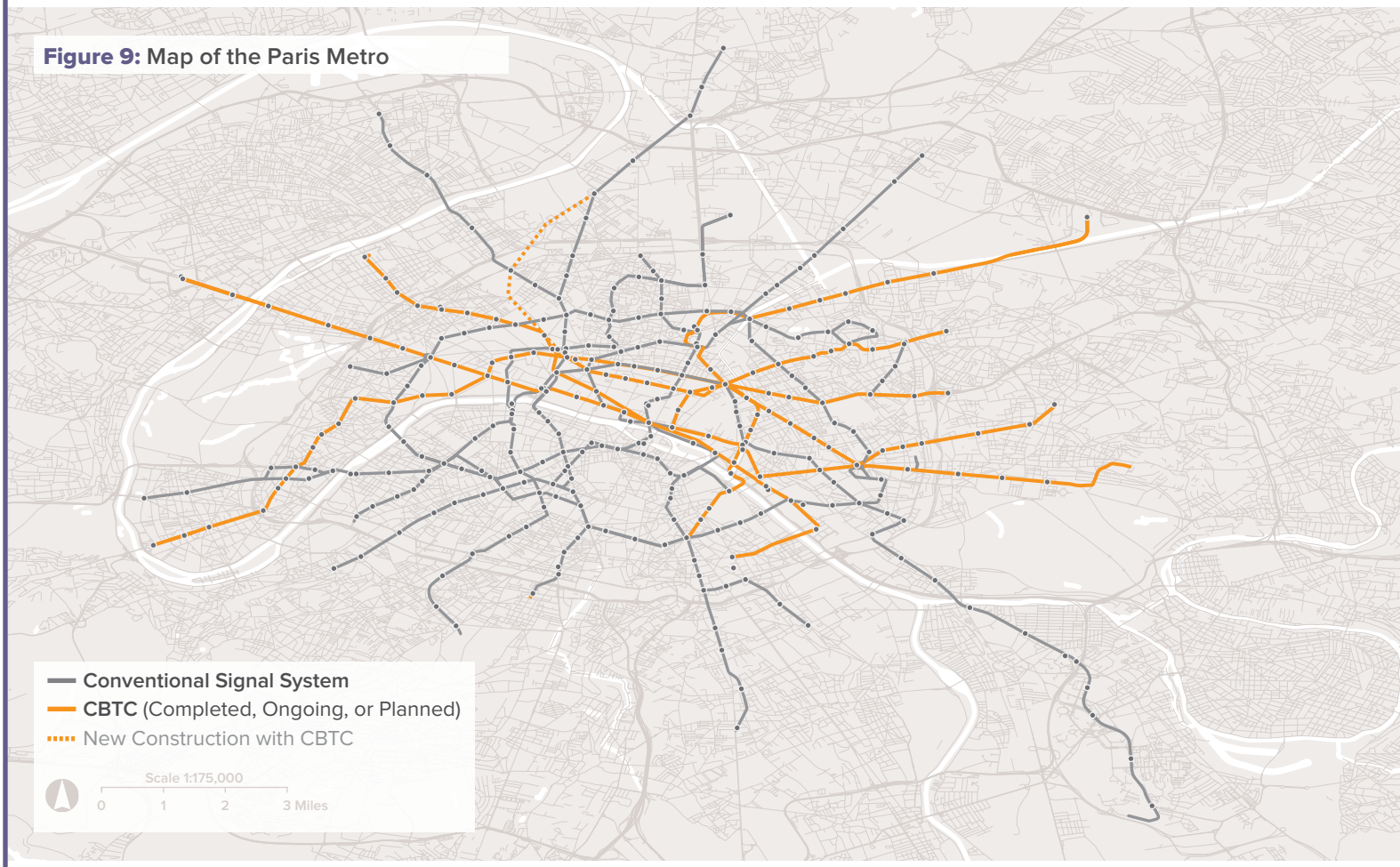


Figure 9: Map of the Paris Metro

The Paris Metro (the Metro) is a spectacular mix of old and new, celebrating the history of the 113-year old metro, yet being unafraid of embracing new technologies and operating models. The Metro has trains where a lever must still be flipped to open the doors and others that are completely driverless. RATP, the Paris Metro operator, plans to curb additional labor and operating costs as it increases service to meet future ridership demand. To accomplish this, RATP is in the midst of an operating paradigm shift that involves management and labor as well as the adoption of new signaling technologies.

Since the 1950s the Paris Metro has invested in new technologies to continually update its aging network to serve ridership demands. RATP refers to this period from 1955 to 1975 as the first wave of modernization. These investments upgraded all 13 metro lines to a semi-automated state (controlled manual driving) and consolidated railway operations. However, like most legacy metros, it still relied on track circuits "fixed blocks" as the underlying signaling system for safe train separation. This began to change in 1998 with the construction of the all new Line 14, Paris's first new metro line in over 60 years. Line 14 was a proving ground for new train technologies – "virtual block" signaling and unattended train operations (UTO) – and the complementary infrastructure investments, like platform screen doors. Lessons learned on Line 14 were applied to the second wave of modernization that commenced in 2000. Paris plans to modernize all of its metro lines by the 2035's, with some lines being completely driverless. Currently, three lines (L1, L3 & L5) have had their signals modernized, one is underway (L13) and two are in development (L9 & L4). Four out of the six lines will still require an operator to monitor the train and open/close the doors at stations. Line 1, Paris's oldest metro line that opened during the World's Fair in 1900, was fully automated in December of 2012. It has no operator. Platform screen doors were also installed at its stations to prevent track intrusions. The success of Line 1 has led Paris to speed up its plans to convert a second line, Line 4, to driverless operations before 2020. The RATP's

Paris Metro, Gare de Lyon Station on Line 1
Photo: Siemens

long-term modernization strategy also includes the concept of interchangeability – creating a standard system architecture to which all suppliers must conform. Three suppliers will each supply components for CBTC upgrades[76]. This interchangeability concept allowed RATP to contract the deployment of CBTC on 5 lines for a total amount of $140 million (€100 million).

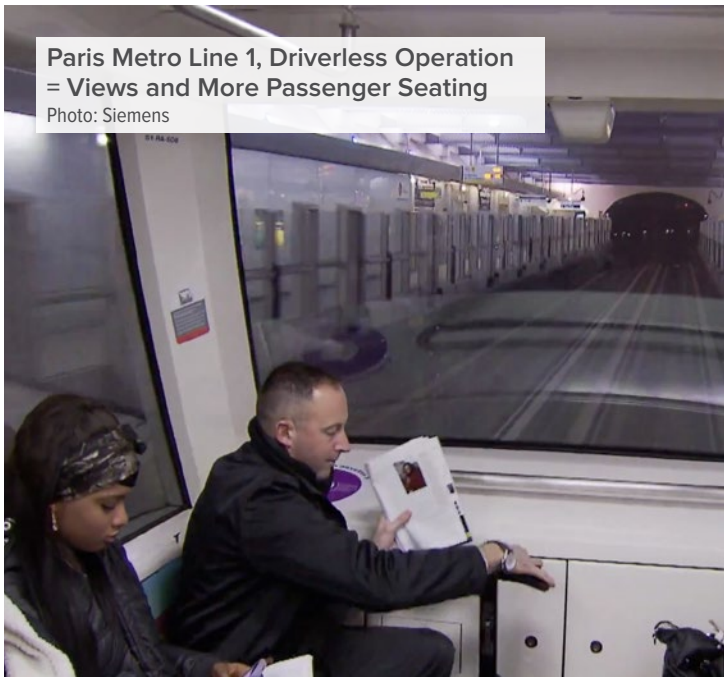
Paris has invested in CBTC and full automation for safety, labor savings and operational efficiency benefits. As demand grows, the agency wants to run more trains, more reliably with the same size labor force it has today. Unlike London, most of the Paris metro is not at capacity. It can hire more drivers and buy more trains to increase service. However, RATP has concluded that this would be more expensive and less efficient than upgrading to CBTC. The estimated cost of CBTC in Paris is $55 million (€40 million) per line, which does not include possible interlocking upgrades or new rolling stock. In addition, the costs to prepare a line for driverless operation have been estimated at $140 million (€100 million). While most of the lines upgraded to CBTC will still maintain their operator, driverless lines would generate an annual savings of approximately $14 million (€10 million) – the average annual total cost of train drivers per line. This indicates that an investment in a fully driverless metro could pay for itself in 14 years or less.

RATP negotiated with unions for over a decade to lay the groundwork for the acceptance of full automation and CBTC. There was recognition that both labor and management had to make concessions to improve service for the metropolitan area. RATP could not afford to keep expanding its workforce to serve growing demand; without concessions from both sides the Metro would become less frequent and more crowded. Capping the size of the existing labor force at current levels and creating the new supervisor positions were two major concessions made during the course of negotiations, but there were many more included in the final labor agreement. It was agreed that signal modernization and automation would not result in a system-wide reduction of drivers/operators. While some lines would be completely automated, most would still require a driver. As demand grows, RATP will still need to hire more drivers on those lines to increase service. This, coupled with a new management/supervisor position[77] for senior train operators on the fully automated lines, would maintain the current headcount. In 2007 a principles/framework agreement was ratified by the union membership. There have been several addendums to this agreement over the past five years, the last one being negotiated this past year.

Not only adding more trains per hour, RATP is focused on improving reliability and maintaining even train spacing through the management of headways and dwell time reduction. CBTC ensures the even spacing of trains through constantly adjusting the speeds of all the individual trainsets in unison. This balances passenger loads and creates the feeling of greater capacity and frequency for riders, even without adding more vehicles. Increased train frequency also lessens platform conges-

76 There is only one supplier for the completely automated/driverless Line 1.

77 As part of the conversion of Line 1 to UTO, 40 supervisors (a position first created for Line 14) were created for more senior operators. These are higher paid and higher skilled positions, in which drivers work out of the centralized operations control center (OCC) to monitor and remotely control trains in situations where manual override is needed. They also at times go out to the field to take local control if there is a systems failure.



Paris Metro Line 1, Driverless Operation = Views and More Passenger Seating
Photo: Siemens

Paris Metro Line 1, Platform Screen Doors
Photo: Siemens

tion, which in turn speeds up boarding and alighting, helping to reduce dwell times. In conventional systems, delays – lost seconds due to excessive dwells and variation in driver's skills – accumulate, allowing trains to close on one another. When trains "bunch" their individual capacity is not used efficiently, in many cases the first train is overcrowded, the second train is partially full and the third is almost completely empty. Many passengers experience the overcrowding of the first train plus an extended wait time. RATP experienced the benefits of reliable even train spacing on Line 1 since its automation, with a significant increase in equipment utilization and greater reliability. In fact, Line 1's operation is so efficient that its fleet has actually shrunk from 52 to 49 trainsets, resulting in additional operating and maintenance savings.[78]

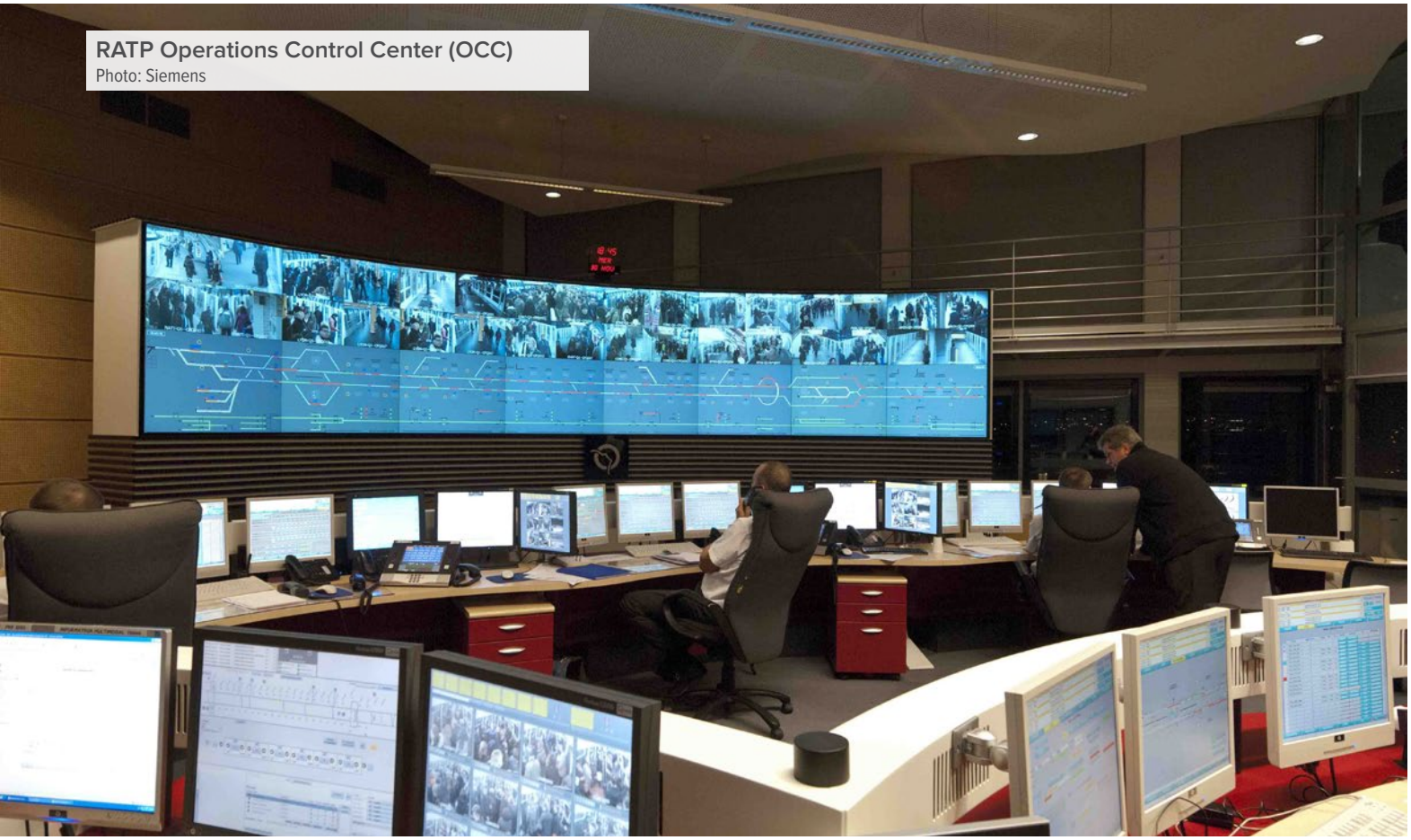
Platform Screen Doors (PSD) were installed in Paris as part of driverless operations on lines 1 and 14. Paris has also installed PSD on Line 13, the most congested metro line, on 13 out of its 33 stations and plans to install them at an additional 10 stations. Every year Line 13 experienced 600 minutes of service disruptions or delays due to track intrusions, which PSD drastically reduces. They also reduce tracks fires, improve system security, dampen noise and allow trains to enter/exit stations faster, among other benefits. RATP has seen a correlation between PSD and station dwell, riders appear to "respect" the pocket doors and do not typically try to hold open both sets of doors. This has sped up boarding and alighting at stations and has allowed operators to more closely adhere to scheduled dwell times. Stations along lines 1 and 13 are more comparable to the physical operating environments of New York City and other legacy systems than most other places where PSD are installed. The Paris PSD were customized for curved platforms (lasers to detect intrusions and flexible rubber edges to protect passengers from falling in the gap), ventilation constraints (¾ height doors to allow air to circulate through tunnels) and other idiosyncrasies of the older metro. The cost of installing and operating these custom doors are high, $140 million (€100 million) for Line 1 alone, much higher than the standard full-height PSD installed on Line 14. This was because of the work required to adjust and reinforce platforms in preparation for PSD. Over time it is anticipated that these installation[79] costs will decline.

CBTC makes up only 10 to 20 percent of line automation costs in Paris. The remaining costs are predominately attributed to new rolling stock and other wayside upgrades – switches, platform screen doors. Upgrading older trains[80] typically costs half as much as buying new replacement units. This investment also extends the life of the vehicle from typically 35 years to over 50 years. Trains must be gutted and electrical systems and radios installed to support the CBTC subsystems, this is also an opportunity to modernize onboard customer information systems and refresh the vehicle's interior. RATP upgraded trains that first

78 While Paris is operating three fewer trains per day and car maintenance costs are overall less for driverless operation due to uniformity of operation, Line 1 as a whole is still generating the same number of train kilometers or "wear and tear" per day as it did before. The difference is that there is now more km of use per car than in the past, increasing the maintenance burden on the cars. This nuance makes it difficult to quantify the cost savings, especially when also accounting for the line's short operational history.

79 Line 1 PSD installation required three weeks per platform.

80 A "free axle" is required to measure speed for the CBTC system, it's a redundant method used for train positioning in combination with the wayside transponders. If the brake is removed from this one axle the other brakes must be capable of maintaining specified braking performance.



RATP Operations Control Center (OCC)
Photo: Siemens

entered service in 1967 for the modernization of Line 3 and has similar plans for other lines. The labor costs for upgrading the cars would likely be higher in New York City than Paris – eroding some of the benefits – and experience in Paris has shown that the political support is not as great as the introduction of new rolling stock.

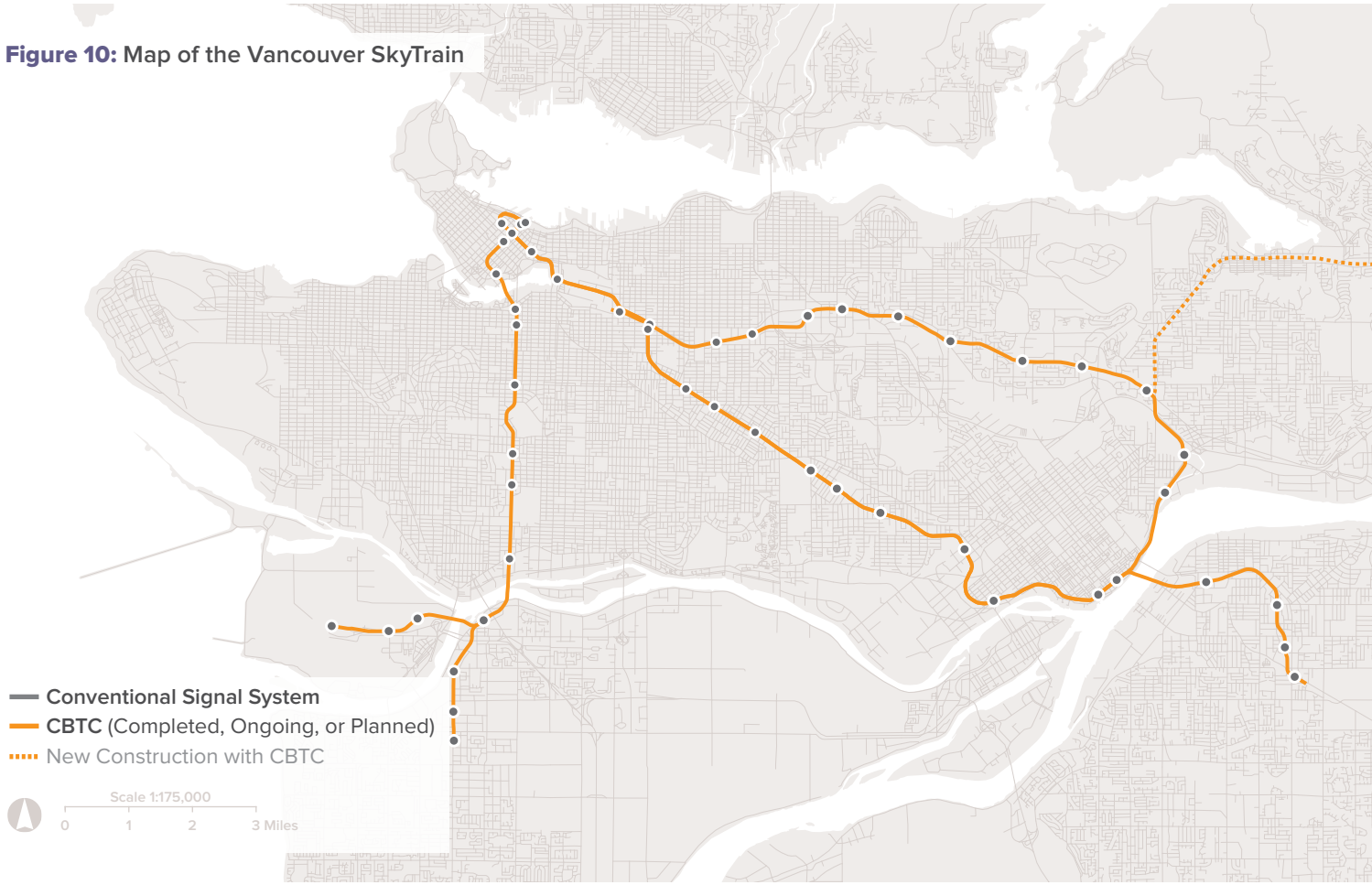
The flexibility and responsiveness of CBTC has allowed the Paris Metro to more adeptly respond to high-demand events, incidents and planned service outages. The Metro has only two tracks and benefits from the bi-directional CBTC signaling – the ability to run trains in any direction on either track safely – that allows trains to route around each other in case of an incident. RATP experienced the flexibility and responsiveness of CBTC and full automation when the RER A, carrying over 160,000 daily passengers, was interrupted between the city center and La Défense, a major business district. The only remaining public transit line serving La Défense was Line 1, which runs parallel to the RER. The full automation of Line 1 allowed the RATP to bring all trains into service in a matter of minutes, not hours. They also ran the service late into the evening, something that would have been very costly and in all likelihood impossible due labor constraints. They also used this "point and click" strategy on Line 1 to increase off-peak service during the last presidential election to respond to a variety of high-demand events that took place along the Champs-Élysées until 3am in the morning.

The Paris metro consumes 30 percent less traction energy due to its use of regenerative braking, first deployed in 1977. RATP sees great potential in CBTC and automation to deliver additional energy savings, with introduction of smooth running/coasting. Demonstration of 11 percent savings has been made on line 14 since 2010. Once the entire system is modernized there is the potential for another 15 percent energy savings with the use of smooth running/coasting and dynamic synchronization of train courses.

Paris is an early adopter of new technologies and one of the most innovative metro systems in the world. It was the first legacy metro to fully automate an existing line, its oldest, for driverless operation. RATP sees technology as its means of doing more with less. It cannot afford to serve a growing population operating as it has in the past – a conundrum faced by New York and other legacy metros as well. CBTC will allow Paris to maintain (and increase) the frequency and reliability that its customers have come to expect while also improving the efficiency, capacity and flexibility of the system.

Vancouver
Pioneering CBTC

Figure 10: Map of the Vancouver SkyTrain



Vancouver's SkyTrain, its first elevated metro, was built to connect two far-flung sites of the 1986 World Exposition and simultaneously showcase the latest in transit technologies such as linear induction motors and steerable trucks. It was also the first application of driverless CBTC technology; today it holds the unique distinction of being the most mature CBTC installation in the world, with almost three decades of continuous operation. SkyTrain has proven the reliability and capability of CBTC and, by the virtue of being an early adopter of the technology, enabled TransLink, the local transit operator, to develop modern best practices in labor and operations that have guided transit agencies around the globe.

Since 1986, Vancouver's rapid transit network has grown from the single 16.6 kilometer Expo line (10.3 mi) and 15 stations to a three line system – Millennium and Canada lines – with 68.6 route-kilometers (42.6 mi) and 47 stations. A fourth line – the Evergreen line – is currently under construction. These investments have spurred a near tripling of ridership in the last 14 years, from 43 million passengers in 1999 to 123 million passengers this past year. SkyTrain, along with TransLink's extensive bus network, has concentrated the region's growth within downtown Vancouver and surrounding transit oriented centers, contributing to metropolitan Vancouver's standing as one of most "livable" places in North America[81].

All three lines of the SkyTrain were constructed and designed for CBTC and fully automatic operation. Because its CBTC system was not retrofitted using the existing fixed-block signals as London, Paris and San Francisco have done, the SkyTrain has no Auxiliary Wayside System (AWS). This has made TransLink completely dependent on CBTC for its operations and has required it to develop new ways to deal with failures without the support of a backup signaling system.

SkyTrain's CBTC and driverless operation have proven to be extremely reliable. Over the past 26 years, TransLink has

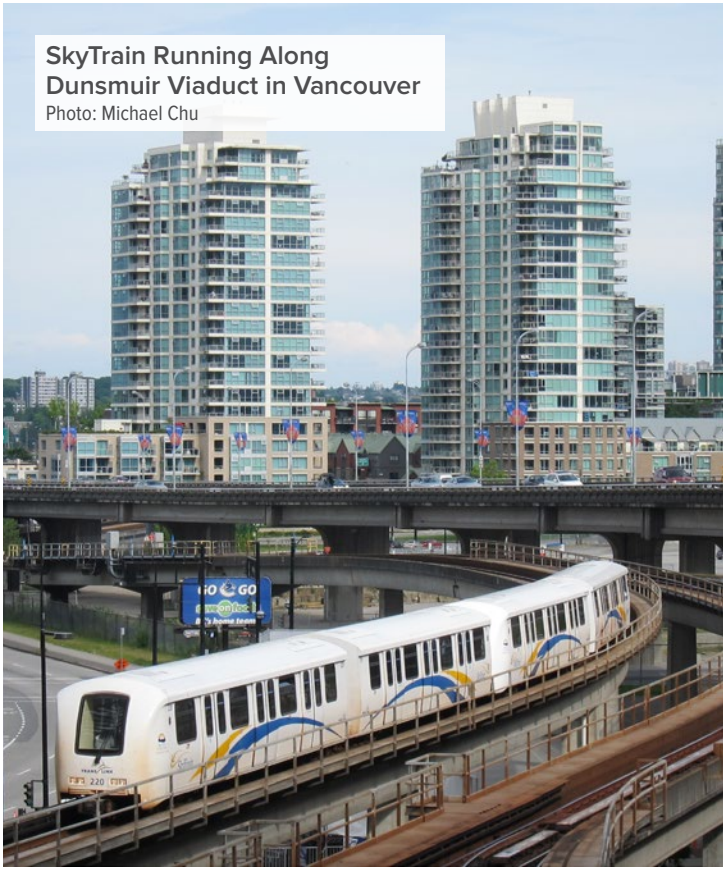
81 " A Summary of the Livability Ranking and Overview." Economist. Aug 2013. Web. 22 Oct. 2013. <http://www.scribd.com/doc/163738151/Most-Livable-Cities-Economist-Intelligence-Unit>.

never experienced a system outage lasting more than four hours. And in recent years the Expo line's second generation CBTC equipment, installed in 1994, has never experienced equipment failures of more than a few minutes. There have also been no accidents due to the malfunction of CBTC equipment, further highlighting the added safety of CBTC. The only accidents on SkyTrain have been caused by human error when operating under manual control – derailments and minor collisions. In the rare cases when CBTC does fail, TransLink has developed methods for recovering service.

In Vancouver's experience, most failures tend to occur when CBTC equipment on the car either loses communication with the track-side for more than three seconds or when excessive vibrations or abnormal sensor readings erroneously disable the vehicle. This is referred to as a "timeout" failure, when the train comes to a complete stop until it's manually reset by a field technician. Newer generation CBTC systems have a "creep" mode whereby the train will slowly continue along the track until it regains communication, comes in contact with an object or reaches a station. TransLink's responds to these incidents by dispatching staff to the affected vehicle and by directly communicating with its customers on the train. SkyTrain has a dedicated system, separate from its CBTC network, to allow the railway control center (RCC) to centrally monitor (visually with cameras) and communicate in real-time with passengers on the vehicle. While RCC operators are instructing the passengers, they are simultaneously instructing the system to adjust headways throughout the network to keep the remaining trains in motion and provide a buffer for schedule recovery once the disabled train is "re-entered" and back in service. Once the staffer reaches the train he resets its onboard systems and then manually drives the vehicle until the RCC recognizes it again and automatic operation resumes. In rare cases when there is a more severe system failure, trains will automatically run to the nearest station and then hold there until the issue is resolved. Service holds – typically lasting 3 to 4 minutes in duration – are sometimes used in less severe situations to prevent trains from bunching, which can stress SkyTrain's fragile power system causing a substation to trip-out, further compounding delays.

SkyTrain has never needed conductors or drivers to operate. However, they have personnel in positions throughout the system to respond to events and assist customers. To perform these various tasks TransLink has cross-trained station personnel to respond to train failures, maintain stations and interact with customers. The agency successfully negotiated flexible work rules with their union, which created a position that – at the time – was unique in the industry. Employees are paid higher wages, but are given greater responsibilities and required to multi-task. Station personnel are trained to empathize with disabled passengers, deal with minor vehicle faults, and manually drive trains, among other responsibilities. They are typically assigned two stations, where they are responsible for maintaining the station environment and customer service. Driver training/practice is done in the off-peak to familiarize operators with switches, stations and track geometry.

Station personnel are also trained to look out for suicide attempts, an unfortunate reality that SkyTrain faces because it does not have Platform Screen Doors (PSD). Similar to New



SkyTrain Running Along Dunsmuir Viaduct in Vancouver
Photo: Michael Chu

York City, Vancouver has different rolling stock lengths and widths, making it impossible to install PSD unless trains dimensions are standardized – a significant cost. Instead, it relies on an Intrusion Detection System (IDS) that stops the train if an obstruction is detected by trackside sensors. The system is not foolproof and cannot stop a train instantaneously if someone falls or jumps in front of the train as it is entering the station. Yet, the system's quick response to track intrusions usually prevents fatalities. Suicide attempts, which are beyond the operator's control tend to cause the longest delays, but IDS keeps the successful suicide attempts down, even without PSD, with only 54 suicides from train strikes from 1985-2008[82].

SkyTrain has proven to be very efficient to operate over its life with operating cost of US$1.3 million per km (C$1.5 million per km), lower than many of its peers due to labor and maintenance savings afforded by CBTC and driverless operation – no AWS means that TransLink does not need to send track crews to actively inspect its trackside equipment. They also rely on track inspection vehicles, like London, with additional visual inspects to detect defective rails before they break. In their 26 years of operation only two derailments have been attributed to broken rails.

Expo/Millennium line ridership increased 6 percent per annum between 1999 and 2008, straining the capacity of the system to serve future demand. While the signaling system has sufficient capacity to run more frequent service, station circulation issues and an inadequate fleet size threaten to create untenable congestion and limit growth. In response to these physical constraints, TransLink has developed a plan to lengthen trains

82 British Columbia. Coroners Service. Suicide Deaths 2002-2011. Web. <http://www.pssg.gov.bc.ca/coroners/publications/docs/stats-suicide.pdf>.

VCC-Clark Station on the Millennium Line of the Vancouver SkyTrain

and platforms and reconfigure stations to relieve circulation bottlenecks. These investments, as also shown in London, Madrid and many other systems, are essential to ensuring the efficient throughput of passengers and overall carrying capacity of the metro system. A 2010 study completed by TransLink estimated the capital cost of these improvements at around US$741 million (C$783 million) – for station improvements, yard upgrades and additional rolling stock. The investments would also result in a recurring annual operating cost increase of US$674 million (C$712 million), mostly attributed to greater costs of maintaining and operating a larger vehicle fleet.

Vancouver has been in the unique position to serve as a proving ground for CBTC. Over the course of several decades the technology has proven itself to be more robust and reliable than conventional fixed-block wayside systems. As a pioneer in this area, TransLink has developed methods and practices to create a nimble labor force capable of serving its customers and responding to incidents. This process has established an entirely new form of transit professional. Yet, the agency is not immune to limitations of train detection technologies or more "brick and mortar" physical constraints that threaten to dampen the strong growth that SkyTrain has enjoyed in recent years.

Key Case Study Findings:

The four case studies provided insights on how CBTC has worked and how other systems are deploying it, including the challenges and benefits of change. The major takeaways are as follows:

- Full automation can dramatically increase the flexibility of the system, allowing operators to rapidly increase service or reroute trains in response to events.

- CBTC increases the capacity and reliability of metro operations. Lines in Paris, London and San Francisco all experienced capacity increases once CBTC was adopted. Capacity increases not only come from running more trains, but from allowing more efficient utilization of existing trains that are more evenly spaced.

- CBTC systems rarely fail, and if they do, the failures are localized. For this reason, systems find that backup is unnecessary. Vancouver has operated using only CBTC for decades without a critical system-wide failure and London is planning to remove its fixed-block system once CBTC is installed.

- The entire system does not need to be converted to CBTC to see benefits. Hybrid systems, networks with CBTC on trunk lines and conventional signals or street running on branches can still gain capacity, reliably and efficiency benefits.

- CBTC does not require new rolling stock. Paris, London and San Francisco have equipped older analog vehicles to operate on their CBTC networks. Paris even found the option to be cost-effective, San Francisco did it out of necessity due to new rolling-stock procurement delays.

- New signal technologies are easier to maintain and can save tens of millions of dollars on maintenance costs. There are real maintenance savings with CBTC: Paris and London both saw a decline in their maintenance costs. London experienced an 18 percent reduction in its maintenance cost per track km and Paris was able to eliminate three trainsets from Line 1, yet provide the same level of service to its customers at a lower cost. However, some of these savings were partially offset by higher costs associated with maintaining CBTC equipped vehicles and the additional vehicles miles incurred by the trains over the course of the day due to an increased frequency of service.

- CBTC dramatically changes how the system operates by centralizing the control of the network. Management must be prepared to adapt to the new operational possibilities that CBTC affords to fully realize its benefits. For example, cars are an integral part of the CBTC system, adding essential onboard components that must now be maintained. Management must be prepared to adapt to the new operational possibilities that CBTC affords to fully realize its benefits.

- Labor needs to be brought into the discussion early. Implementation can take many years, often decades, and many current tasks will be phased out over time. This can provide an opportunity to create new roles for employees that increase their prestige – greater responsibility and skills – while improving service for passengers. Paris worked with its unions of over a decade to prepare for CBTC and negotiated a new senior position for train operators to monitor and operate trains remotely in their OCC. Vancouver never had train operators and has created an entirely new class of employee that is cross-trained in assisting customers, maintaining stations and responding to emergencies –even operating the vehicle if needed.

- Additional "brick and mortar" investments, like improvements in station circulation or correcting system bottlenecks, can magnify the benefits by eliminating limits on throughput that would otherwise be possible with CBTC. London has spent billions of pounds to expand stations (new entrances, wider concourses, etc.) in order to further improve circulation and train throughput after installing CBTC.

Figure 11: CBTC in New York

The New York Experience

Since its inception in 1968, the MTA has invested over $100 billion to improve and maintain transit in its 14 county service area.[83] Most of these investments were funded through successive capital plans, a process that began in 1982. There have been five plans since (see Table 9), with most of this funding – approximately 45 percent – dedicated to New York's subways with the lion's share of that funding for state of good repair (SOGR) investments in core infrastructure, which includes signals. As shown in Figure 12, some core components of the subway system are currently in or close to a SOGR. Critical elements like tracks and line equipment have all seen significant investments over the past three decades with cumulative investments of $6.959 and $2.617 billion, respectively. The subway's fleet has also been transformed – over $11 billion in mostly new rolling stock and more than 5,000 car procurements since 1982.[84] Yet, significant investments are still needed. The poor conditions of many stations are still very visible to the public, but some of the most critical part of the subway, like its antiquated signaling system, are not.

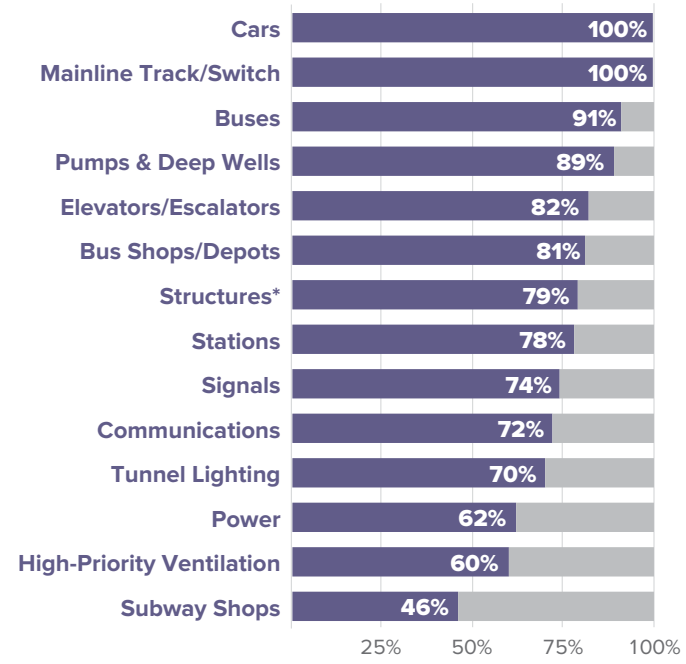
Table 9: MTA Capital Expenditures by Plan
(in billions of dollars)

Years	Expenditures (Nominal$)
2010-2014	$24.27
2005-2009	$24.49
2000-2004	$21.76
1992-1999	$18.11
1982-1991*	$15.39
Total	$104.12

Note: * Combines the first two capital plans and does not include MTA B&T (TBTA) expenditures. Source: MTA

The MTA's recent 2015-2034 Twenty Years Needs Assessment recognized signals and communications as the subway's singular largest investment need for the next two decades. The agency has identified signal failure as the leading cause of service delays in the system today. The Needs Assessment recommended that 23 percent or $15.6 billion of the $68.2 billion twenty year needs for New York City Transit be spent to repair and modernize the subway's signals[85]. This works out to $780 million annually, a significant increase over today's annual expenditure of $573.9 million, which has historically (over 58 percent) been spent on refreshing and replacing existing fix-block signals with in-kind components. Only during the past fifteen years has the MTA begun to invest in technologies to modernize how the subway operates,[86] in particular, investments in Automatic Train Supervision (ATS) – a digital overlay on the existing fixed-block signaling system for centralized dispatch and train routing – and the installation of CBTC on the Canarsie (L) and Flushing (7) lines and the Culver test track. There are also plans to upgrade part of the Queens Boulevard line (QBL) with CBTC as part of the MTA's 2015-2019 capital plan.

Figure 12: Repair Status of NYCT Equipment by Category



Note: Structures not present in new TYN b/c of new component based strategy so the percentage from 2010 has been substituted. Source: Metropolitan Transportation Authority. MTA Twenty-Year Capital Needs Assessment 2015-2034. 2013. Print.

Automatic Train Supervision

In 2008, the MTA completed the installation of an Automatic Train Supervision (ATS) system on the 175 revenue track mile A Division which is comprised of all the numbered lines and 42nd Street shuttle, except for the Flushing (7) line – about a third of the subway.[87] ATS was a $166 million investment to centralize train dispatching functions at a new $54 million railway control center (RCC). It consolidated several dozen interlocking towers and their 65 employees in one facility in midtown Manhattan (and another backup location).

ATS is a digital overlay on the existing analog fixed-block signal system. It uses existing track circuits, radio frequency

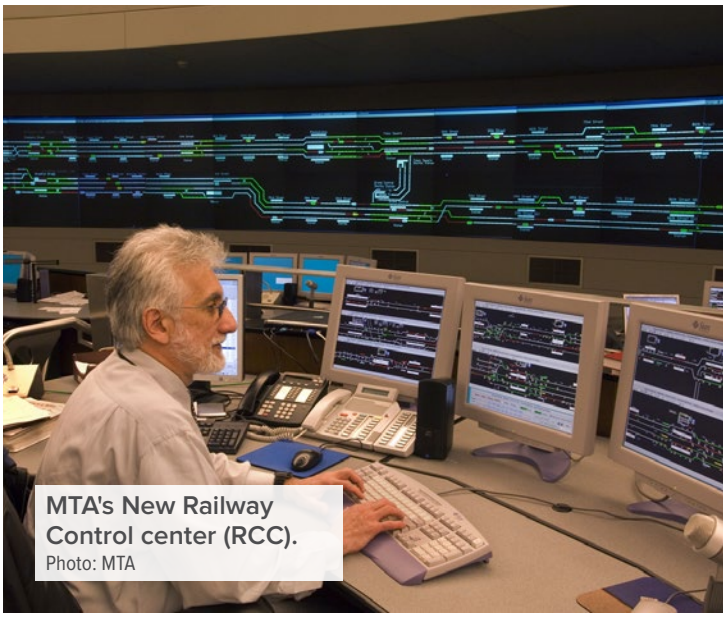
83 The MTA service area covers 12 counties in New York and 2 counties in Connecticut. In New York these include: Bronx, Brooklyn, New York, Kings, Queens, Richmond, Dutchess, Nassau, Orange, Putnam, Rockland, Suffolk, and Westchester counties. Fairfield and New Haven counties in Connecticut are served as well.

84 Metropolitan Transportation Authority. Capital Plans. 1982-2010. Print.

85 Metropolitan Transportation Authority. MTA Twenty-Year Capital Needs Assessment 2015-2034. 2013. Print.

86 Metropolitan Transportation Authority. 2010-2014 Capital Plan. 2010. Print.

87 The Flushing line is currently receiving a CBTC installation and thus was not part of the ATS roll out.



MTA's New Railway Control center (RCC).
Photo: MTA

identification tags (on trains) and readers (at major junctions/interlockings), wayside computers, a high-speed fiber optic network and complex software to locate and centrally display the positions of all A Division trains in the RCC. It also allows dispatchers in the RCC to centrally control interlockings/switches – a prerequisite for moving-block signaling systems – throughout the A Division, yet it does NOT allow them to centrally control the trains themselves, it only monitors their positions and controls their routing. While the system's capabilities are essentially unchanged, the dispatchers gain the ability to monitor entire lines in real-time and control all their interlockings, allowing them to respond to incidents much faster than before. In the past, dispatchers had to communicate with the tower operators to determine train locations and interlocking positions, these orders were relayed from the train dispatchers in the operations center over the phone to the towers – a very fragmented and inefficient process. Unfortunately, this is still how two-thirds of the subway operates today. The MTA plans to install a less feature-rich version of ATS on the 481 revenue track miles of the B Division – the lettered lines – over the next 3 to 5 years called Integrated Service and Information Management or ISIM. ISIM will allow train tracking and monitoring by the RCC, but will not have the automatic control features of ATS. This will allow the MTA to respond to significant pressure from the public for more of the most visible benefits of ATS – countdown clocks.

Central train monitoring has allowed the MTA to introduce countdown clocks at A Division stations. These popular devices approximate the arrival times of the next two to four trains and identify the service. They also serve as variable messaging screens for relaying alerts to customers. More recently, the MTA has shared this data over the internet, enabling application developers to include real-time subway arrival information on the web and mobile devices.

Outside of providing internal operating efficiencies and external public communications, the ATS system will also serve as the upper management layer for Communications Based Train Control (CBTC). Centralized control over interlockings/switches is required for moving block signaling systems and is something without which CBTC cannot function (as currently implemented by the MTA on the subway). ATS will be responsible for managing the dispatching and interlocking functions in concert with the automatic train operation of CBTC. While ATS was an important evolutionary step to improve the operational awareness of our manual and analog system, CBTC is transformative and will revolutionize how the subway operates. The Canarsie line (L) was selected as the first subway line to be equipped with CBTC to test both the concept and technology.

CBTC Comes to Canarsie (and Chelsea)

The Canarsie line (L) extends ten miles (16km) from the Canarsie neighborhood of Brooklyn to 8th Avenue in Manhattan. The line is made up of vestiges of steam railroad lines, Brooklyn Rapid Transit elevated lines, and a subway portion built from 8th Avenue in Manhattan to Broadway Junction in Brooklyn in 1931[88]. It is double tracked for its entire length with the exception of a storage track near the Halsey Street station and is one of just two lines in the system that run independently. In the 1980's the MTA briefly considered abandoning parts of the line due to low ridership, with L stations serving only 40,000 people per day in 1985[89], a low number by New York standards. Once this plan was abandoned, this simple two-track configuration, without any major junctions with other revenue services, the age of its signaling system, and low passenger volumes made the Canarsie line an ideal candidate for the MTA's first CBTC installation. The L's fixed-block signaling system had a maximum capacity of 20tph, CBTC was estimated to increase the line's throughput to 22tph and further out to 28tph after additional investments in power, shops and yards were made.

In 1999 the MTA signed a contract to install CBTC on the Canarsie line. While the supplier it selected had successfully installed a similar system on Line 14 of the Paris Metro, a brand new line, the age and condition of New York's system presented an entirely new set of challenges. Thus, the first three years of the project were used to design a CBTC system that was robust and flexible enough to not only withstand the extreme physical environment (temperature, moisture, track geometry, etc.) of the subway but also to conform to the operating rules of a mature system. The CBTC installation on the Canarsie line was also one of the first radio-frequency (RF) based systems to be installed in the world. The supplier's prior installation on the Parisian Line 14 had used inductive loop technology which made use of a continuous wire laid along the length of the track to enable communications between the train and trackside systems. Radio based systems eliminate much of the maintenance hassle associated with inductive loops which are susceptible to damage by debris hanging from trains. An RF system uses radios placed at intervals along the track and on the trains to facilitate the communications required by CBTC. Because the use of RF technology for

88 Feinman, Mark. "Early Rapid Transit in Brooklyn, 1878-1913." NYCSubway.org. 2001. Web. 22 Oct 2013. <http://www.nycsubway.org/wiki/Early_Rapid_Transit_in_Brooklyn,_1878-1913>.

89 This number does not include transfer stations, or stations serving other lines in addition to the L.

The Canarsie line (L)

CBTC implementations was still relatively uncommon when the Canarsie line's CBTC system was being designed Siemens had to develop a proprietary radio system capable of handling the line's winding tunnels and open air viaducts.[90] The MTA also planned to procure new CBTC-compatible trains for the line. The project cost $340 million, with $78 million to install CBTC equipment and the remaining funds used to upgrade interlockings, purchase new trainsets, and other necessary improvements.[91]

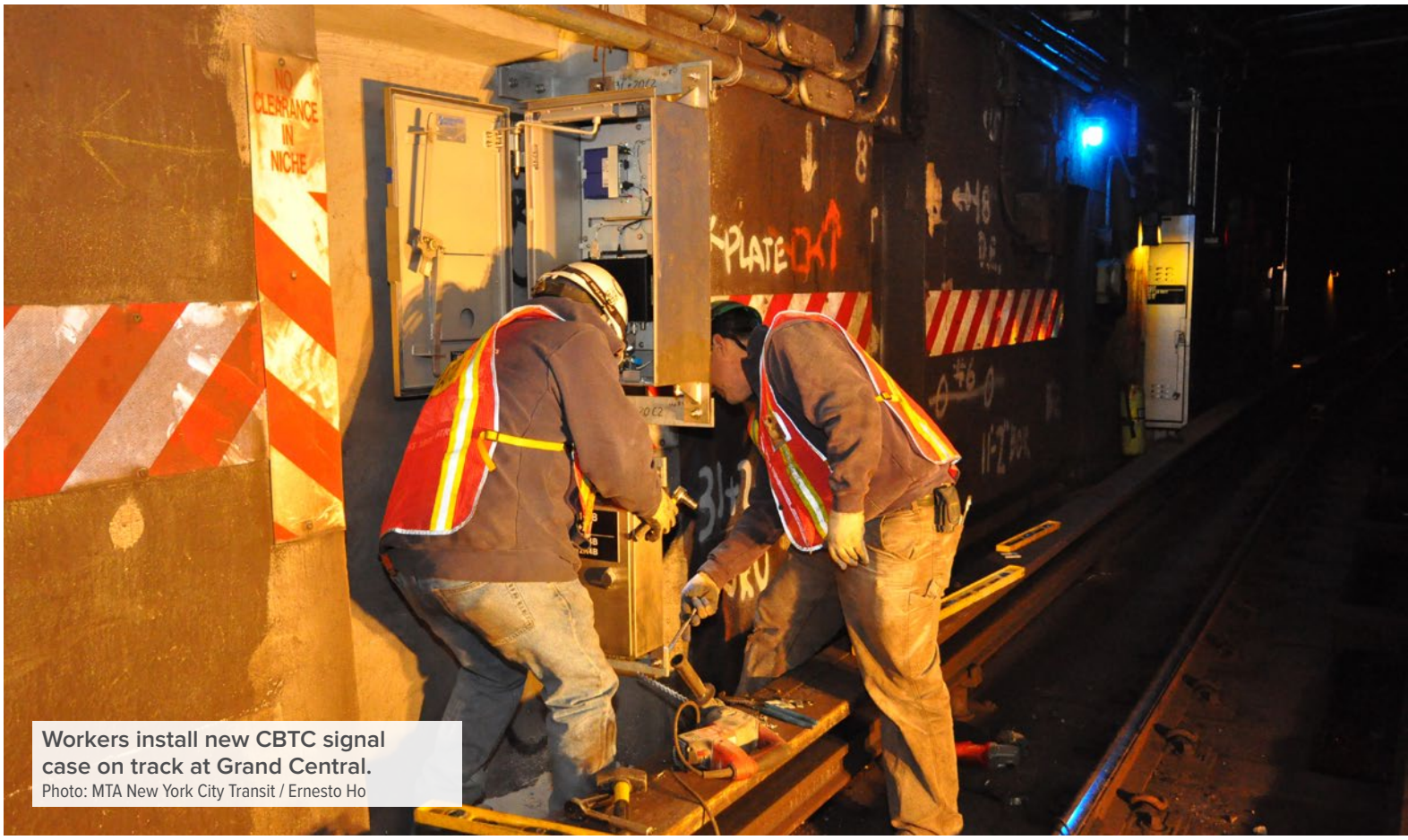
Installation of the CBTC equipment began in 2003 and by January 2006 the first segment of the Canarsie line between Broadway Junction and Canarsie began automated operation. Next, segments from Broadway Junction to 8th Ave in Manhattan were cut-over. All operating segments required trains to operate in both moving and fixed-block environments, limiting the realization of the full benefits of CBTC. Even after the full system was cut over in 2009, the Canarsie line was still not able to run completely in CBTC mode for several more years due to a shortage of CBTC equipped cars.

The reason behind this shortage was the surprising rise in popularity of the communities along the L line, where the surrounding population grew by 5 percent over a ten-year period, between 2000 and 2010, more than twice the rate of the rest of the city. Much of this growth was concentrated in the neighborhoods of Williamsburg and North and South Bushwick in Brooklyn served by the western end of the line, which grew in population by almost 9 percent over the same ten-year period.[92] This growth, completely unanticipated by the agency, along with the rise of these areas as tourist destinations created a tremendous amount of demand for the L, one of the few subway lines connecting these neighborhoods to Manhattan. From 1999, when the CBTC project began, to 2012, ridership along the line grew 93 percent![93,94] Complicating matters, these new riders did not follow the traditional peak/off-peak commuting pattern. For instance, L line weekend ridership is roughly 7 percent higher on average than other lines in the system which made it more difficult for the MTA to schedule weekend work windows without inconveniencing the large percentage of riders who continue to use the line after the work week.[95] This not only made the installation of the new system even more of a challenge by forcing the MTA to reduce their weekend work windows but also required them to purchase and equip more cars than they originally planned to serve the morning peak ridership.

The MTA initially procured 212 new CBTC-compatible R-143's, but later purchased an additional 64 cars (R-160A) to meet the growing demand. The cost of equipping these cars for CBTC operations was approximately $68 million or about a million dollars a car.[96] Without the additional rolling stock the line was forced to run mixed-mode operations with some trains operating manually using the fixed block system and others using the CBTC system restricting the line's capacity to 17 trains per hour or approximately a train every three to four minutes.[97] By November 2011, the MTA had enough CBTC-compliant rolling stock to finally cut the line over to automatic operation.[98] After about a year of testing and evaluation of the new signal system, new timetables were developed to take advantage of the increased throughput provided by CBTC.[99] One of the first measurable benefits of the conversion was a 3 percent decrease in terminal to terminal travel time.[100]

The installation of CBTC on the Canarsie line was a learning experience for both the MTA and its supplier. Many challenges had to be overcome to complete the installation. The

90 Sullivan, Tom. "CBTC Radios – What to Do? Which Way to Go?." Transportation Systems Design. 2005. Web. 22 Oct 2013. <http://www.tsd.org/papers/CBTCRadios.pdf>.
91 http://nypost.com/2010/08/01/riders-in-delay-hell-on-the-l/
92 New York City. Department of Planning. Neighborhood Tabulation Area Population. Web. <http://www.nyc.gov/html/dcp/html/census/demo_tables_2010.shtml>.
93 Annual Ridership Reports. MTA.
94 Station complexes, those serving multiple lines, were not included in this count because the MTA is unable to separate the boardings at these station to determine which line is used. As a result, six of the 24 stations were not included in these growth rates. Still, the magnitude of growth experienced by the L is captured.
95 Prendergast, Thomas. "L and F Service."06 Sept. 2011. Web. 22 Oct. 2013. <http://www.nysenate.gov/files/pdfs/MTA L Train Response to Squadron.pdf>.
96 Metropolitan Transportation Authority. *Capital Program Oversight Committee Meeting July 2012*. 2012. Web. <http://www.mta.info/mta/news/books/pdf/120723_1400_CPOC.pdf>
97 Prendergast, Thomas. "L and F Service."06 Sept. 2011. Web. 22 Oct. 2013. <http://www.nysenate.gov/files/pdfs/MTA L Train Response to Squadron.pdf>.
98 While the movement of the trains on the Canarsie line is controlled by the CBTC system, the conductor is still required to operate the doors and the operator must press a button to instruct the train to leave each station and respond to a signal every 20 seconds or the train will begin to brake.
99 Prendergast, Thomas. "L and F Service."06 Sept. 2011. Web. 22 Oct. 2013. <http://www.nysenate.gov/files/pdfs/MTA L Train Response to Squadron.pdf>.
100 Rumsey, Alan, Alan Ghaly, Nabil, et al. United States. Federal Transit Administration. Assessment of the Business Case for Communications-Based Train Control. 2013. pg. 64. Print



Workers install new CBTC signal case on track at Grand Central.
Photo: MTA New York City Transit / Ernesto Ho

MTA's decision to go with a relatively new RF based CBTC system instead of the industry standard at the time, inductive loop system, required additional time for their vendor to develop and test a system that was capable of operation in the subway. Additionally, the unpredicted resurgence of the neighborhoods along the L also complicated matters by forcing the MTA to order additional rolling stock to meet demand which further pushed back the completion of the project. Fortunately the MTA seems to have learned from both of these challenges and is applying these lessons to the installation of CBTC on the Flushing line.

The #7 Line: CBTC's Next Act

The Flushing line (7) is similar to the Canarsie line in many respects: it shares no revenue tracks with other lines and it features a mix of aboveground and tunneled sections. However, it is distinct in that it operates two services, the #7 local and the diamond express – a peak-direction express service that uses a center third track. Like the Canarsie line, it was the obvious choice for the MTA's second CBTC installation. The line is part of the A Division and runs just over nine miles (14.5 km) from Times Square in Manhattan to Flushing in Queens. It was opened in segments from 1915 to 1928 and was fitted with a state of the art automatic routing system in the 1960s. The system, called IDENTRA[101], made use of a radio antenna which broadcast a signal indicating whether a train was running express or local to receivers along the line. The receivers would then set the interlockings in front of the train accordingly.[102] This system was deactivated in the 1990's. Currently, the line is undergoing an extension to 34th Street and 11th Avenue on the Far West Side which is expected to open in 2014.

In 2010 the MTA awarded a $343M seven-year contract to install CBTC on the Flushing line.[103] The eleven year gap between the Canarsie and Flushing contracts saw an increase in CBTC installations around the world accompanied by a significant maturation of the technology. RF based systems are now the industry standard, eliminating many of the complications that arose from the MTA using the technology on the Canarsie line when it was in its infancy. As a result, installation was able to begin with minimal delay, only a year after signing the contract with the technology vendor, using the experience gained from retrofits it had previously performed on lines in London, San Francisco, and Korea.[104] Barring any unforeseen delays in the installation process, the MTA should begin to test the system in shadow mode in late 2014 and perform the final cut-over in mid-2016 followed by the system being "substantially completed" in early 2017.[105] This would amount to a six year installation period which is generally comparable to the time required to install

101 Identification of Trains and Routing Automatically

102 The system was also capable of setting signs on station platforms indicating whether the next train was running express or local.

103 "New York Flushing Line CBTC contract awarded." Railway Gazette. 28 Jun 2010: n. page. Web. 22 Oct. 2013.

104 http://new.mta.info/press-release/nyc-transit/new-signal-system-installation-begins-flushing-line

105 Smith, Frederick. "Presentation to the Permanent Citizen Advisory Committee to the MTA." . Metropolitan Transportation Authority, n.d. Web. 22 Oct 2013. <http://www.docstoc.com/docs/161891114/pcac_april-2011fes1ppt---The-Permanent-Citizens-Advisory>.

CBTC on the Canarsie line. However, the time required to design the system and begin installation was greatly reduced for the Flushing line and presumably will be for future installations as the technology further matures and the MTA's comfort with moving-block signaling systems increases.

To take advantage of the new CBTC signals and to serve the new extension of the line to 11th Avenue and 34th Street the MTA has procured 126 new R188s and 380 retro-fitted R142A CBTC-compliant rolling stock for $613.7 million to form the new Flushing line fleet. [106],[107] The deliveries of the new rolling stock and retro-fitting process have already begun, indicating that the MTA has learned from the issues it had with insufficient CBTC-compliant fleet size on the Canarsie line that hamstrung a rapid cut-over to the new system after the trackside equipment had been installed. However, the conversion of the R142As requires that these cars be taken from another line, in this case the Lexington Avenue Local (#6). As these cars are removed from the Lexington Avenue line they are being replaced with R62As from the Flushing line, which are older and do not have many of the technological features present on the newer R142As such as automated announcements, LED line maps, and variable messaging signs that display service announcements and the train's next stop.

While the MTA appears to have learned from the challenges it faced with rolling stock shortages on the Canarsie line, they have run into new ones during the Flushing project. The spike in demand seen on the Canarsie line during the installation of CBTC was unforeseen. However, the Flushing line has been and currently is one of the MTA's most heavily used lines, accounting for 10 percent of all subway ridership.[108] The line's eastern terminus, Flushing-Main St., was the eleventh busiest station in the subway system in 2012. This historically high level of usage has allowed the MTA to anticipate and attempt to mitigate most of the impacts of the CBTC installation. However, the MTA will continue to deal with the inherent conflicts between the need for planned service outages to install CBTC and the need to provide service to its customers. So far, the MTA has tried performing much of the work over the weekend and only shutting down portions of the line when doing so. It has also restricted work when there are major events at locations served by the line such as at CitiField or the Billie Jean King National Tennis Center. Consequently, the contractors only have access to the line for short periods lengthening the overall system install time and thus the number of years riders are likely to be inconvenienced.

The MTA's second challenge is one that was partially self-inflicted. As part of the CBTC installation process, the MTA must run test trains to verify that the installed systems are functioning properly and to work out any software glitches before the final cut-over. The line's heavy usage throughout the day and week will not make this a simple task. Luckily for the MTA the Flushing line has a third track from Flushing-Main Street to Queens Plaza. This track is currently used during peak periods for the diamond express as well as train re-routes when necessary. It is on this track that the MTA will conduct its final CBTC tests. This means the MTA will again be forced to work around its customers and avoid performing tests during the peak periods. Using the third track during off-peak periods will also eliminate the redundancy it provides in the event of a problem on one of the other tracks. However, there was an alternative that could have helped lessen this conflict.

In late 2007 the MTA and the City of New York began a project to extend the Flushing line from its western terminus at Times Square to a new station at 34th Street and 11th Avenue. The extension is to serve the neighborhood's growing population and the massive Hudson Yards Redevelopment Project which is currently underway. The extension is scheduled to be opened in the spring of 2014, two years before the completion of the Flushing line CBTC upgrade, and will be outfitted with both CBTC and fixed-block signals. This would have made it the ideal location for the MTA to use for running test trains. Unfortunately, the two projects were not coordinated to ensure that the test period of the CBTC installation coincided with the final stages of the extension's construction. Doing so would have allowed the MTA to run test trains along the extension without hindrance and save the millions on a revenue-service caliber fixed-block signaling system.

The agency appears to be tracking towards a 2016/2017 completion of CBTC on the Flushing line. The total project cost is currently $550 million for the signals and other trackside infrastructure and $613.7 million for a CBTC compliant fleet. It should be noted that the number for the Flushing line is quite high not only because it includes new cars to serve the extension but also because the Flushing line is the only line in the subway system to run 11-car trains rather than the standard 10 or 8 car trains.[109] Once complete, the new CBTC signals will benefit the 73 million annual riders on the line.[110]

The MTA currently plans to continue to roll out the technology on major trunk lines in the system, with the Queens Boulevard line (QBL) next in line. The MTA should look for opportunities such as the 7 line extension to coordinate its capital projects to minimize the inconvenience experienced by its riders. While well intentioned, the MTA's policy of only allowing a line to be shut down for short periods of time actually extends the installation process and riders' frustrations. In the same manner that one rips off a bandage quickly to avoid prolonging the pain, other options should be explored to shorten installations, like the FASTRACK program, which will save costs and allow their customers lives' to more quickly return to normal.

Culver Test Track: Interoperability and CBTC

The Canarsie and Flushing lines are not typical of New York's subway network. They have simple alignments and do not represent the complexity of the subway that was designed with

106 http://web.mta.info/mta/news/books/pdf/130722_0145_CPOC.pdf

107 These new cars will be used to create 46 new trains, 4 of which will expand the Flushing line fleet to serve the Flushing line extension.

108 Neither the MTA total or Flushing line total include station complexes due to the inability to properly assign ridership to the lines served by these complexes. In the Flushing line's case this is especially important because two of its station in Manhattan, Times Square – 42nd Street and Grand Central, are respectively the first and second busiest stations in the system.

109 Metropolitan Transportation Authority. Capital Program Oversight Committee Meeting April 2012. 2013. Web. <http://www.mta.info/mta/news/books/pdf/130422_1300_Cpoc.pdf>

110 Does not include station complexes.

lines that intermingle and branch in various directions to allow for greater "one-seat" ride opportunities. Most lines merge at the core of Manhattan feeding one of several major north/south four-track trunks – there are also complex junctions in Brooklyn and major trunks in Queens that run beneath Northern and Queens boulevards. Upgrading all branches and trunk lines simultaneously would be impossible. Not only isn't there adequate funding but it would be impractical since the entire system would grind to a halt in the process. Incremental installation of CBTC over several decades is the most feasible option, but the rollout of CBTC is unlikely to be contiguous as some sections of the subway will have more urgent needs than others – older signals or greater capacity constraints. It will be critical that CBTC components from various vendors be able to interoperate as segments are upgraded.

The Canarsie line's CBTC is a proprietary system and the Flushing line CBTC incorporates some of the interoperability standards, yet parts of it are still proprietary as well. The aim of the MTA's interoperability project is to create common interface standards so that most [111]wayside and onboard car equipment can communicate with each other. It does not require the vendors to have identical hardware or underlying software. The electronics and software running inside the black-box will still be completely proprietary. But it is vital that the black boxes be able to talk to one another. For example, one supplier's zone controller must be able to communicate with another's car's onboard computer.

As part of this project the MTA is facilitating the cooperation of different CBTC equipment providers to develop interoperable systems. Currently, the MTA has contracted two CBTC vendors, Siemens and Thales, to develop a standard CBTC system design as well as the standardized specifications that will allow other vendors to supply equipment that is compatible with the published specifications.[112] Siemens and Thales are funders of this study. The MTA and the two contractors are jointly equipping a section of track called the Culver Test Track,[113] an integrated test facility that will be used to demonstrate the interoperability of their equipment as well as to allow other suppliers to demonstrate the compatibility of their equipment with the other two existing suppliers.[114]

These testing and validation exercises must be completed to the satisfaction of the MTA to pre-qualify any CBTC vendors for the right to bid on future CBTC projects. The MTA has plans to contract with one more additional CBTC vendor, for a total of three, a strategy that other properties like Paris have also pursued.

Once finalized, the new CBTC specifications will be codified and required for all future CBTC procurements. The standard will not only prevent the MTA from being locked into a single proprietary system but also ensure that individual lines and services can be outfitted by different CBTC suppliers and still be interoperable. This will allow the MTA to retain the operational flexibility and routing options that are inherent in the subway's design.

111 CBTC radios remain proprietary devices.

112 Colceag, Gabriel, and Gerard Yelloz. "New York's Culver CBTC Test Track Project." 28 Mar 2012. Web. 22 Oct 2013. <http://www.alamys.org/media/61869/26_metrorail.pdf>.

113 The test track uses the non-revenue express tracks on the Culver line in Brooklyn between 4th Avenue and Church Avenue – a distance of 2 miles.

114 Hubbs, G P, and Alan Rumsey. "CBTC-NYCT'S QUEST FOR INTEROPERABILITY." Rail Transit Conference Proceedings, 2000 American Public Transportation Association, 2000. 325-329. Web. 22 Oct. 2013. <http://trid.trb.org/view.aspx?id=657972>.

The MTA's Long-Term Plans for CBTC

The 2015-2034 MTA Needs Assessment estimated that the agency will need to spend $15.6 billion over the course of the next two decades to bring the signal system to a state of good repair (SGR) and, in the process, would modernize about half of the network. Included in this number is the modernization of 73 interlockings that are not in a state of good repair, a step required to ensure that they are compatible with the new CBTC signals. RPA has estimated that this investment accounts for over 2/3 or approximately $10 billion of the overall $15.6 billion plan.

Table 10: MTA Subway Signal Modernization Plan (2013)

Signal Type (Revenue Track Miles)	Today	%	2034	%
Fixed Block	706	97	362	49
Moving Block (CBTC)	22	3	374	51
Total	**728**		**736**	

Note: 2034 track miles include SAS Phase 1 (4.6 mi) and Flushing line extension (3 mi)
Source: MTA and Regional Plan Association Analysis

The MTA's current plan takes a mixed approach, leaning toward upgrading to CBTC whenever possible. According to the needs assessment, 26 percent or 190 track miles of the signaling system are not in SGR. The agency plans to convert an additional 322.5 track miles, almost half of the system, to moving-block CBTC by 2034 at which point the MTA plans to have completed the western portion of the Queens Boulevard line, the 8th Avenue line, 6th Avenue line, Broadway line, Lexington Avenue line, and Broadway-7 Avenue lines.[115] This translates to approximately 16 track miles converted per year over the next 20 years, an ambitious goal based on past performance. Thus far, the agency has only converted 22 track miles, with the modernization of the Canarsie line (L) and is currently in the process of converting the over 26 track miles of the Flushing line (#7). Assuming these investments are indicative of the current pace of implementation then the rate of conversion has been closer to 4 track miles per year, meaning it would take the agency over 85 years to convert half the system to CBTC. At this glacial pace parts of the fixed block signal system would be over 100 years old by the time they were replaced.

In addition to the signals themselves, the modernization of the interlockings (switch complexes) and rolling stock is required for CBTC. The MTA currently plans to upgrade all of the system's interlockings to be CBTC-compatible by the 2025-2029 capital program.

An interlocking is a combination of signals, switches, and other signal appliances which is designed to prevent conflicting, dangerous, or improper train movements. The interlockings on the subway were originally mechanical in nature and operated by hand with interlocking tower operators manipulating levers to manually route trains. Over the years these mechanical

115 Metropolitan Transportation Authority. MTA Twenty-Year Capital Needs Assessment 2015-2034. 2013. Print.

interlockings have been replaced by electro-mechanical and relay interlockings. However, not all of the interlockings throughout the system have been upgraded to these newer versions, a requirement for CBTC to be installed so that CBTC can properly route trains. These newer interlockings use relay logic to operate and are capable of being controlled remotely via high bandwidth communications lines. This allows CBTC to interface with the interlocking itself and is also advantageous in that any changes in the rules governing the interlocking can be implemented by changing the arrangement of the relays rather than by mechanically re-configuring the interlocking itself. According to the plan, 40 interlockings are backlogged for replacement and an additional 34 interlockings are to come up for normal replacement during this period meaning that 73 (40 percent) of the 183 interlockings in the system must be upgraded or replaced over the next 20 years.

The subway's fleet of railcars must also be upgraded to be fully compatible with CBTC. Currently, all new cars starting with the R142, introduced in 1999, are either CBTC-compatible or are CBTC-ready. While not equipped with CBTC equipment when delivered, both types of cars have the ability to be upgraded, with CBTC-ready cars being the easier to upgrade of the two. [116][117] This amounts to 55% of the current fleet.[118] Subway cars must be equipped with radios and other equipment so that they are capable of interacting with the CBTC wayside equipment and receiving and following instructions from these systems. Unlike the subway's interlockings, the fleet has been in a normal replacement cycle since 1992 and the MTA plans to continue on this cycle while purchasing additional cars as needed to accommodate future growth. All new cars purchased by the MTA, such as the R-188s on the Flushing line, will be CBTC-ready. The agency is currently evaluating making the R211s, under development, the first cars to be CBTC-equipped. Through the current normal replacement cycle and upgrading CBTC-ready cars the MTA plans to have the entire fleet capable of interfacing with CBTC-based signals by 2027.

According to the needs assessment, after twenty years the MTA will have only installed CBTC equipment in Manhattan and a handful of lines in Queens (two of the busiest, the Flushing line and the western segment of the Queens Blvd line will be converted) and Brooklyn with no implementations in the Bronx and this assumes that the MTA is able to quadruple its rate of conversion from the current 4 miles of track per year to 16 miles per year. Thus, for the MTA to install CBTC over the majority of its system before the CBTC systems currently being installed come up for normal replacement, it must increase its current rate of implementation, both of actual CBTC signals as well as the required supporting components such as interlockings and rolling stock. While some lines such as the Dyre Avenue line in the Bronx may not need CBTC for any reason other than lower maintenance costs, there are trunk lines in the Bronx, Brooklyn, and Queens such as the Eastern Parkway line (2/3/4/5) in Brooklyn that could benefit from the capacity increases brought by CBTC. In addition, expanding the area signaled with CBTC will allow the MTA to reap greater operational benefits from the system as it will be able to dynamically manage trains for longer periods of time. To this end, the next chapter will evaluate need and options for a quicker roll out of CBTC throughout the subway.

116 Not all newer cars have CBTC equipment installed but instead are "CBTC-ready" and just need to have the equipment put in place.

117 Cars that are "CBTC-compatible" do not always have the space or wiring for necessary CBTC equipment to be installed but can be overhauled to work with the system for a cost. "CBTC-ready" cars have been designed from the outset with the space for wiring and to accept CBTC equipment, with an upgrade cost far less than "CBTC-compatible" cars.

118 MTA.

Leonard Zhukovsky

Chapter 5

CBTC Priority Setting

The upgrade of the subway to CBTC will take decades. The MTA must still serve over 5 million riders daily while it transitions to moving-block signals, all while it faces continuous funding constraints and conflicting priorities. Choices will have to be made as which parts of the system are more important to implement first. This chapter addresses this question using three factors to set priorities for early CBTC implementation, which can then be translated into a long-term implementation program.

- The age of signals, assuming that older signals would be in relatively poor condition and therefore would be likely to be subject to earlier replacement with CBTC;
- Lines and segments that are now at or approaching capacity during peak times, a condition that could be mitigated by the more frequent service that CBTC could make possible; and
- Lines and segments at or close to capacity which are likely to add still more riders as shifts in the City's population and its make-up generate growth in subway ridership.

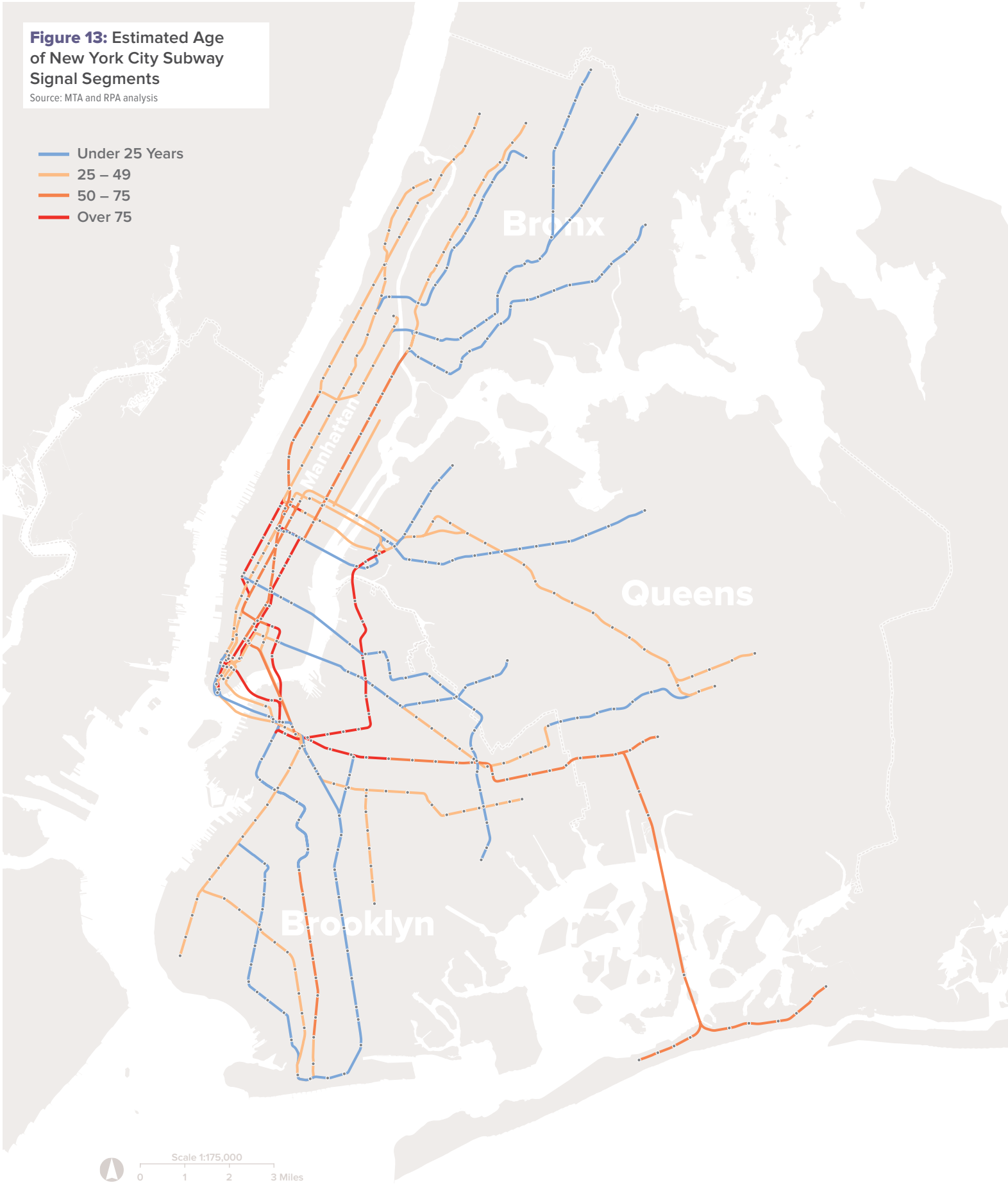
Evaluating the subway's age, capacity and ridership growth requires a more granular examination of the existing network. While most riders identify the subway by its service letter or number, the network is actually made up of 34[119] distinct lines with names like the Eastern Parkway line and Dyre Avenue line, to just name two. There are 12 IRT, 12 BMT and 10 IND lines, each with ten services (e.g. 1, A, Z ...) for a combined total of 26 distinct services. The BMT and the IND, also known as the B Division share many services because they are of the same dimensions and are compatible – unlike the IRT/A Division which has narrower tunnels and shorter platforms. And even within the IRT itself there is interchangeability as the #2, 3, 4 and 5 lines merge and branch as they wind their way between the Bronx and Brooklyn via Manhattan.

The 34 subway lines were further parsed into 60 analysis segments by RPA, based on line merge points/ junctions (major interlockings) and the age of infrastructure. These 60 segments are used here to analyze the age and capacity of the system.

119 The number of lines is actually 33, RPA added the Grand Central Shuttle as an additional line.

Figure 13: Estimated Age of New York City Subway Signal Segments

Source: MTA and RPA analysis



Age

The last major signal modernization took place back in the 1950s when the IRT/Division A's signals were completely replaced and "dark"[120] areas of the subway signalized. Since this era, the IND/B Division, the last major section of the subway completed in the 1940s has continued to age – it has the oldest signals in the system, some over 80 years old. Additionally, the signals installed during the modernization of the IRT, completed over 50 years ago, have reached the age of the signals they replaced.

Since the first capital plan in 1982, the MTA has invested millions to replace signals along parts of its oldest lines, mostly in Brooklyn and the Bronx with a slightly modernized version of fixed-block signals. The only exception to this rule has been the installation of CBTC on the Canarsie and Flushing lines. The former completed, the latter underway.

The age of signals and related data presented here were provided by the MTA, New York City Transit. The agency defines "age" as the last time a particular segment of fixed-block signaling was completely renewed. While it is not the condition rating of the asset, which is continuously maintained with some components replaced over time, it is a proxy for it. The age of signals is shown in the accompanying figure and table. The MTA provided the age of its signal in ten-year ranges for segments of each of its lines, RPA took the midpoint of each range and then weighted the age based on the length of the segment. The average age for each of the 34 lines is shown in Table 11. Of the 60 analysis segments, 20 have signals that are 50 years or older – the typical (desired maximum) lifespan of fixed-block signal is 50 to 60 years. They include the following eight lines:

- East Side IRT/Lexington Avenue line from 125th Street to the Brooklyn Bridge (4, 5, and 6);
- West Side IRT/7th Avenue Broadway line from 103rd Street to 34th Street Penn Station;
- Broadway line in Manhattan from 57th Street to the Whitehall (R) and a segment to Brooklyn from Manhattan Bridge to Pacific (N, Q);
- 6th Avenue line from 57th Street to York Avenue in Brooklyn (F ,B, D, F and M);
- G line in Brooklyn and Queens;
- Rockaway and Liberty Avenue lines in Queens (A,S);
- Fulton Street line with segment of 8th Avenue line from Chambers Street in Lower Manhattan to Lefferts Boulevard in Queens (A, C); and
- 42nd Street shuttle.

The newest signals are on the Canarsie line, with CBTC completed in 2011. Conversion of the Flushing line to CBTC is also currently underway, along with the replacement of the Dyre Avenue line's fixed-block signals. Of the 34 subway lines in the system, 12 are entirely or in part 50 or more years old. If the

120 This refers to sections of track not equipped with track circuits or any form of signaling. Trains must strictly adhere to the timetable (schedules) to maintain separation.


MTA / Patrick Cashin

Table 11: Estimated Weighted Age of Signals by Line

Lines	Services	Route Miles	Track Miles	Weighted Age
42nd Street Shuttle	S	0.44	1.31	78
Crosstown Line	G	6.61	13.23	78
Fulton Street Line	A C	7.45	29.78	72
Lexington Avenue Line	4 5 6	10.45	36.73	69
6th Avenue Line	B D F M	7.88	22.76	63
Liberty Avenue Line	A C	2.20	6.61	58
Rockaway Line	A S	11.28	22.57	58
Broadway Line	N Q R	9.25	30.31	57
Nassau Street Loop Line	J Z	1.82	5.47	48
Queens Blvd Line	E F M R	13.16	52.65	48
8th Avenue Line	A C B D	15.15	53.49	46
Broadway - 7th Avenue Line	1 2 3	15.26	49.83	44
Lenox Avenue Line	2 3	2.99	5.98	43
Clark Street Line	2 3	2.24	4.47	38
Jerome Avenue Line	4	6.24	18.71	38
Eastern Parkway Line	2 3 4 5	6.61	16.92	32
Astoria Line	N Q R	5.36	13.40	30
Archer Avenue Line	E J Z	1.19	4.77	28
Nostrand Avenue Line	2 5	2.60	5.21	28
4th Avenue Line	R	5.76	19.80	28
63rd Street Line/SAS	Q F	5.14	20.57	28
Sea Beach Line	N	5.29	15.88	28
Culver Line	F	12.10	41.96	24
Jamaica Line	J Z M	10.93	21.87	22
Pelham Line	6	7.71	23.13	18
Brighton Line	B Q	9.18	27.54	18
Myrtle Avenue Line	M	2.75	5.51	18
Franklin Avenue Line	S	1.36	1.36	18
White Plains Road Line	2 5	9.39	26.29	6
West End Line	D	5.83	17.49	6
Concourse Line	B D	5.64	16.93	6
Canarsie Line	L	10.13	20.25	5
Flushing Line	7	9.35	28.04	NA
Dyre Avenue Line	5	3.58	10.74	NA

Source: MTA and RPA analysis

Figure 14: Peak Load Points in the AM Peak Hour Subway

Source: MTA

CBTC priorities were based on age alone these would be considered first for conversion to CBTC.

Capacity

Higher priority could be given to some lines that have signals that are less than 50 years old if the introduction of CBTC could relieve congestion by adding new capacity. Yet, the subway's capacity is not easily defined. Other than the signaling system, multiple factors impact the system's capacity, such as dwell times and physical network bottlenecks. There are lines with untapped capacity (discussed in Chapters 1 and 2), mainly the 8th and 6th Avenue lines or D, B and C services while others run at their limit. However, train throughput is a measure of supply, not demand. The MTA's loading standards are the starting point to understand where additional subway capacity is needed for existing passenger loads.

In Figure 14 the busiest point in the morning peak hour (approximately 8am to 9am) on each line is indicated. In Table 12 each of these 24 maximum load points are listed with NYCT 2011 passenger volumes and the volume-to-capacity ratios derived from them using the scheduled number of trains. The capacity for peak-periods is calculated using the NYCT's space standards. This maximum loading guideline for the most frequent routes is determined by the number of seats plus 3 square feet per person for standees, which amounts to about 4.1 square feet per person when considering the full dimensions of both A Division and Division B cars. Loading guidelines have a sliding scale during peak periods, with fewer customers per vehicle allowed on routes with less frequent service. In the past RPA has suggested a more generous standard of 5.0 square feet per persons,[121] based on a more comfortable level of standing. A revised volume to capacity ratio using this more generous standard, but keeping the sliding scale that the MTA uses, is also shown in Table 12. This adjustment was done assuming B Division cars of 60 feet in in length. Using 75-foot cars would make only a slight difference.

Using the NYCT standard, loading guidelines are exceeded at only four locations: the Lexington Avenue expresses southbound from 86th Street (#4 and #5), the Flushing line express west of the 61st Street station (#7), and both the L train and M trains before they cross the East River from Brooklyn. As shown in Table 12, using the more generous RPA standard another six locations with eight lines would exceed acceptable loading. These include both express services on the west side (#2, and #3), the Lexington Avenue east side local (#6), three crossings carrying four lines from Queens (N and Q at 59th Street, and E at 53rd Street, and the #7 express), and two crossings which carry three lines in Brooklyn (F, D, and N). The D and N three have their maximum load points located well before they reach the East River, and the F line's maximum load point is in Manhattan.

As discussed in Chapter 2, the west side and east side IRT's (#1, #2, #3, #4, #5 and #6) trunk lines are all at or reaching capacity limits of their existing fixed-block signals. The Queens Blvd (E) trunk, Flushing (#7) and Canarsie (L) lines are also strained, but CBTC is already planned, underway or installed on these three. The other lines (N, Q, J/M, F, D) still have some excess capacity under their existing signal systems, making them a lower priority.

Only two lines qualify using both the 50-year age criterion and the capacity criterion – the Lexington Avenue #4 and #5 and 7th Avenue/Broadway #2 and #3 expresses. However, the opening of the first phase of the Second Avenue subway will provide some congestion relief to the Lexington Avenue expresses, but it is still likely that the volume to capacity ratio will be at or above the RPA space standard.

Lines that require capacity relief were checked to see if any were between 40 and 50 years old and thus might be considered a high CBTC priority. While there were some lines where small segments met that age cutoff, there were none where all or most of the line did.

Table 12: Analysis of Peak Load Points and Capacity

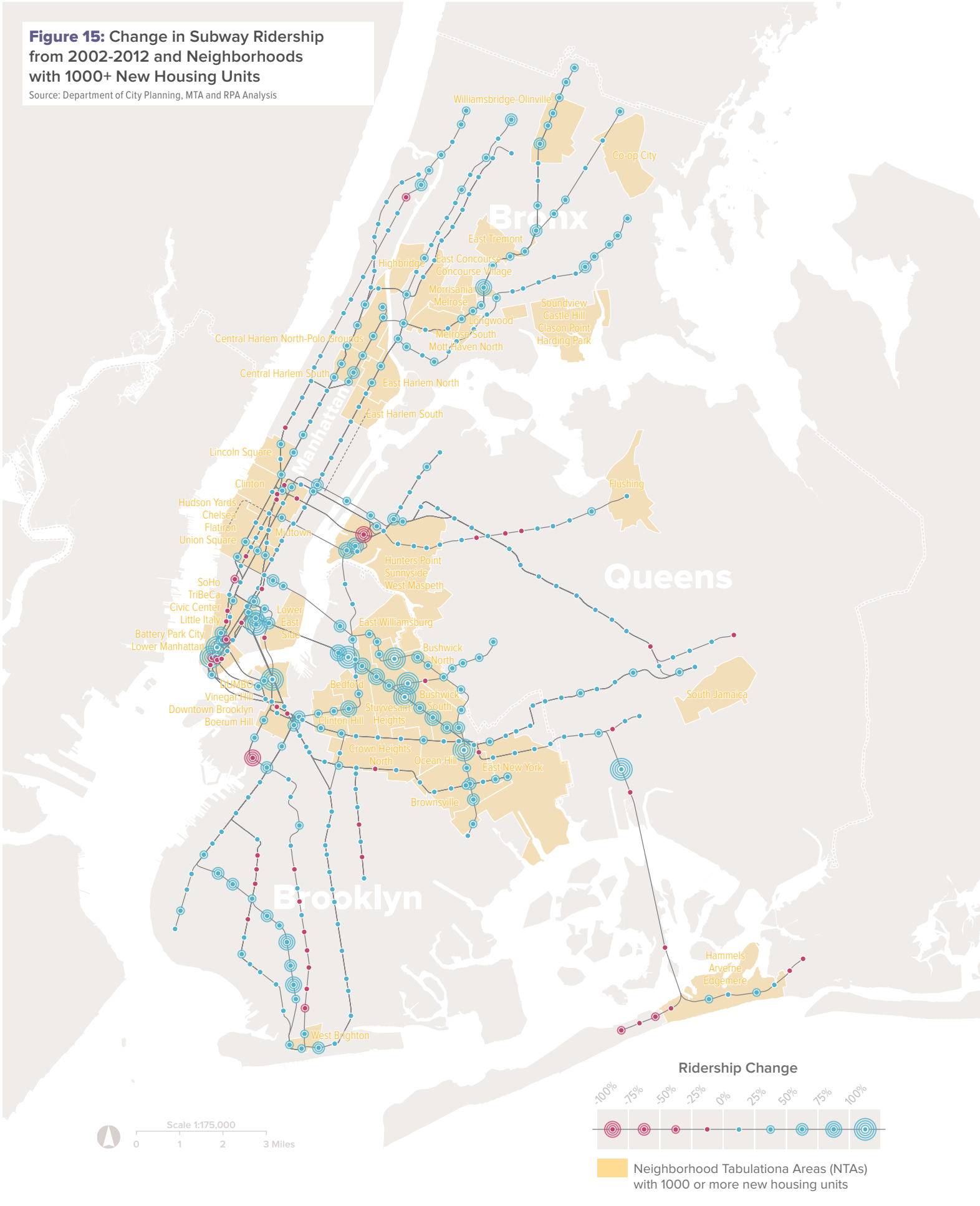
	Route	Peak Load Point	Passenger Volume	Avg. Trains per Hour	Volume to Capacity Ratio with NYCT Standard	Volume to Capacity Ratio with RPA Standard
North of 60th Street	1	103rd St.	17,397	20	0.81	0.99
	2 3	72nd St.	22,685	23	0.91	1.11
	A D	125th St.	22,298	20	0.80	0.98
	B C	72nd St.	9,267	14	0.56	0.68
	4 5	86th St.	29,049	26	1.02	1.24
	6	68th St.	23,515	23	0.95	1.16
Queens	F	Roosevelt I.	17,586	16	0.77	0.94
	N Q	Queensboro Plaza	19,665	15	0.92	1.12
	R	Queens Plaza	9,316	10	0.69	0.84
	E	Jackson Hts./ Roosevelt Av.	22,758	16	0.99	1.21
	M	23rd St. / Ely Av.	5,839	9	0.54	0.66
	7 (express)	Woodside / 61st St.	15,670	13	1.02	1.24
	7 (local)	40th St.	12,872	13	0.81	0.99
North Brooklyn	L	Bedford Av.	21,522	18	1.03	1.26
	J Z	Marcy Av.	11,023	12	0.88	1.07
	M	Marcy Av.	6,793	7	1.00	1.22
South Brooklyn	A C	Jay St. /Metrotech	21,064	25	0.65	0.79
	F	2nd Av.	17,026	14	0.91	1.11
	D N	36th St.	22,902	20	0.89	1.09
	B Q	7th Av.	19,964	20	0.70	0.85
	R	Union St.	8,162	11	0.63	0.77
	2 3	Clark St.	11,405	19	0.55	0.67
	4 5	Fulton St.	1,337	25	0.66	0.81
Intra Queens	G - nb	Greenpoint Av.	3,472	9	0.68	0.83
	G - sb	Clinton / Washington Avs	4,185	9	0.83	1.01

Source: MTA and RPA Analysis

121 Pushkarev, Boris et al, Urban Space for Pedestrians, p.78. MIT Press, 1977

Figure 15: Change in Subway Ridership from 2002-2012 and Neighborhoods with 1000+ New Housing Units

Source: Department of City Planning, MTA and RPA Analysis



Long Island City
Photo: Joe Mabel

Growth and Change

The volume to capacity ratios are based on current (2011) ridership counts. However, future ridership demand could result in crowding that might be alleviated by the introduction of CBTC. But where will this growth occur? Five factors were considered to address this question:

- Recent subway growth that may persist;
- Recent growth in housing in the corridor the line serves;
- Rezoning to higher residential and to a lesser degree higher employment densities;
- Vacant land subject to added development;
- Aging population indicating a possible change in the demographic mix that would use the subway more; and
- Neighborhood household size changes that may signal shifts in settlement patterns that generate more subway use.

Recent Subway Growth

Since 1995 subway ridership has grown by 51.3 percent, and in the last ten years (2002 to 2012) by 17.1 percent. The geographic pattern of this ten-year recent subway ridership growth is depicted by station in Figure 15. [122] In that period ridership in the system rose 38 percent. Growth was concentrated on the L Canarsie line, the inner portions of the J/M/Z Jamaica line and M Myrtle Avenue lines, the A/C line through central Brooklyn, and outer portion of the N Sea Beach line, all in Brooklyn, all stations in Harlem and much of the numbered IRT lines in the Bronx, including the #4 Jerome Avenue line, the outer portions of the #2 White Plains Road and #6 Pelham lines, and the upper portions of the #1 Broadway line.

Rezoning

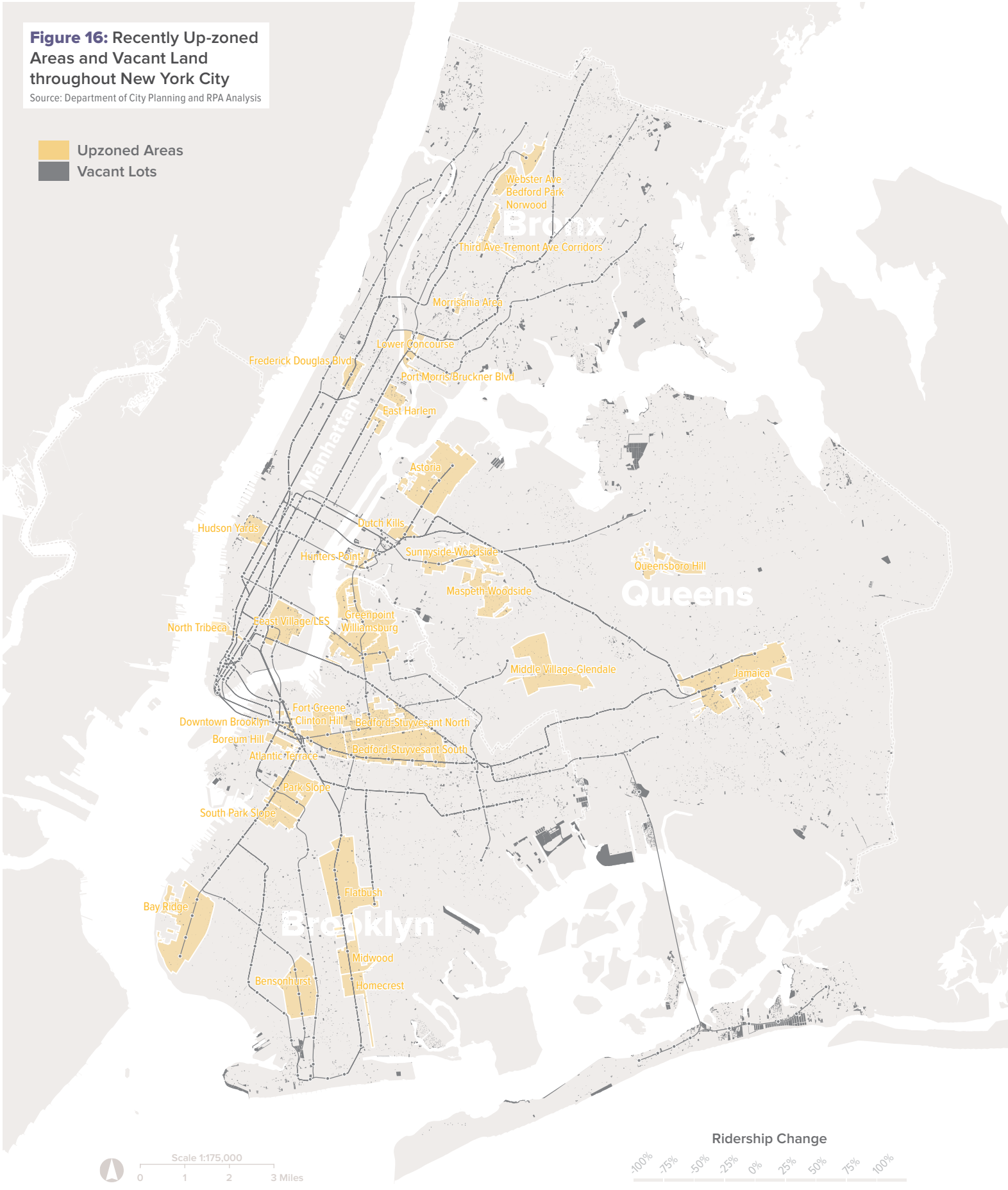
The foregoing suggests that neighborhoods where zoning changes allow for more residential development and areas with significant vacant areas are more likely to add subway ridership in coming years. New York City has rezoned almost 40 percent of its land area during the Bloomberg Administration. While most of the rezoning has been done with the aim of protecting the lower density character of neighborhoods, in some areas high residential densities have been encouraged where they fit in with their surroundings. These are shown in Figure 16. There are 21 areas where this "up-zoning" has occurred.

In the Bronx the up-zoning falls almost exclusively in the Third Avenue / Webster Avenue corridor from 138th Street to the south and as far north as Gun Hill Road. This could produce subway ridership growth on the lower portions of the #2, #4 and #5, but the major impact would be in a corridor no longer served by rapid transit since the Third Avenue El was razed in the 1970s. The up-zoned areas in Queens are dominated by the #7 corridor from Vernon/Jackson station in Long Island City all the way to Flushing. The areas just north of Queens Plaza (7, E, M, N, Q, R), including Astoria, and in Jamaica Center (E, J, Z) round out the Queens picture. In Brooklyn up-zoning has been put in place in Greenpoint/Williamsburg (G, J, L, M, Z lines), Sunset Park (N, R), Bay Ridge (R), South Park Slope and Park Slope (D, F, G, N, R), Fulton Street corridor (A, C), Bedford/Stuyvesant (G and J), and the Flatbush, Bensonhurst, and Midwood neighborhoods all served by the B and Q, to a lesser extent F, N, and D services.

122 In 2004 the N trains in Brooklyn were rerouted over the Manhattan Bridge to serve midtown and in 2010 the M trains were rerouted to Midtown. These changes undoubtedly altered this map, but examination of the years both before and after these changes suggested that the growth on these lines was occurring independent of the service changes.

Figure 16: Recently Up-zoned Areas and Vacant Land throughout New York City

Source: Department of City Planning and RPA Analysis



Nancy Borowick

Vacant Land

Also outlined in Figure 16 are the areas of the City with vacant land. Most of these areas are located at the fringe of the City and largely beyond walking distance of the subway network. Those places with seemingly large tracts of land in southern Brooklyn and Queens are either train yards (Coney Island Yard) or land fill (Spring Creek). A tract in south Brooklyn near Starrett City may be developable, but is not near any subway today. Finally, there are multiple tracts of land in Arverne in the Rockaways. These areas are served by the A train. Thus, with the exception in the Rockaways, the search for vacant land near stations has been largely fruitless. New subway trips generated by new development will have to come from changes in how the land is used near stations and in places accessible to existing subway stations by buses.

Demographic Changes

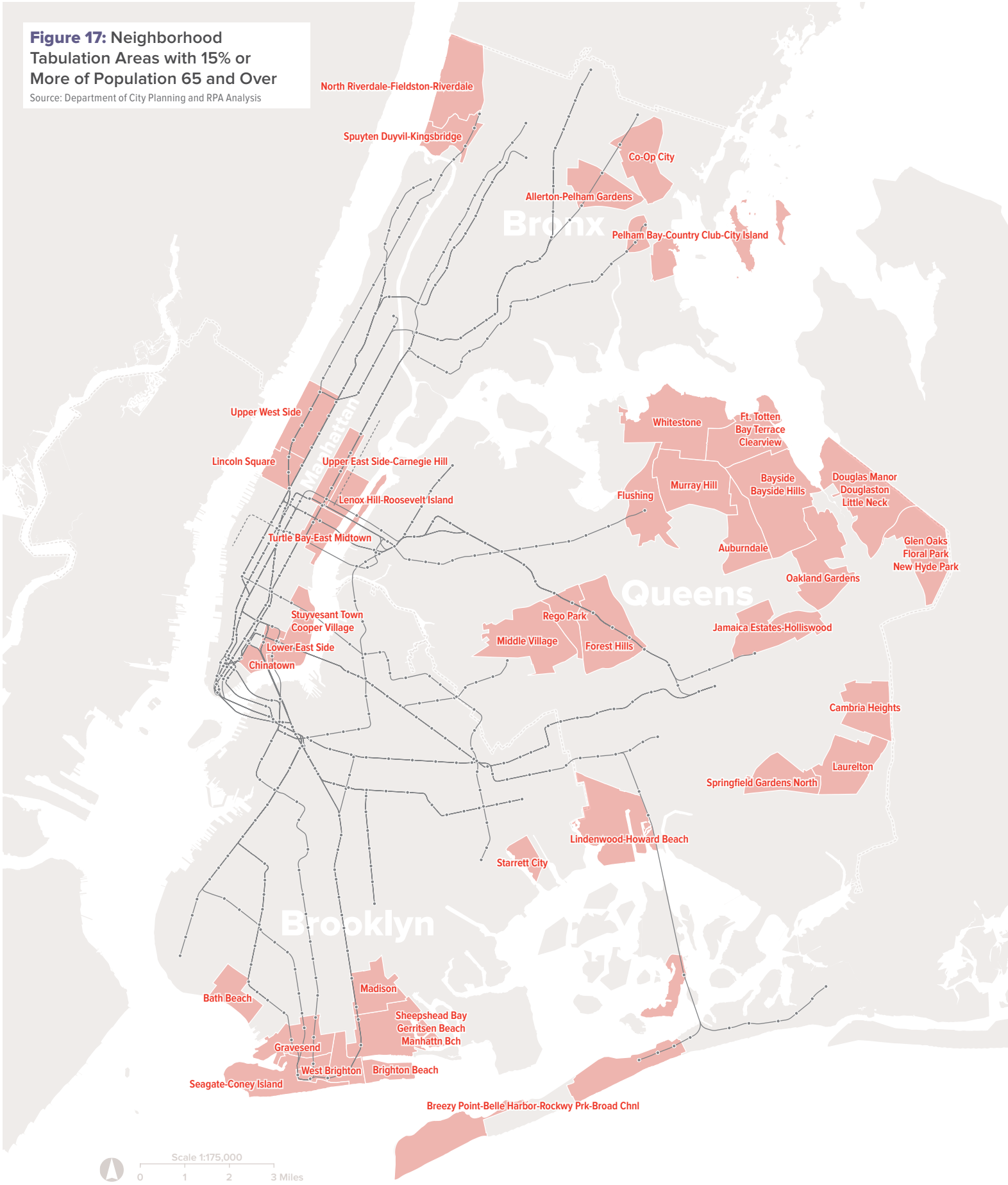
Neighborhoods change and with it come changes in how their residents use the transit system that serve them. Much could be learned from matching the patterns of subway ridership growth by station or line and the changing composition of the neighborhoods served by each station or line. Unfortunately, data that links subway use to the demographics of the neighborhoods and the individual traveler are not easily found or compiled. The phenomenon most often mentioned is the striking growth along the Canarsie L line in Brooklyn (shown in Figure 15), with most of the stations with growth rates well in excess of the system's overall growth. During this period there had been an influx of younger residents looking for reasonably-priced housing within a relatively short commute to jobs in Manhattan. The neighborhoods of Greenpoint and Williamsburg served by that line have seen rapid change toward younger households – the 25 to 44 age households grew from 31 to 38 percent in that Community Board between 2000 and 2010, while the proportion of those 65 and over dropped, reflected in the downward shift in the average household size from 2.86 to 2.61. Thus, a look at where similar growth spurts might be achieved could start with examination of the characteristics of neighborhoods ripe for change: close in places with older populations that could turnover to become younger, particularly where there is lower priced housing.

That younger populations are likely to use the subway more is shown by data for the New York-New Jersey Core-Based Statistical Area (CBSA)[123] which indicates that the daily trip rates per person for all modes are 39.5 percent lower for those over 65 than for adults aged 18 to 64. This may suggest that areas with disproportionally large numbers of older people use the subway less today and as they "age out" the younger people with higher labor force participation rates and more trips to and from work will expand subway ridership. Therefore, a look for areas that are older today could foretell subway growth, if they are also areas where housing is relatively inexpensive. Figure 17 depicts these "older" Neighborhood Tabulation Areas (NTAs). However, of the 44 NTAs where 15 percent or more of the population is 65 or older, most are in higher income brackets – over $60,000 median household income – where housing prices are likely to be high. Almost all of them are on the outer edges of

123 Oak Ridge National Laboratory. United States. Federal Highway Administration. National Household Travel Survey. 2009. Web. <http://nhts.ornl.gov/>.

Figure 17: Neighborhood Tabulation Areas with 15% or More of Population 65 and Over

Source: Department of City Planning and RPA Analysis



the Bronx, Brooklyn, and particularly Queens, mostly far from the subway network. These areas might "age out" but they may not be replaced by significantly younger people, who would be looking for more reasonable housing prices, dampening the extra trip-making effect. The remaining 19 "older" areas that are in the middle to lower income range might be a better source of added trips as they are settled by younger people looking for moderate housing prices, if the commute to Manhattan is not too far.

Unfortunately, this screening device produces limited results; in Queens, Rego Park (M and R) and Flushing (#7) are the only neighborhoods with an older population and moderate income levels and relatively close in commutes. In Brooklyn and the Bronx the neighborhoods in question are all distant from Manhattan. In Manhattan the neighborhoods of Stuyvesant Town, the Lower East Side and Chinatown meet all the requirements, but these areas have already been "discovered," served by the L and by a few stops on lines entering Manhattan from Brooklyn (three stops on the F and one stop one the B and Q).

The average household size in neighborhoods and their changes over time presents some complex but potentially fruitful areas of investigation to identify potential subway growth. On one hand, low household size today could be a sign of an aging neighborhood ripe for turnover to younger populations and more subway use. On the other hand, neighborhoods that have higher household sizes or whose levels are just beginning to drop significantly could be posed for a transition to higher subway oriented populations. Income, housing age and quality, ethnicity, and subway proximity to Manhattan could all be helpful to unravel the complexities of shifts in subway use.

This limited search for the next big thing by examining demographic changes is an important endeavor. The relationship between population shifts and demographics and their effect on subway usage is worthy of more comprehensive investigation as the search for cost effective investments intensifies. It should be the subject of a more nuanced exploration.

Remarkably, when taken together, this examination indicates that most subway lines in the system will experience growth. Standing out are the A and C lines in Brooklyn and the #7 in Queens. The completion of the first phase of the Second Avenue subway should add traffic on the Q and the MTA expects growth on the N from Astoria and continued growth on the J/M/Z and L lines. Only the numbered lines in Brooklyn (#2, 3, 4, and 5), and to a lesser degree the F and D lines seem to be lagging. The Third/Webster Avenue corridor in the Bronx would likely to see substantial growth in subway usage too, yet it lacks only a subway line to make that possible.

Prioritizing Lines by Age, Capacity and Growth

The examination of lines by the three factors – age of signals, capacity, and ridership growth potential – informed our prioritization of CBTC. In some cases lines that scored low are adjacent to lines that scored high; this presents a conundrum because the full benefits of CBTC are not realized until the entire line is upgraded. However, as demonstrated by hybrid systems like the San Francisco's Muni, areas that are experiencing severe capacity constraints or with the oldest signals, would still see significant benefits and should be given higher priority. This exercise is illustrative; its purpose is to provide a public example of how CBTC might be best implemented system-wide and to dimension the MTA's capital need for the full program.

In an attempt to sort out the priorities using three factors, a score was given to each line based on a scoring system using each of the three factors. The factors were also weighted to give the age the most weight and the more speculative growth factor the least weight.

- **Age:** Signals that were 50 years or above scored = 3; 49 years old = 2; less than 25 years = 1. This factor was given a weight of 3.

- **Capacity:** Lines that a V/C ratio (using the RPA crowding standard) of 1 or above at peak-load point or at their line-haul signal capacity score = 3; V/C of 0.85 or higher (85% or greater line-haul capacity) score = 2; anything less score = 1. This factor was given a weight of 2.

- **Growth:** Lines with three or more growth indicators score = 3; two indicators = 2; one or no indicators = 1. This factor was not weighted.

Table 14 (at the end of the chapter) summarizes the finding of RPA's analysis; it suggests a ranking for each of the remaining 32 lines and assigns them to one of seven capital plans.

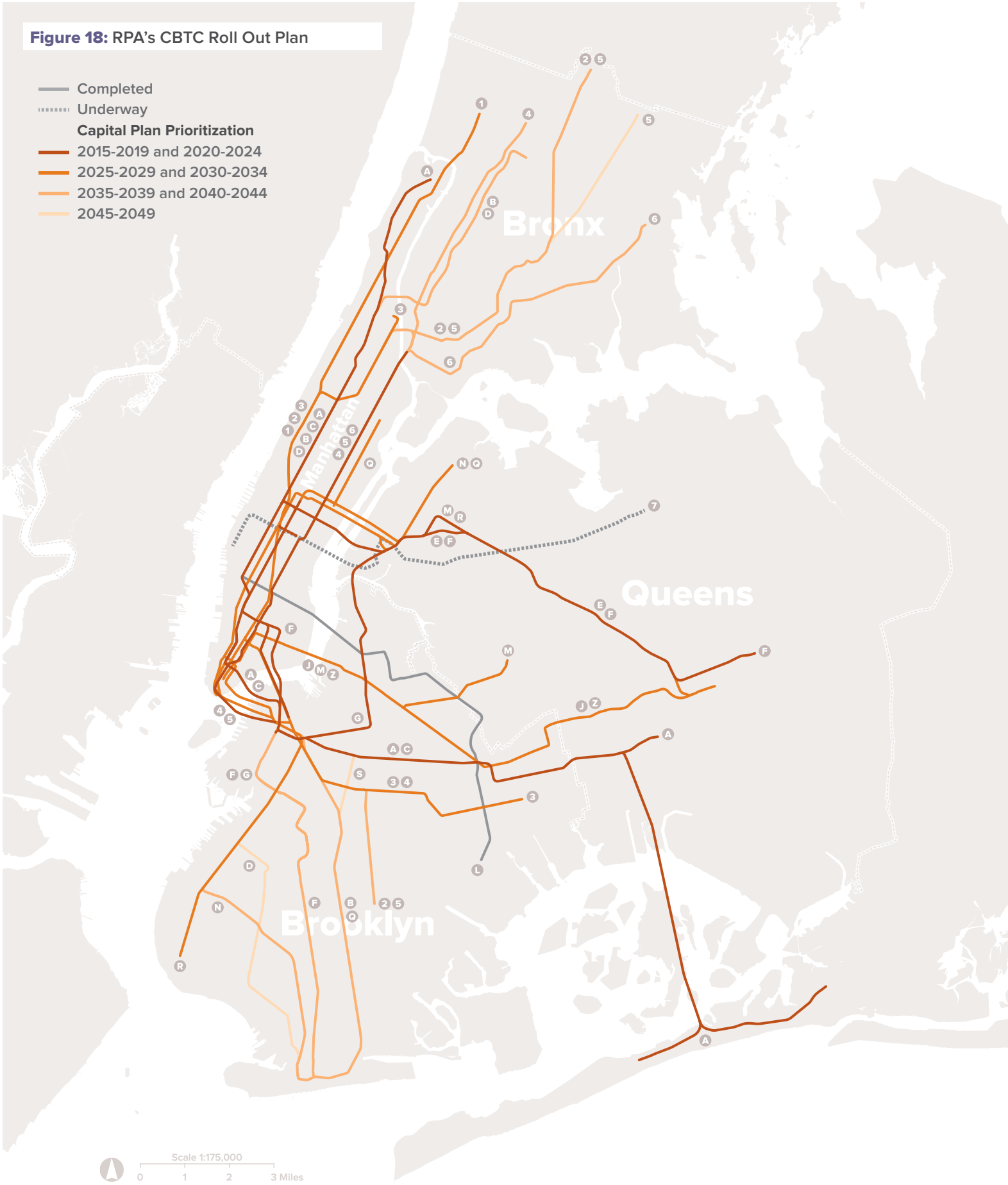
RPA recommends that the MTA set a goal of converting an average of five lines per five-year capital plan. This can vary due to length and the number of tracks, but approximates almost 21 track-miles per year or 105 track-miles for every five-year capital plan. The roll-out plan proposed by RPA in Table 14 front loads more conversion during the next three capital plans to address the advanced age of the signals on some of our lines. The plan also prioritizes adjacent lines to more quickly realize the benefit of CBTC along major trunks. For example, while the 8th Avenue line ranks toward the bottom on all three factors it was given higher priority because the E runs along it and the Queens Boulevard line, which was planned for conversion in the next 2015-2019 plan because it is capacity-constrained. The E express service, a critical subway service for Queens residents, would see additional capacity and reliability benefits if CBTC was extended to its terminus at the World Trade Center.

The final adjustment made to the rankings was to keep the track work to 24 more track-miles or less per year for an overall weighted average of 21 track-miles over the 35 year period of the next seven capital plans, shown in Table 13. This is a 30 percent increase over the MTA's stated goal of 16 track-miles per year. While ambitious and open for debate, it's reasonable when compared to our peers that are converting the same or more – London for example is converting almost 20 track-miles per year.

The Crosstown (G) and 42nd Street (S)[124] lines were prioritized solely because they have very old signals that must be

124 The shuttle could also service as a test-track and staging area for the Lexington Avenue line and later 7th Avenue – Broadway line installations.

Figure 18: RPA's CBTC Roll Out Plan



replaced. The same applies to the Lexington Avenue line, programmed to be upgraded in the 2020-2024 capital plan. While it will experience some congestion relief once the first phase of the Second Avenue Subway opens in 2016, its signals are some the oldest in the system and the line will still be running close to or at capacity. The Broadway – 7th Avenue and Broadway lines were moved up because both lines have segments with aging signals and would also benefit from new capacity.

RPA proposes that the next three capital plans (2015-2019, 2020-2024 and 2025-2029) focus mostly on the major trunk lines in Manhattan, Queens and Brooklyn. The remaining four plans incrementally upgrade branch lines in the outer boroughs, with the last lines being in the Bronx and Brooklyn.

Table 13: Track Miles and Number of Lines Converted by Capital Plan, w/Annual Average

Capital Plan	# Lines	Track Miles	Per Year Average
2015-2019	5	119.7	24
2020-2024	4	119.4	24
2025-2029	6	112.3	23
2030-2034	6	112.8	23
2035-2039	4	99.7	20
2040-2044	4	75.9	15
2045-2049	3	61.6	10
Total	**32**	**701.4**	**21***

Source: RPA Analysis, *weighted average

Table 14: RPA Prioritization for CBTC Implementation

			Line Evaluation				Assignment to Five-Year Capital Plans						
Line	Borough(s)	Service	Age	Capacity	Growth	Score	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049
Lexington Avenue Line	**Manhattan**	4 5 6	9	6	2	17		x					
Queens Blvd Line	**Queens**	E F M R	6	6	2	14	x						
Broadway - 7th Avenue Line	**Manhattan**	1 2 3	6	6	2	14			x				
Fulton Street Line	**Brooklyn**	A C	9	2	3	14	x						
6th Avenue Line	**Manhattan/Brooklyn**	B D F M	9	4	1	14	x						
Broadway Line	**Manhattan/Brooklyn**	N Q R	9	4	1	14			x				
4th Avenue Line	**Brooklyn**	R N D	6	6	1	13				x			
Astoria Line	**Manhattan/Queens**	N Q R	6	6	1	13				x			
42nd Street Shuttle	**Manhattan**	S	9	4	0	13	x						
Jamaica Line	**Queens/Brooklyn**	J Z M	3	6	3	12				x			
Lenox Avenue Line	**Manhattan**	2 3	6	4	2	12			x				
Archer Avenue Line	**Queens**	E J Z	6	6	0	12			x				
Nassau Street Loop Line	**Manhattan**	J Z	6	6	0	12				x			
Crosstown Line	**Queens/Brooklyn**	G	9	2	1	12	x						
Myrtle Avenue Line	**Queens**	M	3	6	2	11				x			
Liberty Avenue Line	**Queens**	A	9	2	0	11		x					
Rockaway Line	**Queens**	A S	9	2	0	11		x					
Culver Line	**Brooklyn**	F G	3	6	1	10					x		
Jerome Avenue Line	**Bronx**	4	6	2	2	10					x		
Sea Beach Line	**Brooklyn**	N	6	2	2	10					x		
63rd Street Line/SAS	**Manhattan**	Q F	6	4	0	10				x			
Pelham Line	**Bronx**	6	3	4	2	9					x		
8th Avenue Line	**Manhattan/Brooklyn**	A C E B D	6	2	1	9		x					
Brighton Line	**Brooklyn**	B Q	3	4	1	8						x	
Clark Street Line	**Manhattan/Brooklyn**	2 3	6	2	0	8			x				
Eastern Parkway Line	**Brooklyn**	2 3 4 5	6	2	0	8			x				
Nostrand Avenue Line	**Brooklyn**	2 5	6	2	0	8						x	
White Plains Road Line	**Bronx**	2 5	3	2	2	7						x	
Concourse Line	**Bronx**	B D	3	2	0	5						x	
Dyre Avenue Line	**Bronx**	5	3	2	0	5							x
Franklin Avenue Line	**Brooklyn**	S	3	2	0	5							x
West End Line	**Brooklyn**	D	3	2	0	5							x

Source: RPA Analysis

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Transformation of New York's Subway

The conversion of the New York subway system to communication-based train control is a springboard for the transformation of the entire system to widespread and lasting benefits. It creates new capacity to accommodate the growing numbers of riders and does so more reliably and safely. The MTA can also realize enormous long-term operating and capital investment efficiencies. The economy of the city, the region, indeed the entire state of New York can be sustained and expanded.

The program of investment and change begins with the upgrade of the signal system and other complementary actions to facilitate the system-wide transition from moving-block technology to CBTC. Companion actions, improving stations and eliminating track bottlenecks, will accrue still more benefits.

Systemwide CBTC Implementation

Upgrade an average of 21 track-miles annually or 5 lines to CBTC during every five-year Capital Plan

The progress to install CBTC on the 728 track-miles of the subway has been painfully slow. Since 1999 on average only 4 track-miles per year have been upgraded. The MTA Needs Assessment has stated a conversion goal of approximately 16 track-miles annually, which would upgrade only about half the system over a 20 year period. RPA recommends that the MTA accelerate the pace to convert on average 21 track-miles annually, transitioning the entire system to moving-block technology decades sooner . While it will still take 30 to 35 years to fully convert the system, many lines would be fully converted much sooner and the benefits to the city would accumulate faster. The transformation would take place over the next seven MTA Capital Plans starting in the upcoming 2015-2019 plan and be completed by the 2045-2049 plan.

This accelerated program would cost on average over $2 billion in each five-year capital plan or $13.8 billion in total.[125] The conversion to equip the subway fleet for CBTC running is estimated to cost another $5.4 billion, or about $1 million per car, based on past experience with the Canarsie and Flushing lines projects. This would bring the total cost for CBTC to over $19 billion in today's dollars over a 35-year period; this figure does not include the cost of upgrading all interlockings or new car procurements. When compared to the MTA's most recent Twenty Year Needs Assessment, RPA's proposal would almost double the investment in CBTC over the next two decades.[126] To meet this goal the MTA will need to expand its FASTRACK program and also explore extended overnight, weekday and weekend closures that might last weeks or months at a time.

The line-by-line prioritization of CBTC was discussed in Chapter 5, and is summarized for each of the next seven capital plans in Table 15. This exercise is illustrative; unforeseen circumstances and operating imperatives can change priorities and the plan should maintain flexibility to address them.

In addition to the proposed subway line roll-out plan above, RPA suggests a number of parallel recommendations to facilitate implementation of CBTC and realize its full value:

These include:

- Conversion of all rolling stock to be compatible with CBTC;
- Replacement of fixed signal assets to CBTC when repair is necessary, rather than investing in equipment that is to be replaced eventually anyway;
- Elimination of the Auxiliary Wayside System (AWS) which currently inhibits the capacity on a line;
- Transforming the organization to adapt to a new operating paradigm instead of holding on to practices from an earlier era;
- Retraining and repositioning workforce to take full advantage of technology investments and better serve customers, creating a "New Deal" with labor to slowly transform how the subway operates ; and
- Converting subway to driverless operations by 2040s to take full advantage of the benefits of CBTC.

These recommendations are fully described in the following section.

All rolling stock CBTC-ready sooner and retrofit mid-life cars for more frequent service

The MTA must accelerate its efforts to upgrade its rolling stock to operate in both moving-block and fixed-block environments. Without the operational flexibility of a larger CBTC-equipped fleet the agency's options will be limited because of the intercon-

125 This cost estimate was calculated using the current cost per track mile in 2013 dollars for the Flushing line conversion and includes additional costs for improving existing CBTC implementations. While the cost to implement CBTC varies by number of stations and unique characteristics of each line, the Flushing line is representative of many lines in the system with subterranean and elevated segments and stations every third of a mile on average. Overtime, as the MTA becomes more adept in rolling out CBTC they should realize greater installation efficiencies, which should help lower these costs.

126 The plan accelerates CBTC investment by frontloading most of the work over the next 20 years, which accounts for $8.6B or 60% of the estimated CBTC installation costs. Over the next 15 years or three plans investment in CBTC tapers off, with the last plan installing CBTC on only 3 lines or 12.3 miles of track.

Table 15: CBTC Line Assignments by MTA Five-Year Capital Plan

Line	Borough(s)	Service	Track Miles	Completed	Underway	Assignment to MTA Five-Year Capital Plan: 2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049
Canarsie Line	Manhattan/Brooklyn	L	28.04	x								
Flushing Line	Manhattan/Queens	7	20.25		x							
Queens Blvd Line	Queens	E F M R	52.65			x						
6th Avenue Line	Manhattan/Brooklyn	B D F M	22.75			x						
42nd Street Shuttle	Manhattan	S	1.31			x						
Crosstown Line	Queens/Brooklyn	G	13.23			x						
Fulton Street Line	Brooklyn	A C	29.78			x						
Lexington Avenue Line	Manhattan	4 5 6	36.73				x					
Liberty Avenue Line	Queens	A C	6.61				x					
Rockaway Line	Queens	A S	22.57				x					
8th Avenue Line	Manhattan/Brooklyn	A C E B D	53.48				x					
Broadway - 7th Avenue Line	Manhattan	1 2 3	49.85					x				
Broadway Line	Manhattan/Brooklyn	N Q R	30.32					x				
Lenox Avenue Line	Manhattan	2 3	5.98					x				
Archer Avenue Line	Queens	E J Z	4.77					x				
Clark Street Line	Manhattan/Brooklyn	2 3	4.47					x				
Eastern Parkway Line	Brooklyn	2 3 4 5	16.92					x				
4th Avenue Line	Brooklyn	R N D	19.80						x			
Astoria Line	Manhattan/Queens	N Q R	13.40						x			
Jamaica Line	Queens/Brooklyn	J Z M	21.87						x			
Nassau Street Loop Line	Manhattan	J Z	5.47						x			
Myrtle Avenue Line	Queens	M	5.51						x			
63rd Street Line/SAS	Manhattan	Q F	20.57						x			
Culver Line	Brooklyn	F G	41.95							x		
Jerome Avenue Line	Bronx	4	18.71							x		
Sea Beach Line	Brooklyn	N	15.88							x		
Pelham Line	Bronx	6	23.13							x		
Brighton Line	Brooklyn	B Q	27.54								x	
Nostrand Avenue Line	Brooklyn	2 5	5.21								x	
White Plains Road Line	Bronx	2 5	26.29								x	
Concourse Line	Bronx	B D	16.93								x	
Dyre Avenue Line	Bronx	5	10.74									x
Franklin Avenue Line	Brooklyn	S	1.35									x
West End Line	Brooklyn	D	17.50									x

Source: MTA and RPA Analysis

Table 16: MTA Rolling Stock Inventory by Category, Year-Built and Model

Category	Years Built	Models	Number	% of Fleet
Old	1964-1975	R32/R42/R46	1,040	16%
Mid-Life	1983-1989	R62(A)/R68(A)	1,764	28%
New	1999-present	R142(A)/R143/R160(A)	3,504	56%
	Total		6,308	100%

Source: MTA and RPA Analysis

nected configuration of the remaining lines that makeup the subway. The full cut-over of the Canarsie line (L) to CBTC was delayed due to insufficient rolling stock and had to operate under the capacity constraints of the fixed-block AWS, negating most of the benefits of CBTC for years.

Table 16 is an inventory of the New York City's 6,308 car subway fleet. Cars can be grouped by three age categories: older, mid-life and new cars. The oldest cars were purchased from 1964 to 1975 (40-50 years of age), they will be replaced during the next 2015-2019 Capital Plan. The newer cars, first procured in 1999 are modern "drive by wire" cars that can be equipped with CBTC – 779 have already been outfitted for the Canarsie and Flushing lines. The costs of equipping these cars have been approximately $1 million per car. The last group of subway cars falls in between these two extremes and were procured in the

1980s. These subway cars have another 20 to 30 years of life before they are retired.

This in-between group was the last of "analog" cars and the MTA has stated they are unfit for CBTC. Yet, there are examples from around the world in Paris and London and right here in the United States of vehicles as old as 40 years being retrofitted for CBTC operation. The San Francisco Muni upgraded their circa 1970s Boeing LRT rolling stock for CBTC operation as part of the Market Street tunnel project

Over a quarter of the subway's rolling stock is not CBTC ready with a lifespan of 20 years or more. RPA recommends that the agency undertake mid-life rebuild on these subway cars as part of the next capital plan, which would include gutting interiors and internal systems to fully modernize the 1,764 vehicles with state of the art communications, train information displays and CBTC – along with new, clean and cutting edge aesthetic improvements. This would transform an old vehicle to a new one, at least from a customer's perspective and extend the life of the asset at the same time. Today, cars are typically retired after 40 years of service and these upgrades could extend their life by 20 or more years. The life cycle cost of this rebuild will be considerably less than buying new rolling stock. In Paris, the RATP has enjoyed savings of 50 percent over procuring replacement cars.

The MTA has stated in its most recent Needs Assessment that it plans to retire its old and mid-life cars by 2027, making its entire fleet CBTC-ready or equipped. We strongly recommend that the MTA stay with its proposed schedule and accelerate it, if possible. The agency should also take steps to overhaul its mid-life cars, which represent almost a third of the fleet. By upgrading these cars and extending their life the agency will be able to increase the frequency of service throughout the system sooner, taking full advantage of the new capacity afforded by CBTC.

Eliminate the Auxiliary Wayside System (fixed-blocks), transition to "pure" CBTC environment

CBTC's lower maintenance cost can save the MTA tens of millions of dollars annually on signal inspections, of which over 90 percent is labor. If it is possible to totally eliminate the AWS, with only CBTC in place, large savings would result. In fact, the FTA recently estimated that an AWS could increase the capital costs of the signaling system by as much as 30 percent.[127]

To date, AWS has been retained for three reasons: as a backup in case CBTC were to fail, as another means of detecting broken rails and to allow unequipped vehicles to run in CBTC territory. None of these reasons stand up to close scrutiny.

CBTC can reliably run without a backup system; the Vancouver SkyTrain is a testament to this statement. It has experienced no accidents due to the malfunction of CBTC in its 26-year operation and has had only two incidents of undetected broken rails over the same period. Its operating agency (TransLink) has also developed and proven operational strategies to quickly recover the system in the advent of a failure. Another example is London. As a system similar in size and age to the subway, it is currently converting its entire Tube system to CBTC and plans to completely remove its fixed-blocks signals to fully realize the cost savings of the technology.

Additionally, the presence of an AWS can actually reduce the overall availability of a signaling system making use of both CBTC and an AWS. This seemingly paradoxical situation is the result of two major factors. First, the backup AWS will require more regular and frequent track-based maintenance, which is more intrusive than that required for a CBTC system. Second, the CBTC system must be able to communicate with the AWS. This requires complex interfaces to facilitate communication between the AWS and CBTC components as well as additional software to interpret these signals, thus introducing additional points of failure to the CBTC system. [128]

With respect to broken rail detection, London and others have determined that track-circuits are not critical for detection and better methods exist. The FTA has also recommended that the limited broken rail protection provided by track circuits not be a major consideration when deciding whether to maintain an AWS.[129]

The best method to mitigate broken rails is preemptive inspection by increasing the frequency of track inspection vehicles (a task that might require the MTA to procure additional track inspection vehicles). This approach ensures that defective rails are replaced BEFORE they break as compared to track circuits that detect the break AFTER it occurs and sometimes not at all.

Finally, there is the desire to maintain the AWS for vehicles that are not equipped, which includes subway cars and non-revenue vehicles. RPA's prior recommendation to equip all subway cars with CBTC by the 2020's addresses revenue vehicles, but not the non-revenue fleet. The MTA has estimated the cost of equipping the work fleet to be approximately $95 million, which includes 172 powered and 289 unpowered cars and also maintenance, spare parts and training costs. This cost could be lowered to between $50-35 million if only powered cars and were equipped, which would require a change in how CBTC recognizes work trainsets[130]. This is less than the cost of maintaining the AWS over a five-year period on just the Canarsie and Flushing lines.

It is also possible for interlockings to be directly controlled by CBTC zone controllers, eliminating the need for additional equipment on the wayside. This is an ambitious change, essentially stripping away the remaining elements of the conventional signaling system, but is a logical and incremental step towards streamlining and reducing the costs of operating and maintaining the system. The MTA has recently stated that they plan to limit the AWS by increasing the block lengths on the Flushing line and potentially eliminate it on the Queens Blvd line, with the exception of the signalized interlockings.

Replace old and damaged signals with CBTC, rather than replace with old technology

CBTC should be the rule, not the exception. Opportunities to modernize the system should not be wasted. The counter argument is that there is little point in installing CBTC if most

127 Rumsey, Alan, Alan Ghaly, Nabil, et al. United States. Federal Transit Administration. Assessment of the Business Case for Communications-Based Train Control. 2013. pg. 118. Print.

128 Rumsey, Alan, Alan Ghaly, Nabil, et al. United States. Federal Transit Administration. Assessment of the Business Case for Communications-Based Train Control. 2013. pg. 116. Print.

129 Rumsey, Alan, Alan Ghaly, Nabil, et al. United States. Federal Transit Administration. Assessment of the Business Case for Communications-Based Train Control. 2013. pg. 114. Print.

130 Under the current CBTC scheme each train set consist of two operating segments, the number of cars in each vary based on the line in question. Longer work trains pulled by locomotives would require the equipage of non-powered cars that are included in the MTA estimate.

trains are not now CBTC equipped or if the fixed-block signals will be retained and need to be replaced anyway. If rolling stock were re-equipped to CBTC sooner and MTA was to move toward a "pure" CBTC environment, removing the AWS and giving zone controllers authority over interlockings, future decisions of this type would tip the scales in favor of replacing the signals with CBTC.

This report recommends that the agency should, whenever possible, replace fixed-block signals with CBTC when they reach the end of their useful life or are damaged. At the very least, the MTA should conduct a system-wide radio survey[131] so it can prepare sites along the railroad for CBTC and possibly to install CBTC while it has extended access, such as post-Sandy repairs. The radio survey would determine the placement of CBTC radios and transponders on the trackside, allowing to lay fiber and place other equipment in preparations for future installations.

Transform organization to adapt to new operating paradigm

While CBTC is a transformative investment, it will not fulfill its potential if the subway operates as it always has. It will not only change the way the subway operates but the role of its workers as well. Subway cars are now an integral part of the signal system. Onboard CBTC equipment is critical to the functioning of the subway, similar to the car's brakes and other vital components. Workers that maintain subway cars need to adapt to this change, with the support and encouragement of management, and provide the same level of service to CBTC equipment as traditional components. The MTA should explore, in collaboration with the labor union, extending rotations for workers that maintain CBTC-equipped vehicles to allow them to gain greater experience with the new onboard train control equipment.

Just as car maintainers must adapt, the subway's managers must do so as well. The hundred-year-old playbook cannot be considered the only and best way of operating the subway. Technology creates opportunities to run the system in different and better ways. Change is difficult and many agencies and organizations hesitate to embrace it. During the implementation of CBTC on the Canarsie line it was found that on time performance was being effected by the NYCT's pre-existing protocol which called for train operators to walk the length of the train after an emergency brake application. While this protocol is useful in older trains to determine the cause of the emergency brake application, the CBTC equipment on the Canarsie line is actually capable of informing the driver as to the cause of the braking. NYCT decided to retain this protocol despite the opportunity to capitalize on a new technological efficiency, effectively shoe-horning the new system into its current operating procedures.[132]

An FTA study of CBTC on the San Francisco Muni further highlights the importance of organizational reforms in tandem with the implementation of new train control technologies. It stated that "Transitioning from a fixed-block signaling based train control system to CBTC requires a dramatic shift in technological and business practices within the transit agency." The FTA also found that, "Open architectures facilitate interoperability between equipment from different suppliers and maximize use of commercial off-the-shelf equipment." To date, the MTA's approach to CBTC has been to adapt the system to its operating environment rather than the other way around. While consistency is important to ensure uninterrupted operations, the agency should explore revisions to its operating plans to take greater advantage of the technology. This could result in even further cost savings, reducing the need to customize the system to the same extent that is typically done today by the MTA (and also others).

Retrain and reposition workforce to take full advantage of technology investments and better serve customers

Transit agencies around the globe are making investments in technology that will allow them to increase their service and reliability with the same or smaller workforce than they have today. The MTA must do the same to control its rapidly increasing costs of operating the subway, of which over 40 percent is attributed to labor – wages and benefits. Under CBTC train operators no longer will drive trains but monitor them. They also manage dwell time in coordination with conductors, who are still is responsible for operating the doors. CBTC, while not a requirement, further eases the transition to one-person-train-operations because it offers another level of safety over fixed-blocks.

New York is the largest system in the world that still has conductors. All of its peers have eliminated them and now have only operators in the cab who are responsible for the doors or have completely automated their trains. Examples of this include London and Paris, both transitioning to one –person train operations (OPTO) decades ago; with Paris just this past year converting Line 1 to driverless operation – eliminating the train driver completely.

Labor must be a partner in this transformation. Systems like Paris have strong unions, but have reached consensus between labor and management that costs are escalating out of control and must be contained. They also understand that this is the only way they will be able to afford to increase service to respond to growing passenger demand. Train operators and conductors in other systems have agreed to transition to roles at stations and control centers.

Today, our system is imbalanced – we have more workers on our trains than in stations. To better serve our customers and provide eyes in the stations the MTA should work with labor unions to shift conductors to customer-oriented services at stations. In Vancouver these workers are cross-trained in many areas, from train systems to providing medical assistance. Beyond this, the agency should explore new roles for their train drivers, which could be to monitor and remotely operate trains in the railway control center – a similar approach that has been taken in Paris.

131 A survey of track geometry and radio reception (interference) to determine the position of CBTC equipment (radio cases and transponders) along the trackside and the spacing of all components (distance in between radios or transponders).

132 Rumsey, Alan, Alan Ghaly, Nabil, et al. United States. Federal Transit Administration. Assessment of the Business Case for Communications-Based Train Control. 2013. pg. 64. Print

Convert subway to driverless operations by 2040s

The MTA should begin to prepare the system for full automation in the 2040s once CBTC is installed. It will save the agency billions of dollars annually and allow it to increase service while keeping their operating costs in check. Full unattended train operations have been implemented around the globe, even in older metros like on Paris's Line 1. Paris has demonstrated that driverless metros can more efficiently use existing fleets, be more energy efficient and can offer greater flexibility, as trains can be put in service through a simple click of a mouse button. However, operating without a train operator does not necessarily mean that all trains will be unstaffed. The MTA could create a new position to provide customer assistance on some or all of their trains. These roving train agents could also be cross-trained to respond to medical emergencies or deal with other crises.

To ensure passenger safety, a driverless subway should have the ability to detect track obstructions or seal off access to the tracks from the platform. Intrusion detection systems (IDS) consist of sensors that alert the CBTC system of track obstructions, replacing the eyes of the train operator. Platform Screen Doors (PSD), erect a wall of glass and steel between the platforms and tracks, preventing objects from entering the tracks. Both options have strengths and weakness. IDS are cheaper, but cannot stop all track intrusions – like a person jumping or being pushed in front of the train. PSD can prevent these tragedies, but are more expensive to install and operate, require a uniform fleet (placement of doors) and our older stations make them difficult to deploy. However, PSD have several added benefits such as:

- Preventing trash from entering the tracks, saving cleaning costs;
- Reducing track fires and resulting delays;
- Eliminating cost of lawsuits filed by families of those killed or injured;
- Securing subway tunnels from access by unauthorized persons;
- Enabling trains to enter and depart stations faster; and
- Installation of Heating Ventilation and Air Conditioning (HVAC) at stations is possible.

Another requirement for full automation is a second wireless network to extend the reach of public announcement and customer information systems to the train. CBTC radios are vital mission-specific devices and do not transmit video and audio; the most they can send is a text message to the train operator. The ability to communicate with customers in real-time is a prerequisite for driverless operation. This report recommends that the MTA explore ways to remotely make real-time announcements on trains and visually monitor their condition, adding safety and security today and to prepare the system for the future. The agency should also explore IDS and PSD. Neither will be easy to deploy but one or the other should move forward. IDS have been proven in places like Vancouver, which does not have a uniform fleet. PSD have helped Paris manage crowded stations and reduce dwell times. If the MTA is able to standardize its fleet, at least within the two divisions, and address station installation issues, the numerous added benefits of platform screen doors make them the preferred option.

Companion Efforts: Station, Rolling Stock and Track Improvements

CBTC will lay the foundation for the amenities and level of service enjoyed by other cities with modern metros, yet it alone cannot remedy all the problems that limit the subway's capacity and threaten its reliability. It will be necessary, at the same time, to pair signal upgrades with additional station, trackside and rolling stock investments, which will inevitably add to the cost of the full program but make it worthwhile. The following two

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recommendations detail the infrastructure investments that will be required.

Enlarge stations, improve vertical circulation to address crowding and other investments

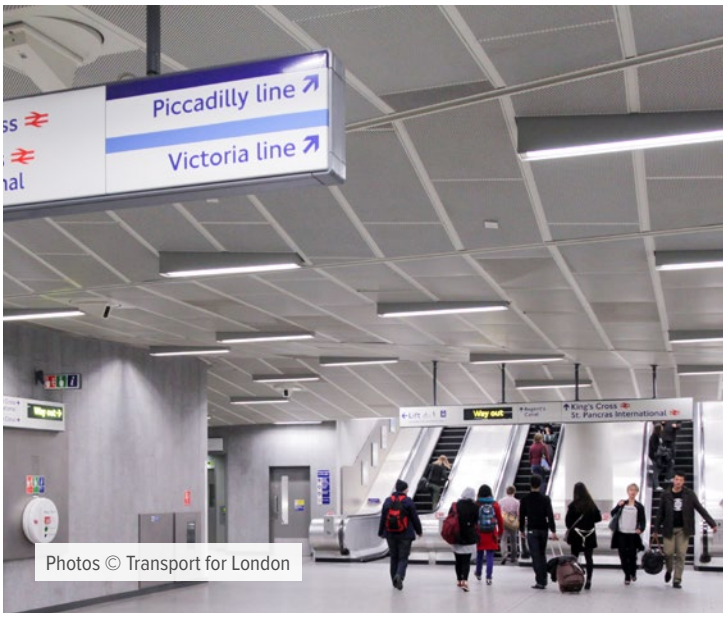
Station dwell time is one of the main restricting factors on a heavy rail line's capacity.[133] When trains are scheduled to run with short headways as is typical with metros, every extra second a train spends taking on or alighting passengers delays the trains behind it. Dwell times in the New York subway can be lengthened by station designs that are inadequate considering the passenger loads they serve. This is especially true at IRT stations which were the first to be constructed and which feature narrow platforms and fewer egress points. These design flaws prevent platforms from clearing quickly and are exacerbated by riders' positioning themselves in cars closest to station exits, causing higher levels of crowding in these cars. One partial solution is to procure articulated or open gangway trainsets which allow riders to more easily redistribute themselves throughout the train while it is motion. These trains also have greater carrying capacities because they capture today's unused space between cars for standees. Platform crowding can also force people closer to the edge of the platform than is safe. Installing platform screen doors would help to protect riders from this danger and would also prevent riders from holding the train doors, a major contributing factor to long dwell times. Finally, especially problematic stations can be physically reconfigured to allow for better circulation by expanding concourses and mezzanines and improving vertical circulation by adding new egress points at platforms and to the street where possible and where problems area most acute. The local platforms at 34th Street on the 8th Avenue (E) and Seventh Avenue lines (#1) come to mind. A redesign of these stations could become part of a larger makeover of the Penn Station complex.

Any or all of these improvements would help decrease dwell times allowing trains to run with shorter headways, thus increasing the system's achievable throughput. Systems around the world have used this strategy to expand their metros to carry greater numbers of riders. In London, the TfL is spending over one billion dollars to add a new train hall at Victoria station, one of the most crowded stations on the Tube. These capital improvements would range from the tens of millions to billions of dollars, a considerable expense but a necessary one.

Eliminate major bottlenecks: inefficient terminals, at-grade junctions and sharp curves

The physical design and layout of the subway's track and stations limit the system's maximum attainable throughput. Terminals are especially critical because of the time required to turn trains there. Although the majority of the terminals in the subway were built using turnbacks which when properly designed should not inhibit capacity, some terminals such as the Parsons/Archer Avenue station on the Jamaica line are problematic. The delays at these terminals are caused by either poor track layout or poor operating practices such as slow crew turnaround time. The first requires that the tracks and switches around the station in ques-

133 Transit Cooperative Research Program. Transit Capacity and Quality of Service Manual. Third Edition. 2013. Web.



Photos © Transport for London

tion be reconfigured, an expensive proposition, while the latter could just take the form of changes in work rules and policies, however this can also take time as any changes would require approval of the TWU but would not require closing a terminal. Fortunately, many of the MTA's terminals are not physically constraining system throughput since they only serve a relatively small number of trains because most subway lines tend to split to one or more branches before terminating.

More critical are investments to mitigate sharp curves and junctions. Track junctions where lines merge can also place limitations on capacity. As with terminal stations they should not inhibit capacity when designed correctly. However, there are problematic junctions in the subway system, most notably at the Nostrand Avenue Junction in Brooklyn where the 2/3/4/5 lines merge. This junction involves a complex merging/diverging of 4 services, some of which must cross in front of each other at grade. This restriction is the result of a conscious policy decision on the part of the MTA so that residents of both Crown Heights (3/4 lines) and Flatbush (2/5 lines) have one seat ride options to either Manhattan's West or East sides. Thus, to retain this feature the MTA would have to physically reconfigure the junction to make it fully grade separated and allow for the 4/5 services to serve the local track on the Easter Parkway line to New Lots Avenue. This would allow for all merging and diverging movements to occur without any impedance. [134] Other junctions such as the 142nd Street one in Manhattan slow trains down not because of service pattern decisions but because of poor design. This junction requires the southbound 2 train to cross the tracks of the northbound 3 train at grade to continue on its route. Any fix to this junction would require a physical overhaul. However, CBTC can help partially ameliorate the delays associated with these and other problematic junctions by allowing the signaling system to "see ahead" and predict upcoming conflicts. When a conflict is predicted the system can dynamically slow and speed trains so that they pass through the junction one after another without having to stop and wait for the other train to clear the junction supporting 120 second headways at problematic junctions which would typically be limited to headways of 150-180 seconds. [135] The MTA should include funding in its 2020-2024 Capital Plan to correct Nostrand Avenue Junction in anticipation of CBTC on the #2, #3, #4, and #5.

Straightening sharp curves is a more difficult proposition. The subway has many S-curves that severely restrict speeds, constraining system capacity. Examples include the 2/3 from Chambers to Wall Street and the 4/5/6 at Union Square, where the station is constructed on a curve requiring mechanical platform-extenders to fill the gap. The MTA should examine the realignment of the subway tunnels in these areas and others. While a substantial undertaking, the benefits of a new short section of track could outweigh its costs.

Conclusion

The subway we have today is far from the subway we need and should expect. Yes, the subway is light-years better than it was 30 years ago when it was neglected and in a state of disrepair. Yet it hardly operates any differently than it did over 60 years ago when we last invested in system-wide changes to modernize signals, improve stations and fix network bottlenecks. The subway is the heart of New York's transit system and of the region's public transit network, which extends like a vast circulatory system through three states with combined population 21 million and growing. It is time to once again transform the subway to a modern world class transit system that will be ready to serve the next generation of New Yorkers and to secure the region's global competiveness.

134 According to the TRB Rail Transit Capacity book, the only time constraint associated with flying junctions is the time to throw and lock their switches which is typically only a few seconds.

135 TRB, Rail Transit Capacity pg. 5-18

Regional Plan Association

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