“Implementing Ultra-Wideband Technology on NYC’s 5 Line: A Pilot Program”

By Jacob Klonsky

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Andy Byford
President, New York City Transit Authority
2 Broadway
New York, NY 10004

Dear Mr. Byford,

Thank you for attending the multimedia presentation that I held at the Bronx-Whitestone Bridge MTA Building on November 15, 2019. Attached is my full project proposal for ultra-wideband signal implementation along the Bronx portion of the 5 line in order to solve the persistent and costly delays that plague the Bronx population.

In the following pages, I will provide a finalized version of my project, starting with a section regarding the variety of problems surrounding the 5's issues. These problems are: the overcrowding and signal age of the 5, which cause delays, the costs that delays inflict on the 346,000 Bronx workers reliant on the subway, the risk of a downward spiral in service quality and ridership due to overcrowding, and the fact that the current plans for the subway neglect using ultra-wideband technology and don't offer any direct solutions for the Bronx. I then move into a series of case studies of signal improvement projects, which includes the L line and the 7 line in New York City along with some specific processes used by the Toronto Transit Commission and the London Underground. These studies provide success-backed methodologies that are applicable in my plan. After this, I apply what is learned from the case studies into a detailed plan that breaks down how to prepare for installation, what to do while installation is ongoing, and what steps to take moving onwards from installation. Next, via a heuristic method, I construct a detailed budget and cost-benefit analysis of this budget that stresses how these costs are necessary, less than what they appear to be, and will save the New York City Transit Authority and Metropolitan Transportation Authority money and time in the long run. Finally, I end with a discussion that summarizes everything in the paper and stresses why it is important that my plan be implemented as soon as possible.

I hope to work with you and the NYCT further in the future, feel free to contact me anytime at 973-864-7225 and jacobklonsky@gmail.com. Thank you for your time.

Sincerely,

Jacob Klonsky

Implementing Ultra-Wideband Technology on NYC's 5 Line: A Pilot Program

Submitted By: Jacob Klonsky

Submitted To: President Andy Byford and the New York City Transit Authority

Address: 2 Broadway, New York, NY 10004

Submitted On: 12/10/19

Abstract

Within this paper, the author proposes a plan to install ultra-wideband signal technology on the Bronx portion of New York City's 5 line. The rationale for this is derived from the adverse effects of delays in the Bronx. The author describes how delays are more common in the Bronx due to overcrowding and poor signal technology and how the these delays increase the chances of economic peril and a downward spiral in subway quality and ridership in the Bronx. As the last piece of rationale, the author explains why current Metropolitan Tranportation Authority plans to improve the subway fail due to implementing inferior signal technology in comparison to ultra-wideband technology and not directly addressing the Bronx's problems. With this rationale in mind, the author then transitions to discussing the successes and failures of methodologies in case studies of signal improvement projects, both in New York City and elsewhere. These case studies include the L line, the London Underground, the 7 line, and the Toronto Transit Commission's testing process, with each study providing successful methodologies and lessons learned to be carried over to the actual plan. The paper then transitions to a detailed plan that runs through many of the necessary actions and considerations that will occur when hiring suppliers, planning installation of new technology, installing that technology, and ensuring post-installation success. The author then runs through all the major costs that their plan would consist of and does a cost-benefit analysis of said costs to justify their necessity. Lastly, the author concludes with a brief discussion, reiterating the major points of the paper and stressing the necessity of immediate action.

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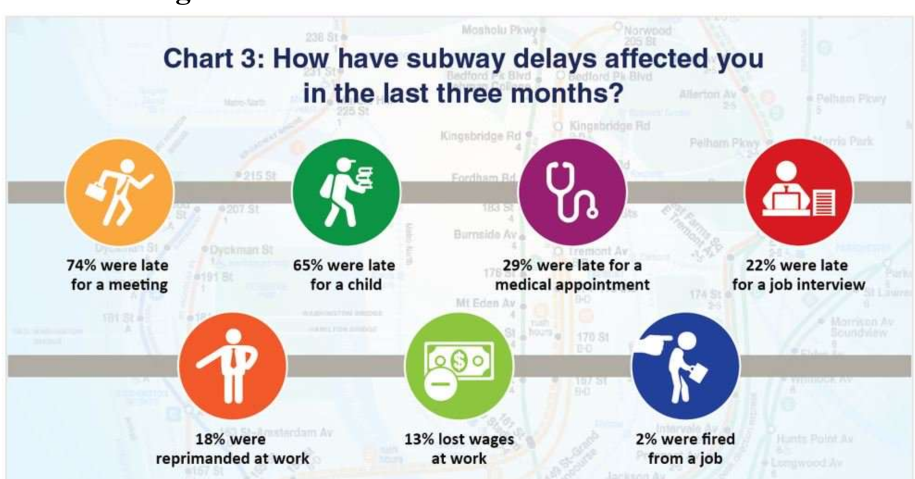
Introduction

Exploring the 5's Problems

The 5 train's signals currently have a weighted age of over 69 years (Regional Plan Association, 2014). This causes inefficient train proximities since old, "fixed-block", signals make train distances "constrained by physical fixed-block boundaries" (Federal Transit Administration, 2013; Farooq & Soler, 2017). To explain this more technically, the way old fixed-block signals operate is that they divide long lengths of subway track into a series of fixed blocks, fixed subsections of the overall length of track. As a subway moves, it occupies multiple blocks at once, alerting other subways that they should not enter any occupied blocks (Zafar, Khan, and Araki, 2011). In practice, this always ensures trains have enough space between them, avoiding any crashes or problems. However, the problem with this is that a block is considered full when even a small portion of a train is in a block, thereby providing much more room between two trains than is ever necessary. "As a result, the biggest drawback of the [fixed-block] system is that a long distance is required between two trains", which limits the capacity of each subway line and the speed of any given train, resulting in high inefficiency (Zafar, Khan, and Araki, 2011). Thus, fixed-block subways have a distance gap, and consequently a time gap, between them, putting a limit on how many trains the 5 line has, how fast they can go, and how often they can run. Coupled with overcrowding, this problem leads to the 5's delays. During rush hour, the 5 regularly has 110% of the maximum passenger amount it can support, well above the system median of 94% (Forman, 2017). With overcrowding, "Dwell time – the period a train spends in the station loading and unloading – balloons" (Fitzsimmons, Fessenden, and Lai, 2017). Extra time at each station adds up, making the 5 increasingly delayed at each subsequent station. Thus, poor signals and overcrowding jointly cause the 5's delays, making only 81.8% of trains reach their destinations within 5 minutes of schedule, compared to the system average of 84% (Metropolitan Transportation Authority, 2019). These delays are the reasoning behind the 5 being called the worst line in the entire New York City (NYC) system by the NYPIRG Straphanger's Campaign (Russianoff & Cohen, 2016). Though improvement has occurred, the 5 remains consistently below-average in its service quality, which is a problem for the people reliant on the 5, especially those in the Bronx (Metropolitan Transportation Authority, 2019).

Figure 1: Human Costs of Delays

Human Costs of the 5's Delays and Overcrowding



(Forman, 2017)

In a 2017 survey by the NYC Comptroller, "sixty-eight percent of Bronx respondents graded subway service a 'D' or an 'F'", the worst rating by far in the survey (Forman, 2017). The reasons for this negative assessment lie in the human costs of the delays of Bronx-serving lines like the 5. Looking at Figure 1, which indicates the percentages of New Yorkers reliant on the subway who experienced specific costs of delays in a three month period, the fact that these specific costs of delays regularly affect a large portion of the NYC commuting population is clear (Forman, 2017). However, these stats are for NYC. With the 5 line and Bronx lines performing worse than the system average, greater percentages of Bronx commuters experience the costs of delays since delays are more frequent (Metropolitan Transportation Authority, 2019). The 53.7% - 60.2% of the 576,863 Bronx workers that rely on public transport also experience more severe effects from these delays than the average NYC worker (American Community Survey, 2017). This is because the Bronx is poorer than the average borough, with 36.8% of Bronx households being below 125% of the poverty level, a low income when considering the costs of NYC (American Community Survey, 2017). This is significantly worse than normal in NYC, as in comparison 24.9% of NYC households are below 125% of the poverty line. Thus, the Bronx working population is poorer than NYC on average while having more delays than NYC on average. Together, these facts lead to another conclusion, that there's far more economic peril in the Bronx due to delays than most other places in NYC. Bronx workers being poorer than average makes them more dependent upon a steady paycheck since they have less saved cash. What this then means is when subway delays make more than 2% of Bronx transport users, at least 11,500 people, lose their jobs in three months, the families reliant on these workers have no excess cash to turn to and fall into serious monetary troubles (Forman, 2017). Even if a Bronx worker isn't directly fired as a result of subways, all the other negative effects of subway costs, like more than 22% of Bronx commuters, 127,000 people, being late for a job interview, still puts poor Bronx workers closer to economic ruin. This is an incredibly costly effect of delays and requires immediate and direct attention.

Yet, this economic peril is not the only cost of poor subway performance. While overcrowding is a cause of subway delays, it is also a consequence of fixed-block technology and delays since overcrowding occurs when subways are not providing service that is adequate to handle rider demand for service. With this causation in mind, the 5's overcrowding causes increased crime and lower customer satisfaction, causing a potential downward spiral in subway service quality. One crime that overcrowding clearly facilitates is theft from passengers. A research paper published in the University of Chicago Press studied some of the truth behind this claim, looking at case studies of public transportation in NYC, London, and Montreal among other places, to find that passenger theft was always greatest at the peak hours of the day, the times with the most overcrowding (Smith and Clarke, 2000). A specific case study from this paper took place in Los Angeles, where it was found that "Ninety percent of crimes on buses and 20 percent of the crime at bus stops occurred when there were twenty or more people present (Smith and Clarke, 2000). These case studies suggest a direct relationship between overcrowding and passenger theft, where more overcrowding leads to more passenger theft. This makes logical sense because overcrowding enables offenders to "operate in crowds where the victims are distracted or unable to protect their property" (Smith and Clarke, 2000). The other major crime facilitated by overcrowding is sexual assault as overcrowding provides an ideal setting for the crime, where victims are distracted and passengers are touching and rubbing against each other. Due to overcrowding enabling these crimes to increase significantly, customer satisfaction typically goes down with increased overcrowding. However, even if not a victim of crime, the average passenger on a train still experiences significant decreases in satisfaction due to overcrowding. Within a research paper pertaining to well-being in public transport, it was found that daily train users tend to have lower consumer satisfaction and that with increases in crowding, satisfaction for all riders decreased (Monchambert, 2015). More precisely, the effect was that on average an extra passenger per square meter reduced customer satisfaction by 1 on a 0-10 scale ranking. This was due to a set of nuisance factors that overcrowding increases. These are: the chance of being forced to stand, overall noise, and wasted time due to increase of dwell time at each station (Monchambert, 2015). Overcrowding's decrease of satisfaction and delay of riders from pressing tasks creates a significant economic cost of congestion, a cost of a decrease in social welfare. As studied in Paris, a subway system of comparable size to NYC, the economic cost of congestion is 64.6 Million Euros per year, or approximately $72.2 million per year for the whole train system (Haywood, Koning, and Prud'homme, 2018). This translates to a decrease in social welfare of about $4.61 million per year per line, which serves as a good estimate of the significant costs the 5's overcrowding has. Being a public corporation, the Metropolitan Transportation Authority (MTA) cares about its customers, so these losses of social welfare, increases in crime, and decreases in customer satisfaction, especially on the 5 but also on every other line, all matter to the MTA. However, what matters even more is the potential for a downward spiral. An unsatisfied Bronx commuter, a customer who has experienced decreases in satisfaction and welfare due to congestion-based crimes and discomfort, won't necessarily just accept poor service, but instead will look for alternatives. Currently in the Bronx, 27.4% of workers commute using a car and 7.6% walk, but these numbers could begin to rise more if customer dissatisfaction with the subway service continues to decrease (American Community Survey, 2017). If this happens, the revenue of the MTA in the Bronx will decrease, meaning that the MTA will have less money to spend and will likely not prioritize that money on the Bronx if ridership is decreasing. This then leads to a downward spiral effect with Bronx subways as less money spent on Bronx subways means the subways will get even worse, so satisfaction will decrease even more and ridership will decrease even more in a repetitive pattern. This is a situation that the MTA should want to avoid at all costs, since this spiral causes the MTA to essentially fail at providing good subway service on the 5 and in the Bronx. This threat of a spiral is most credible in the Bronx because as stated earlier, sixty-eight percent of Bronx respondents graded subway service a 'D' or an 'F'" (Forman, 2017). Thus, customers are more fed up in the Bronx than anywhere else, meaning that they're looking for alternatives more in the Bronx than anywhere else. The MTA certainly should be concerned about this spiral threat and realize that Bronx lines, especially the 5, require help to fix these costs of delays.

Figure 2: The MTA's Plans

(Metropolitan Transit Authority, 2017)

Shortcomings of the Capital and Fast Forward Plans

With the 5 being a significant problem, the MTA has taken steps to try to fix it. These steps come in the form of the 2017 Fast Forward Plan and the 2020-2024 Capital Plan, which both plan for signal improvements on the Manhattan portion of the Lexington Avenue line (which includes the 4, 5, and 6 lines) (Metropolitan Transportation Authority, 2019). However, these plans fail to directly address the struggles of Bronx workers reliant on the 5 by omitting Bronx upgrades from the 10-year improvement timetable

(Metropolitan Transportation Authority, 2017). This is shown in Figure 2, an official MTA graphic (edited slightly for clarity) displaying which portions of which lines will be addressed in the Fast Forward Plan and in what timeframe they'll be addressed. The Lexington Avenue Line, the green line on this graphic, is addressed in Manhattan in the next five years. However, the added yellow line that represents the Bronx portion of the 5 line highlights the fact that no work on the Bronx portion of the 5 is planned for the next decade. This yellow line also calls to attention the lack of any bolded lines at all in the Bronx, showing that no work is planned for the Bronx in the next decade.

Another problem, as shown in the text on Figure 2, is that the MTA plans opt to use Communications-Based Train Control (CBTC) technology instead of better alternatives like ultra-wideband (UWB) technology to improve the subways. While CBTC certainly has merit, and its implementation on a portion of the Lexington Avenue line and NYC will have positive effects, UWB technology is even better. Both signal technologies can work as part of a moving-block system, a newer alternative to fixed-block technology. In this system, "instead of cutting a piece of railway line into fixed blocks, the train's occupying area and some distance in front of it becomes the moving block in which no other train can enter" **(**Zafar, Khan, and Araki, 2011). This concept of blocks moving alongside trains proves immensely beneficial, allowing trains to move much closer together, at faster speeds, and higher frequencies, thereby cutting down on the fixed-block problems of infrequent trains and delays. While both compatible with moving block, these signal technologies have significant differences. According to the University at Albany, UWB would provide a cheaper alternative to CBTC and any other signal technology while simultaneously being more precise, to within 4 inches, thereby allowing trains to arrive at stations more frequently and reduce delays even more than CBTC (Burke & Elgala, 2018; Flaherty, 2004). On top of this, the UWB also is far easier to install than CBTC, provides more accurate speed data, and offers a stronger ability to locate trains even in tunnels and city areas with poor GPS accuracy and signal strength (James, 2018). Right now, the MTA can afford to choose CBTC, but this is the less sustainable solution of the two technologies. The fact is, overcrowding and subsequent delays, will continue to increase. By 2040, NYC will see a 9.5% increase in population and the Bronx will see a 14% increase in population (Department of City Planning, 2018). Seeing as how the current signals of the 5 have been around for more than 69 years, any new signal technology should function well, meaning that it can continue to operate and satisfy consumer demand, until 2040 and beyond (Regional Plan Association, 2014). The fact is, the 5 and the NYC subway must prepare for a much higher demand for trains than there currently is. Seeing how these population statistics are only estimates for population increases and the precise amount of demand for the subway is unknown, it then makes sense to prepare with the best technology possible, UWB, to accommodate high demand. While UWB is in its early stages of testing and I know that you personally have expressed reservations about utilizing unproven technology, it's undeniable that UWB has the potential to provide a cheaper and far more sustainable solution to the problem of delays (Fitzsimmons, 2018). This is exactly why Governor Cuomo has pushed for greater usage of UWB (McDonough). Acting now with UWB would save the cost of having to install CBTC and then inevitably install UWB, for as a better technology than CBTC, UWB will eventually be required to handle the rising subway ridership. Therefore, UWB could work for the NYC subways far beyond the timeframe that CBTC could. Thus, it is problematic that the Capital Plan and Fast Forward Plan neglect plans for further implementation of UWB technology (Metropolitan Transportation Authority, 2019).

Literature Review

The L Line's Installation Process

Seeing as that UWB needs to start being implemented in NYC and the Bronx population, especially along the 5 line, desperately needs assistance, it makes abundant sense to initiate a project for the installation and implementation of UWB along the Bronx portion of the 5. In order to complete such a project, case studies of previous CBTC projects can be looked at to provide lessons and successful steps that are applicable to any signal improvement project. This is applicability is certainly true for the case of the L line, the pilot installation of CBTC technology in NYC (Regional Plan Association, 2014). This project is particularly useful as it being a pilot installation provides significant first-time lessons and problems that may potentially happen in the process of a pilot UWB installation without corrective action. Starting with phase one, where a supplier for the installation was selected, this project consisted of three distinct phases (Braban and Ghaly, 2006). In phase one, through a process where suppliers demonstrated their CBTC systems on a special test track, the NYCT (New York City Transit Authority) selected Siemens, a supplier with experience with CBTC in Paris (Regional Plan Association, 2014). However, Siemens wasn't the only supplier selected. Rather, the selection was a joint-venture between Siemens, Union Switch & Signal, and RWKS Comstock (Braban and Ghaly, 2006). The rationale behind this was a case of cost-benefit analysis, where the benefits outweighed the costs. For a big project, having multiple companies certainly is a significant cost because it makes communication much harder. Rather than just having levels of bureaucracy in a single company and the MTA, there is now even more coordination needed with more bureaucracy and more people involved. However, the significant benefit here is that more companies allows more specialization between the companies involved. This is what enabled the joint-venture to decide that RWKS Comstock would be the lead contractor in phase two, overseeing the actions of the other "follower" contractors (Braban and Ghaly, 2006). Even with a team of technologically advanced companies, with Siemens being especially experienced, significant changes would have to be made from Siemens' last CBTC project in Paris (Regional Plan Association, 2014). This was because the NYCT aimed to use a new CBTC system that wasn't industry standard, leading to a longer period needed to develop and test the system. This extra time is a clear consideration for a UWB project as this project would require contractors to develop and test a system as well. One unique change from Siemen's previous experience was due to the NYCT's system requirement of interoperability, which required that "CBTC-equipped trains running on one line are able to operate over other CBTC-equipped lines, independent of which signal company supplied the equipment" (Braban and Ghaly, 2006). The NYCT's rationale behind this unique request was and continues to be that subways having the flexibility to operate on any signal company's system means they can operate on the best one. Thus, this choice not only potentially improves the quality of the subway system but also fosters competition between suppliers. This choice also ensures that no one supplier has a monopoly on helping the system, keeping costs of projects down since supply of contractors is higher. The significant benefits of this requirement and the fact that this requirement has previously used suggest that this requirement should be added to any UWB plan.

Having chosen the contractors and given them guidelines and requirements, the project moved into phase two. As mentioned earlier, RWKS Comstock took the lead in this phase while other contractors worked as followers (Braban and Ghaly, 2006). An important note is that another contractor not part of the joint-venture that applied for the main contract, Alcatel, was awarded a follower contract where they assisted the joint-venture in phases two and three. Phase two consisted of re-signaling the L line and designing and installing CBTC equipment on the new trains cars to be used (Braban and Ghaly, 2006). Each company was assigned a specific part of this overall step, with the details of each company's work laid out in Figure 3. Note that Alcatel's task wasn't specified in any sources, likely because they were helping all the other companies with tasks instead of having their own unique task. While in the proposed project, these tasks would be with UWB, the fact is that all these specific portions are steps needed in any UWB project. Thus, it's important to recognize that we will need to do all these tasks, and that this kind of subdividing of tasks between contractors has proved effective in the past.

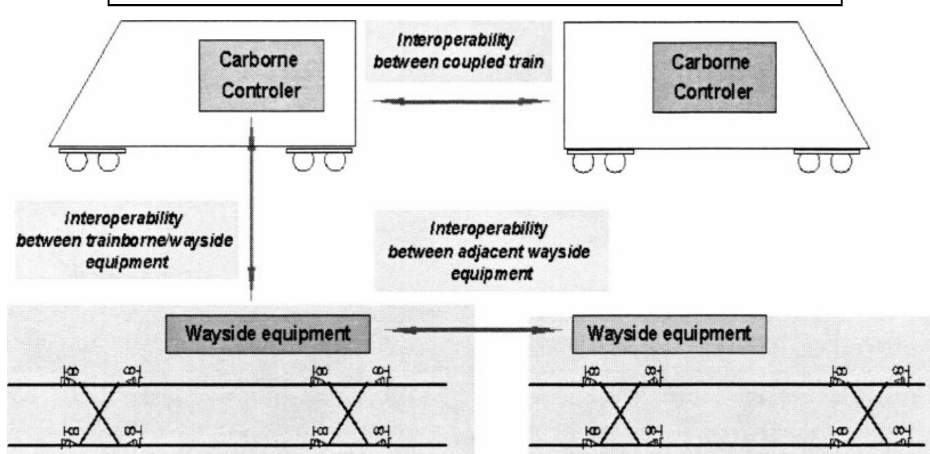
Figure 3: Subdivision of Contractor Tasks for the L

Siemens	U&S	RWKS Comstock
• Design and provide CBTC equipment (wayside and carborne) • Project management and system integration	• Provide signaling equipment that can automatically stop a train if needed	• Lead contractor • Install all equipment • Develop standardized interoperability specifications for follower contractors

(Braban and Ghaly, 2006)

Phase two had two other things of note. First, there was another company involved in the phase 2 process, Kawasaki, the provider of the trains (Alexander, Mortlock, and Hamilton, 2005). Note that this providing wasn't just dropping off a basic design either, but instead required intense coordination due to the carborne equipment, equipment used on the train car, being the most complex system to install upgrades in. Thus, Kawasaki coordinated heavily with the other contractors to develop cars of the proper specifications along with an installation manual, detailing exactly how the workers RWKS Comstock could install the carborne technology (Braban and Ghaly, 2006). One last remark is that the entire upgrade process was completed with minimal shutdown of the L line itself. The only shutdowns that occurred were during non-rush hour service and weekends. This was certainly difficult to do, requiring that CBTC-equipped cars function on fixed-block technology so that they could run on the full line even when only part of the line had CBTC installed (Regional Plan Association, 2014). With phase two complete, phase 3 began. While given its own phase, this process was simply a demonstration of interoperability between all the developed CBTC technology (Braban and

Figure 4: The NYCT's Interoperability Requirements



(Braban and Ghaly, 2006)

Ghaly, 2006). The interoperability requirements, requirements that we will continue to follow in a UWB project, are diagrammed in Figure 4. Utilizing a CBTC-compatible test track, all these interoperability requirements were checked and satisfied for the L line, concluding the phases of the project and enabling full integration of CBTC to occur.

With the contractors' process fully studied, some other lessons and methodologies can be extracted from a more comprehensive overview of the improvement of the L. One such lesson is evident from the budget for the project. Despite the goal being CBTC on the L, only $78 million went towards CBTC installation while $262 million went towards general upgrades (Regional Plan Association, 2014). This was because the L's general equipment had to be at a high level of functionality for CBTC use to work. Necessary general equipment improvements include tasks like track maintenance and improvements to line equipment, line structures, traction power, and anything else that is necessary (Metropolitan Transportation Authority, 2019). With regards to the timeline for improvements, initial installation ran from 2003 to 2006 (Regional Plan Association, 2014). Then, from 2006 to 2009, when installation of CBTC along the entire L was finished, trains were required to operate with both CBTC and the old fixed-block technologies. This was a necessary step as it allowed a partially improved operation of the line while installation was still in progress (Federal Transit Administration, 2013). However, even with a partial improvement, the line's operation was lackluster, substandard for NYC. From the partial integration of CBTC on the L line in 2006 until after completion in 2009, several other problems arose. First, it took the L several years after 2009 to run fully on CBTC due to a shortage of CBTC-equipped cars. This shortage was a result of the communities along the L line receiving a population surge at "more than double the rate of the rest of the city" (Regional Plan Association, 2014), causing a 5% increase in population over ten years. This growth was unanticipated and coupled with rising tourism along the L line to create a 93% increase in ridership from 1999 to 2012. Without enough CBTC cars, even after 2009, the L line had some trains on the old signals while others used CBTC, substantially lowering the hourly train frequency of the L. One last difficulty that rose from this population surge came from how weekend ridership of the L was 7% higher than other lines, making scheduling maintenance and improvements of the line that didn't inconvenience riders difficult (Regional Plan Association, 2017; Braban and Ghaly, 2006). This led to reduced weekend work hours, and a slower overall job as a result.

Though it had its problems as a pilot program, CBTC on the L line did ultimately lead to success. Over the past four years, the L line has averaged over 90% of trains arriving at their destinations within five minutes of schedule (Metropolitan Transportation Authority, 2019). This is metric, called the on-time performance, is "roughly 30 percentage points better than the system as a whole", showcasing the efficiency of modern signals (Regional Plan Association, 2014). This achievement was coupled with other tangible effects of decreased terminal to terminal travel time and improved flexibility of operation. This is because better signal technology allows trains to be more precisely routed and move at a faster speed, meaning that rerouting a train becomes much easier than before with fixed-block technology. These statistics reinforce the conclusion that the L line was a quantifiably successful project with new signal technology and speak volumes about the potential benefits UWB could have, given that it is more powerful than CBTC.

The London Underground's Experience

Moving away from America, the London Underground's (LU) implementation of CBTC gives another valuable perspective on how to modernize train signals due to the LU's "similar age and complexity to New York's subways" (Regional Plan Association, 2014). In response to a 300% increase in subway usage from 1980 until today, the LU decided to create the Tube Improvement Plan with hopes to "increase capacity by 33%" through the rapid roll-out of CBTC (Federal Transit Administration, 2013). This plan is happening now, after a CBTC installation on the Jubilee, Waterloo & City, and Victoria lines while the LU was switching between private and public control. This switch led to three different vendors used for installation, resulting in incompatible technologies that make maintenance on these lines complex and costly (Regional Plan Association, 2014). This is an important lesson for the 5's plan, because in pioneering the use of UWB technology it needs to be setting uniform standards for use in future UWB projects. With regards to the LU's current plan, an important step following CBTC installation is planned, the removal of old technology. The rationale is that "maintaining both systems is expensive" and fixed-block technology wouldn't help the CBTC (Regional Plan Association, 2014). Thus, there's no point in maintaining the fixed-block signals. In addition, while CBTC does allow for driverless control of subways, the LU plans to use a conductor to operate doors and monitor performance. Overall, this plan is expected to "offer the best return on investment with the lowest implementation risk" while improving service (Federal Transit Administration, 2013). These high expectations are due to the previous successful CBTC installations, which have resulted in the renovated lines having the lowest train delays over 15 minutes, the lowest extra time spent on a train, and some of the lowest wait times in the London system (Transport for London, 2019). These lower wait times are a direct effect of how CBTC allows for more trains to run per hour (TPH), increasing Jubilee's TPH by 33% and Victoria's TPH by 22% and improving the "Tube" in general (Regional Plan Association, 2014).

The 7 Line

Back in NYC, the recent installation of CBTC along the 7 line, finished in 2018, provides another set of successful decisions and lessons (Cook, 2019). The success here is already quite measurable, "with an on-time performance that jumped from 74.7% in November 2018 to 91% in March" (Cook, 2019). Now, the 7 line's on-time performance, the percentage that trains arrive at a station within five minutes of schedule, is constant at 92%, showing that the 7's quality jump due to improved signal technology is sustainable (Metropolitan Transportation Authority, 2019). This jump was the result of eight years of procedural steps, beginning in 2010. First, the MTA awarded a $343 million contract to install CBTC on the 7, with installation starting with minimal delay due to the hiring of a vendor with extensive CBTC experience. (Regional Plan Association, 2014; Fitzmaurice, 2013). On top of this, they budgeted $550 million for signals and infrastructure improvement and $613.7 million for a CBTC-compatible fleet. In its next steps, the MTA tested the system in "shadow mode", with conductors controlling trains with fixed-block signals while monitoring CBTC functionality. This was a necessary step since CBTC does nearly all the work of the conductor, so testing with the conductor assured the CBTC could function alone. After this step, the final checks for the CBTC system were completed, and the system became "substantially completed" (Regional Plan Association, 2014). These steps provide a framework applicable to UWB, and the 7's success proves this framework's validity.

Testing Guidelines from Toronto and the L line

While “shadow mode” certainly is a helpful guideline for testing, it’s far from the only test that a typical CBTC installation requires. Thus, there is a necessity to look at how the Toronto Transit Commission (TTC) approaches testing and preparations for integration of new technology along with some extra notes pertaining to how the L line was tested. A case study of the TTC’s methodology on how to test new subway extensions on the recently-opened Toronto-York Spadina Subway Extension (TYSSE) provides a great look at a successful testing methodology. With installation of equipment complete, the process of commissioning is initiated, where all equipment and systems are audited for functionality (Toronto Transit Commission, 2017). While this same level of depth of audit doesn’t necessarily have to be applied to a UWB project, since it may keep some of the old infrastructure in place, significant aspects of the audit apply to the renovated aspects of a UWB project. While commissioning consists of many parts, this case study will focus on what is relevant to this current project. The first relevant step in commissioning is integration testing (Toronto Transit Commission, 2017). In this step, station to station communication and station communication with control centers is tested, measuring how effectively information is being relayed between all components of the integrated system that monitors and directs the subways. Naturally, a very high standard of communication is necessary so that subways are being correctly monitored and routed effectively without incident. This is of great importance to a UWB project as bringing in UWB technology may disturb current methods of communication since UWB is a fundamentally different way of tracking train movements (James, 2018). The next major step after integration testing is to turn on traction power and test run trains, this is where “shadow mode” is of use, but also where a look at the L line’s testing also proves useful. The L’s testing consisted of a series of different tests, starting with a single static train test (Alexander, Mortlock, and Hamilton, 2005). This test involves testing carborne signal equipment via simulated commands produced and communicated by carborne emulator software. These commands emulate the commands of a zone controller, the control station that manages trains in a given area. After being fed a simulated command, the carborne signal equipment’s response to these commands is measured, giving an indication of if carborne signals are responding quickly and if they are responding with the appropriate response to the instruction given (Alexander, Mortlock, and Hamilton, 2005). The L’s work also contained two other relevant tests for a UWB project. First, the L used radio tests. These tests checked the ability of onboard signal equipment to transmit information and receive information at typical levels of signal strength and levels of signal strength with some communication loss. Good performance here implied that even if signal conditions were for some reason worse than typical conditions, functionality would not be significantly affected. The last useful test of the L is a non-CBTC configuration test. This test is a prerequisite before any shadow mode testing as it ensures CBTC can work in a state where it’s functioning but not control of the train, meaning that the CBTC has the functionality to engage in shadow mode testing (Alexander, Mortlock, and Hamilton, 2005). This is a test of importance to the 5’s UWB implementation since a UWB system must be able to pass this test in order to run in shadow mode. With these tests in mind, we can move back to the finishing elements of the TTC’s process. After testing, the TTC moves fully into preparations for full functionality. This implies a series of steps consisting of completing facility certification, beginning TTC staff training, and then signing off on a system safety certification and opening the line (Toronto Transit Commission, 2017). The most important takeaway from these last few steps is the necessity of training. While easily forgotten, it’s logical that new technology like UWB or CBTC will require new procedures and thus a newly trained staff that is comfortable with these procedures. This is something that must be included and given a significant amount of time to complete in a UWB project since UWB will fundamentally alter operations when compared to the antiquated fixed-block system (Zafar, Khan, and Araki, 2011). While lengthy, the commissioning process in Toronto is a strong check on operability that has led to demonstrated success. This commissioning process proved undoubtedly effective, leading to Toronto's 1 line maintaining an on-time performance around 91.7% and contributing to Toronto's system of four lines having a mean distance between train failures of 514,587 kilometers (Toronto Transit Commission, 2019). Thus, this process led to the 1 line maintaining a high degree of excellence in its functionality and to the TTC's system as a whole having a high level of technological quality, leading to the average distance between train failures being nearly 13 times the circumference of the earth. Therefore, just as how the L's process has been proven effective, through similar metrics the methodology used by the TTC has proven effective as well and consequently been proven useful and applicable to the 5's UWB.

Synthesis of Case Studies

Figure 5, the chart below, summarizes our main considerations from each of the case studies in the section above, showing steps that we will be utilizing in our plan for the 5 line:

Figure 5: Synthesis of Case Studies

Subsection	Uses and Lessons Learned
The L Line's Installation Process	• Experienced suppliers in a joint-venture • Subdivide work between companies with leaders and followers • Coordinate heavily with car providers, make a manual • Avoid shutdown of line if possible • Use two technologies on cars while still installing • Interoperability requirements with demonstration of compliance • General upgrades matter • Pay attention to population, tourism, and overall ridership
The London Underground	• Remove fixed-block technology when finished • Use a conductor while new signal technology operates • Pioneer uniform standards as a pilot program • TPH metric for performance
The 7 Line	• Experienced supplier leads to minimal delay • "Shadow Mode", an important testing step • Recent proof of new signal technology being effective
Testing Guidelines from Toronto and the L Line	• Commissioning and its main steps • Integration testing • Single static, radio, and non-CBTC (now non-UWB) configuration tests • Necessity of training staff

Plan

Preparations for Installation

Figure 6: Greater Bronx Subway Map

(Metropolitan Transit Authority, 2019)

Our project is a pilot program, installing UWB along a portion of the 5 line in hopes of displaying the power of the technology and encouraging further implementation of UWB in the NYC subway system. To begin this project, we must exactly define where we will install UWB. Referencing Figure 6, the area that we want to focus on is the two branches of the 5 that follow the go from 138 St-Grand Concourse station to the respective ending stations of Eastchester Dyre Avenue station and Nereid Avenue station, for this is the full portion of the 5 that stretches in the Bronx and isn't being addressed in current MTA plans. Note that this area does overlap with a segment of the 2 line, but this is of little consequence because we will minimize closure of the line during construction and preserve the fixed-block technology on the overlapping portions of the 2 line while adding UWB technology. With an established for UWB, the next step is to find contractors. We do this by having contractors develop preliminary attempts at UWB systems. Just as with the L, we can evaluate these attempts on a test track and use them to help us choose which contractors we want (Braban and Ghaly, 2006). While we will certainly consider all our options, a joint-venture of experienced contractors is the logical choice since they have already considered how to organize themselves and split up tasks. This experience should allow us to start the project quickly since our contractors will be prepared, just as what happened with the 7 line. Even if we do hire a joint-venture though, we should still consult with the joint-venture on the viability of having other follower companies join our project. Through a separate process we'd also need to select a supplier of the subway cars we will make compatible with UWB technology if this hasn't been done already for the Capital Plan's CBTC installation on the Manhattan portion of the 5. Overall, when choosing contractors experience on the L is of particular use since a company with L experience would be more familiar with the mindset and overall process required for a pilot project. Once contractors are hired, we can sit down with them to create a proper timeline and divvy up tasks between contractors. Here, the L's time of three years for partial integration of the new technology and four years for planning is a good total time estimate for those portions of this project because the L is another project of similar size that used new technology (Regional Plan Association, 2014). Additionally, for dividing tasks, Figure 3's division of contractors for the L works as a useful model. This means that if we had four contractors, A, B, C, and D, we would assign A the lead role, putting them in charge of actual installation, while B would be assigned the responsibility of designing a proper system that utilizes UWB, C would be assigned the responsibility of optimizing the UWB signals of the system, and D would act as a follower that could assist all of the other firms. While this splitting of tasks effective, it won't lead to a desired product unless we are very clear about the requirements needed for the UWB system. These requirements, which should be discussed internally, should include interoperability as described in Figure 4, where carborne equipment should be interoperable with itself and wayside equipment and wayside equipment should also be interoperable with other wayside equipment. It is also at this point that we would also confer with contractors to determine a formalized budget for the process, checking the feasibility of our budgeted amounts with the approximate budget in the section of this paper following the plan, which has been in part derived from the L's inflation-adjusted total expenditures. With all this preparation out of the way, the next step is simply to begin installation.

Installation and Post-Installation

While this part of the process certainly consists of installation of UWB technology, it also consists of replacement and renovation of existing infrastructure along the Bronx portion of the 5 as well. This is because in order to fully utilize the UWB technology, all the supporting features that help the technology must also be improved. We know for a fact that the 5's train cars need to be replaced, but we also need to do extra work on line structures, traction power, line equipment, and miscellaneous extra things like emergency services. With these improvements and UWB installation both happening, it certainly will be difficult to maintain operational capacity of the 5, but we have steps that can allow us to accomplish this. First, we will continually monitor population growth, tourism, and general ridership trends on the 5 in order to find the best times to close the line and perform necessary installation. Monitoring this data also helps us to project future ridership, which we can then use to purchase enough UWB-compatible cars to ensure that we'll have enough usable subway cars upon completion of installation, avoiding a mistake made on the L. To keep the 5 running during installation, we will also ensure that the UWB-compatible cars are also compatible with CBTC and fixed-block technology. This is so that as we start putting UWB-compatible cars on the 5, trains can run on parts of the 5 that have new UWB technology, old fixed-block technology, and the new CBTC technology that is being installed as part of the Capital Plan and Fast Forward Plan. This is a very attainable goal though as CBTC and UWB systems are similar and thus fairly compatible and we already know that it's possible run new technology and fixed-block technology together from our knowledge of the L. Note that to get UWB-compatible cars, we need to work with our car supplier to create a manual detailing how to install all the necessary technology on our cars. This is not a quick process and shouldn't be, through our manual we want to make installation easy and clear in order to avoid any functionality problems. Installation won't be quick either, but with these steps in mind, it should go smoothly. If anything goes wrong though, we must weigh our options and act rationally. This is to keep in mind what the LU taught us, that as a pilot program we must pioneer uniform standards that can be used in the future. This applies to the whole installation process, so we should make decisions that we believe would be applicable in the future, but this is especially true with regards to decisions to remedying problems as chances are that similar problems will appear in similar UWB projects. Thus, it is our job to set standardized methodologies of solving these problems for use in the future.

Another main note is that as we install and complete UWB technology, we cannot simply use it immediately on the 5, we must test it first. Fortunately, we have strong knowledge of the kind of tests we should be doing from our study of the L's testing and the TTC's commissioning process. Referencing the TTC's process, we will do integration testing as the first step, checking how effectively information is being communicated between aspects of the UWB system. Next, we run through the tests utilized on the L, applying them to every car we outfit with UWB technology. We will start with the single static car test, then move onto radio tests, and end with a non-UWB configuration test. This non-UWB configuration test is a similar version of the non-CBTC configuration test seen on the L, but where we check if subways can run passively on UWB. We should keep in mind that there will likely have to be tests on the new cars for the CBTC installation in Manhattan to make sure the cars work with CBTC too, but this these tests should be very similar to our UWB tests and shouldn't take any longer. After these tests and before we do "shadow mode" testing, we would test the interoperability requirements outlined in Figure 3 to ensure that our suppliers' UWB system is to our specifications. This would best be done through a demonstration of compliance on a test track. With this checked, we can then move to "shadow mode" testing, running UWB technology while we utilize fixed-block technology on the 5 to validify that the UWB system is working as intended. The useful thing about this test is that it helps us avoid line closures as this test can be done during regular operation of the 5. While these tests ensure functionality, it is then necessary to thoroughly train all the staff assigned to work on that portion of the section on how to use the UWB technology. This implies training on day-to-day operations, like how to interpret data from the UWB system, along with procedures in rarer instances like how to perform maintenance. While this certainly is a detailed and lengthy process of training, it can be done while the 5 is running under "shadow mode", not adding to the length of installation. With all tests and training done for a specific section of the Bronx portion of the 5, and with all other improvements finished and tested thoroughly for functionality, as we will do throughout the specific UWB system testing, we can then move into a stage of partial integration. This is where the completed section of the 5 can fully utilize UWB as we install and improve on another section. We essentially just repeat this general process as we install for different sections of the 5 until we have completed installation of UWB along the Bronx portion of the 5.

When construction progresses to the point of completion, fixed-block technology can be removed, for with functional UWB, fixed-block serves as an unneeded burden. However, fixed-block technology cannot be removed everywhere. Referencing the map in Figure 6, one can see that the 2 line currently runs on fixed-block signals on the left branch of the 5. The consequence of this is that currently fixed-block technology can only be removed from the right branch of the 5 from East 180th Street station to Eastchester Dyre Avenue station since that branch has no intersection with any fixed-block lines. Despite this limitation, we still do save money and time by removing the old signals, just as expected with the LU. Then, once we have removed fixed-block signals in some areas and fully converted to utilizing UWB in the Bronx, we will follow the LU's idea of keeping conductors for trains. Though UWB does allow for driverless trains, conductors still should be used to monitor performance and control the subway doors, working better to do these tasks than an automated system would. As the 5 trains now run in the Bronx on the UWB system, the next step is to analyze performance data in the Bronx. The metric of TPH from the LU can be used as a good measure of the impact UWB has had on capacity and comparisons of on-time performance with UWB versus without UWB also speak about the difference UWB has had. Having calculated these metrics along with others for a substantial amount of time, then we can analyze what these performance metrics tell us. This analysis, if favorable, points towards consideration of further UWB projects on other NYC lines as a safely implemented UWB is both cheaper and more accurate than CBTC technology (Burke & Elgala, 2018). Thus, this project serves as a proof-of-concept, affirming the theoretical benefits of UWB with real-world evidence and likely leading to a new wave UWB-implementation and improved train performance that can effectively manage the significant increases in population and ridership that are soon to come (American Community Survey, 2017).

Budget

The table below gives a cost breakdown of an approximate budget for this project, with each line item being a necessary expenditure explained in the benefit column. A discussion of the table follows below:

Figure 7: Cost-Benefit Analysis of Budget

Item	**Cost (in millions)**	**Benefit**
UWB-Compatible Rolling Stock	$298.78	Trains compatible with UWB, a must-have
Track Maintenance	$126.32	Improved track reliability, minimal random problems
UWB Signals	$246.05	Less cost, more precision, future sustainability
Line Structures	$117.53	Ensure structural integrity of elevated pathways
Traction Power	$128.52	Vital improvement for UWB
Line Equipment	$20.87	Tunnel lighting – supporting maintenance
Misc./Emergency	$54.92	Safety systems and documentation for future projects and analysis
Total	$992.99	UWB on the 5!

(Regional Plan Association, 2014) and (Metropolitan Transit Authority,

This table was my best estimates of cost given the limited budget information about previous projects available from the NYCT and MTA. To create this, I considered the inflation-adjusted total cost of the 7 line and multiplied it by the cost percentages of the line items from the total budgeted amount for the NYCT subway's portion of the 2020-2024 Capital Plan to get costs for each of the line items above. I worked with the resulting totals by multiplying the total cost of UWB signals by a fractional amount since UWB signals are cheaper than the Capital Plan's CBTC and keeping the UWB-compatible rolling stock fee significantly lower than the $613.7 million spent on rolling stock for the 7 line (Regional Plan Association, 2014). This second choice was done rationally though, as rolling stock has already been budgeted for in the Capital Plan. Since the Capital Plan includes work on the 5, then this means subway cars have likely already been purchased for the 5, though the quantity purchased is impossible to know for sure as the NYCT doesn't release that information. However, a considerable sum must still be budgeted for cars because we must work to make the cars UWB-compatible by installing new technology onto already-purchased cars. While these values are rough, they do provide ballpark values that our budget should be reaching. Though as mentioned in the plan, we should certainly make a much more formalized budget by discussing costs with all our contractors.

A relevant note about this table is that this budget doesn't include the amounts we must pay contractors, but only the expenditures related to the actual project. Using an inflation adjusted-amount from the 7 line's paying of $343 million for contractors, the suppliers here would be paid roughly $404.8 million (Regional Plan Association, 2014). While this appears to significantly raise the cost significantly, there are a lot of costs values included here for the sake of a conservative estimate that we in reality will pay far less for. This is because the Capital Plan has already budgeted for track maintenance, line structures, line equipment, and miscellaneous other costs including preparation for emergencies (Metropolitan Transportation Authority, 2019). Thus, these costs are likely to be fully covered if not mostly covered by the Capital Plan's large budget, leaving the cost of this project's budget at about $673.35 million or $1,078.15 million when considering the cost of supplier contracts. This is a miniscule number when considering the $37.3 billion budgeted for the full Capital Program and is certainly worth it due to the benefits this expenditure would have (Metropolitan Transportation Authority, 2019). This is a project that paves the way for a higher-quality, sustainable future for the 5 and the NYC subway while addressing the current costs and risks associated with the 5's poor performance in the Bronx. When considering the costs later that we will save through this project, the costs of inevitably having to switch from CBTC to more sustainable UWB technology, this $1,078.15 is clearly a necessity. Instead of an intermediate CBTC step, we can go straight to UWB lines, which will last much longer than CBTC as a sustainable, cost-effective solution that will handle substantial ridership increases. Therefore, while large, this budgeted amount is much bigger than what will actually be paid and will certainly be worth it, with the benefits of this expenditure massively outweighing the costs.

Discussion

While the prospect of acting now, while the Fast Forward and 2020-2024 Capital Plans are both being implemented, may be daunting, the cost of inaction is too high for further delay of a UWB project. The fact is that with rising populations and crowding, CBTC technology will not offer a sustainable solution for NYC, and the current use of fixed-block technology isn't satisfactory either. Rather, the continued use of fixed-block technology has led to poor subway service, and nowhere is this truer than on the 5 line. The 5 line's population continually experiences adverse effects from the 5, including risk of economic ruin, and the NYCT needs to care about these effects of the 5's delays and overcrowding because they create the risk of a downward spiral in terms of service quality and ridership. Thus, there is a need for another solution and that solution is UWB subway systems. Through case studies of the L line, 7 line, LU, and TTC, we have acquired the knowledge of how to effectively implement a UWB system and applied that knowledge to create a thorough plan detailing all the considerations and steps necessary to implement UWB along the Bronx portion of the 5. This plan has a significant cost, as detailed in its budget, but this cost is necessary. Spending this money immediately instead of senselessly waiting not only solves the effects of the 5 and makes a downward spiral in the Bronx much more improbable, but it also paves the way for a brighter future for NYC subways. This is because without a pilot test run now, any large-scale UWB operation, an operation that would massively benefit NYC, save the NYCT money, and make subway performance sustainably improved, is further delayed. This matters because fixed-block and CBTC technology are simply inferior and unsustainable in comparison. With population increasing at a rapid rate in New York, the importance of sustainability is going to start mattering more and more, thus action now is necessary. Acting now also cuts down on potential cost later, as UWB is cheaper to install than CBTC and the NYCT can then skip the inevitable intermediate step of upgrading CBTC systems to UWB systems by upgrading straight from fixed-block signals to UWB. Thus, we must act now, to remedy the harmful effects and risks of the 5 in the Bronx and to pioneer the use of the best, most sustainable technology available right now in the face of an impending population swell.

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