



**For Action**

## **Automatic Train Control Re-Baselining and Transit Systems Engineering Review**

**Date:** April 11, 2019  
**To:** TTC Board  
**From:** Chief Capital Officer

### **Summary**

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Automatic Train Control (ATC) has been successfully deployed on Line 1 (Yonge-University) from Vaughan Metropolitan Centre to Dupont Station.

This has provided tangible results including a service improvement of one train per hour, more reliable service, and quicker movement of trains from the maintenance yard into service.

The ATC project budget in the 2018 - 2027 Capital Budget was \$563M with a scheduled in service date of Q4 2019. There have been several challenges including the Toronto York Spadina Subway Extension (TYSSE) project, dividing Phase 3 into three sub-phases, Wilson Yard's implementation, and the inclusion of Automatic Train Protection (ATP) on additional workcars that have adversely impacted the project schedule. This has resulted in schedule slippage with a revised completion date of September 2022. The current estimated impact to the budget is an additional \$98M resulting in a total project cost of \$661M.

### **Recommendations**

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It is recommended that the Board:

1. Endorse the re-baselining of the project;
2. Direct staff to include any changes to schedule and budget in the 2020 – 2029 Capital Budget submission; and
3. Direct staff to continue to report to the Board through the Major Projects section of the quarterly Financial Update.

## **Financial Summary**

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TTC's 2019 to 2028 Capital Budget approved by Council on March 7, 2019 included funding of an additional \$98M for the ATC project, increasing the total cost to \$661M to address the schedule impacts. This growth is primarily driven by the requirement for: TTC staff (\$22M); consultants and the contractor (\$45M) due to the longer duration; the additional subway closures required (\$14M); and the additional scope for ATP installation on workcars (\$7M).

Given our experience with the project to date and the Transit Systems Engineering (TSE) report findings, we believe these amounts are reasonable, but they are subject to ongoing review and revision given the project risks set out in Part II - Risk Analysis on pages 13-15 of TSE's report, which is included as Attachment 3 to this report.

After the completion of a quantitative risk analysis of the schedule and budget, any subsequent changes will be included in the 2020 to 2029 Capital Budget submission.

The Chief Financial Officer has reviewed this report and agrees with the financial impact information.

## **Equity/Accessibility Matters**

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A cornerstone of the TTC's Corporate Plan 2018-2022 is accessibility, and as a proud leader in providing accessible public transit in the city of Toronto, we are committed to ensuring reliable, safe and inclusive transit services for all our customers. This is supported through the continued work of the ATC project, which will allow increased capacity for TTC's Line 1.

The TTC is working toward achieving a more inclusive and accessible transit system that meets the needs of all of its customers.

## **Decision History**

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At its meeting on March 26, 2015, the TTC Board approved the changes to the TTC's re-signalling contract transferring the previously contracted work from Ansaldo to Alstom. This change had no impact to the existing approved budget of \$563M and scheduled completion date of 2020.

[http://www.ttc.ca/About the TTC/Commission reports and information/Commission meetings/2015/March 26/Reports/5 2 Staff Report %26 Attachment.pdf](http://www.ttc.ca/About%20the%20TTC/Commission%20reports%20and%20information/Commission%20meetings/2015/March%2026/Reports/5%20Staff%20Report%20Attachment.pdf)

At its meeting on January 24, 2019, the TTC Board received the Financial Update for the period ended September 29, 2018 including the update on the ATC project identifying the requirement for an additional \$98M.

[http://www.ttc.ca/About the TTC/Commission reports and information/Commission meetings/2019/January 24/Reports/8 Financial Update for the Period Ended September 29 2018.pdf](http://www.ttc.ca/About%20the%20TTC/Commission%20reports%20and%20information/Commission%20meetings/2019/January%2024/Reports/8%20Financial%20Update%20for%20the%20Period%20Ended%20September%2029%202018.pdf)

At its meeting on January 24, 2019, the TTC Board approved the TTC 15-Year Capital Investment Plan & 2019 – 2028 Capital Budget & Plan, including an increase of \$98M for the ATC project.

[http://www.ttc.ca/About the TTC/Commission reports and information/Commission meetings/2019/January 24/Reports/10 TTC 15 Year CIP 2019 2028 Capital Budget.pdf](http://www.ttc.ca/About%20the%20TTC/Commission%20reports%20and%20information/Commission%20meetings/2019/January%2024/Reports/10%20TTC%2015%20Year%20CIP%202019%202028%20Capital%20Budget.pdf)

At the Special City Council Meeting on March 7, 2019, City Council approved the TTC's 2019 – 2028 Capital Budget, including an increase of \$98M for the ATC project.

<http://app.toronto.ca/tmmis/viewAgendaItemHistory.do?item=2019.EX2.5>

## **Issue Background**

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Line 1's conventional "fixed block" signal system has been in place since it opened on March 30, 1954, over 65 years ago. A fixed block signal system divides the subway line into geographical blocks. Only one train at a time is allowed in each block, while the adjacent blocks provide a buffer zone. While this system remains safe for operations, and despite staff's significant focus on preventive and corrective maintenance, its reliability is diminishing. The replacement of the current signalling system is necessary to provide reliable customer service.

From 2006, the TTC has incrementally awarded contracts to address the immediate, medium and long term challenges related to the re-signalling of Line 1 and the TYSSE.

The re-signalling of Line 1 will improve reliability and increase capacity on Canada's busiest subway line. ATC provides the benefit of real-time central train control with precise train location. With ATC, train speed and separation between trains is controlled automatically, through a moving block system, as opposed to a fixed block system. This allows for reduced travel times and more reliable service.

Re-signalling of Line 1 with ATC includes the design, installation, testing and commissioning of an upgraded Centralized Signalling System. It also includes the design, installation, testing & commissioning of ATC train-borne equipment on the Line 1 Toronto Rocket (TR) fleet. To provide context of the work required, installation activities include installing new cable paths and new multiple runs of fibre and copper cables along 78 kilometers of track, many of which have no splices.

The ATC system is very complex and the installation, testing and commissioning activities can only be performed during non-revenue hours or scheduled subway

closures. The 2018 project delivery strategy is based on phased geographic segments of Line 1 as shown in Attachment 1.

The project delivery plan for each phase includes:

1. Design and Engineering:
  - a. Surveying the subway alignment and identifying the placement of ATC equipment. Each phase is unique and based on the track geometry including crossovers, centre tracks, guideway structure (box, tube or open cut), distance and equipment quantity.
  - b. Providing design reviews for documents and drawings of each phase and generating as-built drawings for maintenance and operations.
2. Construction:
  - a. Depending on complexity and length, up to eight weekend closures may be required per phase.
  - b. Construction includes the installation of two new parallel fibre optic cable networks, wayside antennas, beacons, signals, junction boxes, axle counters, and splice enclosures throughout the entire line and yards. After installation, the ATC equipment requires resurveying to confirm its location for the ATC software system database.
3. Low and high speed testing:
  - a. Separate closures are required for low and high speed testing.
  - b. Post installation check of all ATC wayside equipment including antennas, beacons, signals and axle counters.
  - c. Verification of the fibre network.
  - d. Software simulation testing.
  - e. Communication testing of both wayside and train radios.
  - f. Dynamic low speed testing.
  - g. Dynamic high speed testing of single and multiple trains.
4. Commissioning:
  - a. Decommissioning of the legacy fixed block signal system.
  - b. Loading new software on all of the fleet.
  - c. Conducting eight hours of trial operations.
  - d. Loading final software in the Transit Control Centre.

### Accomplishments

ATC now operates between Vaughan Metropolitan Centre and Dupont Stations, which represents approximately 40% of Line 1. Customers riding southbound from St Clair West to Dupont Station are experiencing an approximate increase of 6% in the number of trains per hour, equivalent to an additional train or 1,100 passengers, more reliable service and fewer delays due to signalling issues.

ATC's positive impact extends throughout the entirety of Line 1, even where ATC is currently not installed. Today, the scheduled southbound service in the morning peak at Yonge and Bloor station is 25.5 trains per hour, whereas previous achieved service was approximately 22 trains per hour. Through run-as-directed trains, pro-active station management and ATC service, on average the service delivered now meets the schedule and on many occasions has exceeded 28 trains per hour.

Based on current forecasting, the ridership demand in the southbound direction at Yonge-Bloor in the AM weekday peak in 2023 will reach 31.3 trains per hour, or 34,400 passengers per hour per direction. With the planned network improvements, 31 trains per hour is expected to provide sufficient capacity through to 2026.

The economic impact generated by time savings due to ATC on the converted portion of Line 1 (from Dupont to Sheppard West stations), based on reduced trip time and fewer delays, is \$94,000 a day (based on \$17.50/hour, consistent with Metrolinx's valuation of customer's time). The annualized impact is approximately \$29M/year. (The impact is higher when comparing Dupont to Vaughan Metropolitan Centre; however, there is no previous comparison for the TYSSE segment as it opened with ATC).

In December of 2018, the ATC, conventional signalling, and track work was completed for the Wilson Yard main line interface to optimize scheduled service run outs. Work has already commenced on 3A, the next segment of Line 1, from Dupont to St Patrick stations with anticipated revenue service in late May 2019 and is currently on schedule. Installation of ATC equipment in the Phase 3B and 3C areas from St. Patrick to Rosedale Stations is also currently underway.

## **Comments**

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When appointed, Acting Chief Executive Officer Richard Leary directed the review of most of the significant projects/programs the TTC is delivering. With regard to the ATC project, this direction required both an internal and external review.

The internal review highlighted the challenges the project was experiencing in terms of schedule and budget as outlined below. In addition, to meet the forecast capacity growth, it culminated in the development of the Line 1 Capacity Requirements and Preliminary Implementation Strategy which is the subject of a separate Board Report (April 11, 2019).

### Schedule

The challenges with respect to meeting the schedule fall into five areas discussed below.

The intense work required in 2017 to ensure that the TYSSE opened with a fully functional ATC signalling system required the exclusive focus of the entire ATC team. This resulted in the work for subsequent phases being delayed. As the project's focus

was to meet the TYSSE opening timeline, the delayed work for the remaining phases re-commenced in Q1 2018. The impact of this on the overall project schedule was approximately three months.

An operational review concluded that the required Phase 3 closures were overly disruptive to customers as one continuous section. These closures would have required the shut down of subway service from St. Clair to St. Clair West Station. To mitigate this disruption, the revised plan divided the area into three sub Phases 3A, 3B and 3C. This ensures that the entire “downtown U” is not shut down at the same time, allowing customers the use of either the Yonge or University side of the line during closures. The resulting closures are shorter in track length, but greater in number. The increased number of closures, coupled with the limited availability of closures during the year, results in a delay of approximately nine months.

For operational reasons it was essential to advance Phase 6 (Wilson Yard, which was re-named phases 2A, 2B and 2C) and implement it prior to both Phase 1 and 3 to allow for continuous, uninterrupted service from Vaughan Metropolitan Centre to Dupont Station. This phase was extremely complex to ensure that the morning service runouts of approximately 46 trains from the yard would not be impacted, requiring it be divided into three manageable sub-phases, resulting in a delay of approximately nine months.

The Phase 4 area (Rosedale to Eglinton Station) is mostly outdoors with surveying and construction activities limited to spring, summer and fall and includes Davisville Yard which has a similar level of complexity as Wilson Yard. Based on the Wilson Yard installation, a similar delay of nine months is expected. This results in Line 1 being fully ATC operational from Vaughan Metropolitan Centre to Eglinton Station by November 2021.

The Phase 5 area (Eglinton to Finch Station) requires asbestos removal before cabling and wayside equipment can be installed. Significant coordination between various workgroups is required to safely survey, identify and install wayside equipment.

The full implementation of automatic train protection (ATP) on maintenance workcars was not included in the 2015 schedule. This requires the installation of ATP on an additional 20 vehicles, bringing the total to 28 workcars. ATP is required on workcars for efficient travel speeds in ATC areas when travelling to work zones. The uniqueness of each workcar requires these assets to be grouped in specific rolling stock categories with each specific category being defined in the ATC system database. Software releases must be tailored for each specific category and also tested on the main line to allow for deployment in an ATC commissioned phase. The re-baselined schedule includes the implementation of three specific workcar categories per Phase starting with Phase 3A. In addition, the four-car TR trains that operate on Line 4 have ATC equipment installed but the software for its use needs to be developed and the trains subsequently commissioned with ATP, allowing them to efficiently travel on Line 1 for

servicing and maintenance. The overall schedule delay attributable to ATP installation on workcars and four-car TR trains is approximately three months.

The loss of two scheduled full weekend closures due to Employment Standards Act (ESA) overtime restrictions, preventing the planned use of alternate bus service required to support the closures, resulted in a two-month delay to the project.

One of the risks that is difficult to quantify is the impact of the Eglinton Crosstown LRT project construction. The construction of the Crosstown requires moving the Line 1 Eglinton station platform to the north by approximately 23 metres to allow improved distribution of customers transferring between the Crosstown and Line 1. The platform construction is currently scheduled by Metrolinx to be complete by Q2 2021. To ensure proper positioning at the station, coordination is required between the ATC and Crosstown projects for weekend closures.

After review of the remaining phases, which included comparison with completed phases, anticipating 12 dedicated subway weekend closures per year for construction/testing and avoiding parallel activities that can impact quality, the revised schedule service date is estimated to be September 2022. The schedule delays and a comparison between the 2015 and revised schedule is shown in Attachment 2.

### Budget

The \$98M impact to the budget is primarily driven by the increase in the project duration and the requirement for project staff for a longer period. The additional requirement includes \$22M for TTC staff and \$45M for consultants and contractors imbedded in the project team. Additionally, due to the increased number of closures, the increased cost for alternate bus service and support staff is \$14M.

The costs associated with developing, testing and commissioning additional workcars and the four-car TR trains with ATP has increased the budget requirement by \$7M. This is a result of adding ATP to 20 additional workcars and six four-car TR trains, as opposed to only eight workcars.

### Transit Systems Engineering (TSE) Review

Concurrently with the internal review, an external review was initiated to provide an independent third party review.

TSE consulting was engaged based on their significant experience in ATC and Communications Based Train Control Systems (CBTC). The three primary consultants had between them over 100 years of experience in ATC/CBTC project delivery and operations. A copy of the report is provided in Attachment 3.

Two broad areas TSE reviewed included:

1. Determine whether Line 1 capacity can be increased to meet increasing demand; and
2. Review the ATC Project with respect to performance, schedule and cost risks to achieving overall project goals.

TSE's general comments included: "The performance of the project associated with the installation of a modern ATC system appears well managed and effective in accomplishing the tasks associated with the installation. The project team's effort in managing all the parameters that will realize the goals of installing and commissioning the ATC system is impressive." The review also stated that the TTC should adopt an integrated program approach to deliver increased capacity on Line 1.

TSE's findings include:

1. The project is delivering a state-of-the-art train control system that is providing reliable service;
2. Successful Phase 1 and 2 implementations;
3. The previously revised schedule with completion in Q4 2021 and budget is reasonable, based on the scope of the work; however, there is no contingency remaining in the schedule;
4. Other factors than the ATC system may now become the restrictive influence in achieving required capacity in 2026. The TTC previously recognized the need to address these factors and has assigned staff, identified budget and schedule requirements to resolve. This is documented in the Line 1 Capacity Requirements and Preliminary Implementation Strategy Board Report (April 11, 2019). TSE agreed that the TTC had identified all of the potential restrictive factors;
5. Further develop the Concept of Operations including all operating modes, operation under degraded mode, and investigate the benefits of reverse running and its use as appropriate;
6. Even though the system has demonstrated high levels of availability/reliability, there is limited redundancy based on the axle counter block backup system; and
7. Develop operating and maintenance rules and procedures to address the future ATC requirements.

TSE's recommendations include:

1. Current management plan be kept in place for the duration of the project;
2. Ensure the critical path is monitored to maintain the project schedule;
3. Conduct a formal quantitative risk analysis of the project, including assessing the risks identified in the report;
4. Develop a technical requirement for implementing simulation software; and
5. Continue to develop a plan, budget and schedule that addresses the other factors that are needed to achieve capacity goals.



## TTC's Next Steps

The following steps are being undertaken to adopt TSE's recommendations of the ATC project on Line 1:

1. Conduct a formal quantitative risk analysis;
2. Develop a technical requirement for an improved simulation software;
3. Refine the plan, schedule and budget; and
4. Report out on any subsequent changes to schedule and budget.

The planning for ATC and associated capacity enhancements for Line 2 will adopt TSE's recommended approach by:

1. Adopting an integrated program management structure; and
2. Implementing a comprehensive risk plan, including quantitative analysis.

## Organizational Realignment

In January 2019, the ATC project was transferred from Operations to the Engineering, Construction and Expansion Group. This ensures consistency of project controls and reporting with all of the major capital projects and programs. In addition, the construction of the project was transferred to the Infrastructure and Engineering Group as they are responsible for the providing all workcars, scheduling all work at track level and performing the majority of track level work.

## **Contact**

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## **Signature**

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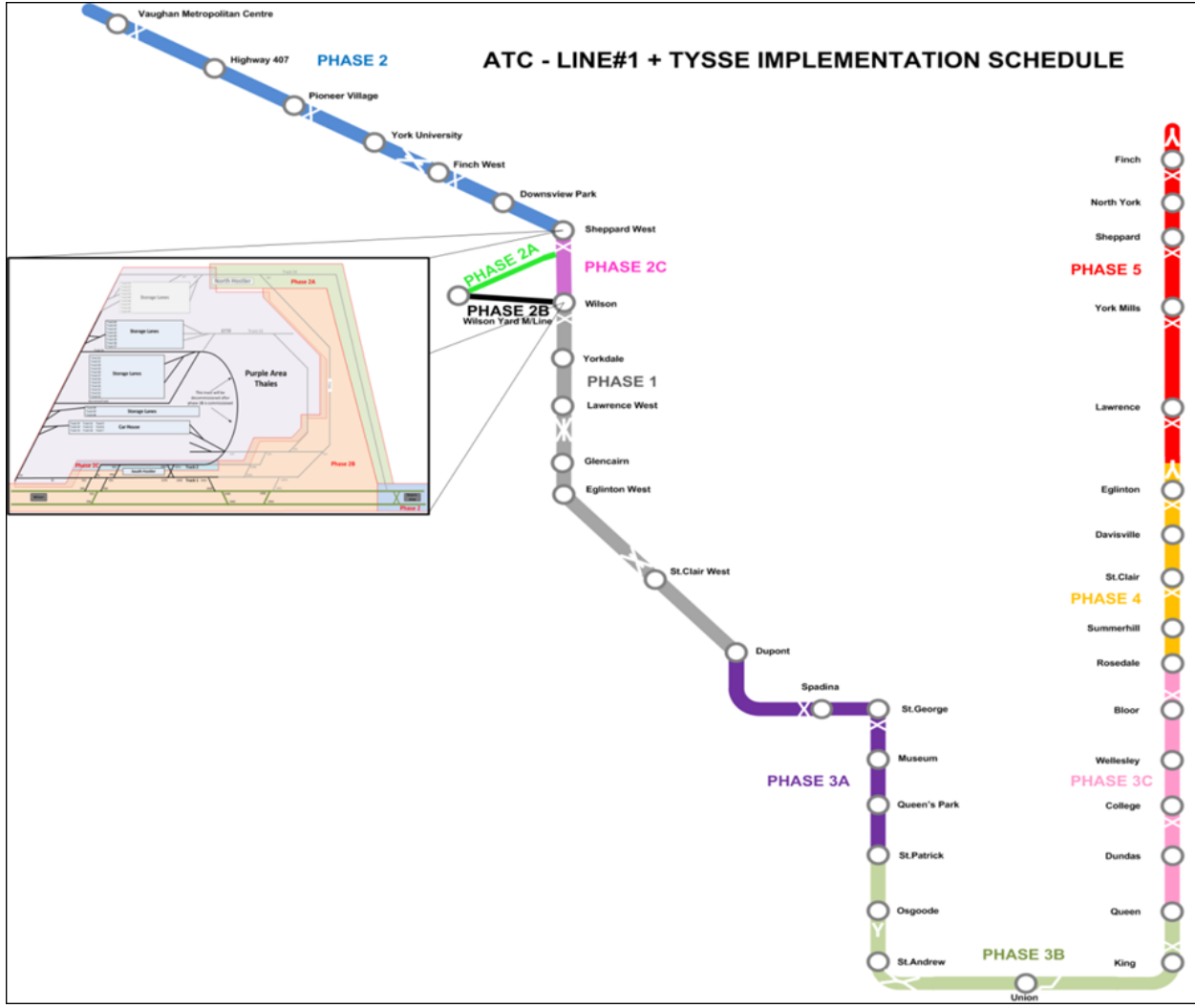
Susan Reed Tanaka  
Chief Capital Officer

## **Attachments**

Attachment 1 – ATC Project Revised Phases  
Attachment 2 – ATC Project Revised Schedule  
Attachment 3 – Transit Systems Engineering Report

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# ATTACHMENT 1 ATC PROJECT REVISED PHASES



## ATTACHMENT 2 ATC PROJECT REVISED SCHEDULE

Impact to Schedule	
Challenge	Impact
TYSSE	3 months
Three sub-phases for Phase 3	9 months
Wilson Yard	9 months
Davisville Yard	9 months
Workcars	3 months
Loss of closures	2 months

ATC - Key Dates			
Phase	Revenue Area	2015 Commissioning Schedule	2019 Revised Commissioning Schedule
1	Wilson to Dupont	Dec 2017	Oct 2017 - complete
2	Sheppard West to Vaughan Metropolitan Centre	Dec 2017	Dec 2017 - complete
2A-2C	Wilson Yard and Main line	<b>Dec 2019</b>	Aug 2018 - complete
3A	Dupont to St. Patrick	Dec 2018	May 2019 – on schedule
3B	St. Patrick to Queen	Dec 2018	Feb 2020
3C	Queen to Rosedale	Dec 2018	Nov 2020
4	Rosedale to Eglinton	Mar 2019	Nov 2021
5	Eglinton to Finch	Jun 2019	<b>Sep 2022</b>

**ATTACHMENT 3  
TRANSIT SYSTEMS ENGINEERING REPORT**



# *TSE Team Report*

## **TTC Line 1 ATC Project**

Prepared: January 13, 2019



Transportation Decision Systems



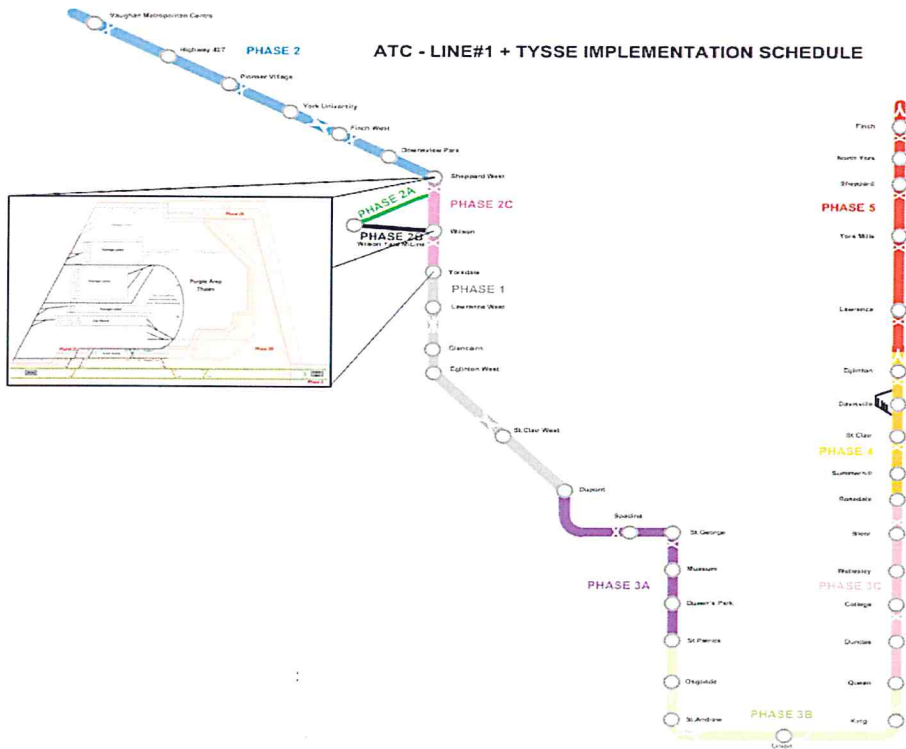
# TSE Team Report

## — ATC Project Background —

### BACKGROUND

#### YONGE-UNIVERSITY-SPADINA LINE (LINE 1)

Line 1 is the longest and busiest subway line in Toronto. The alignment currently runs 38.8 km in length with 38 stations in a “U-shaped” configuration running generally in a south and north direction. Line 1 is mostly an underground transit line, but it also has above-ground sections, which run between Sheppard West and Eglinton West, Bloor-Yonge and Summerhill, and St. Clair and Eglinton.



The original Line 1 signalling contract has evolved since the original agreement in April 2008, when the Board approved the YUS Line 1 contract. Since then, however, there have been several revisions of the Signalling System contract relating to the expansion, completion and configuration of the signal systems. This includes the Communications Based Train Control System (CBTC), the Secondary Train Control System, signal system installation phasing and the modification of passenger and work trains for Automatic Train Control (ATC) operation on Line 1.

The ATC project schedule for Line 1 has seen a series of changes since its inception, therefore a review of the past contract changes and associated decisions follow:

■ **2008 Contract C31PV07834** — This was the award of the first upgraded signal system to Ansaldo for Line 1 (St. Patrick to Eglinton Stations), which was approved to provide a replacement of the existing wayside, fixed block based train control system using a modern and reliable wayside system. The new fixed block installation was also to be used in the future ATC signal system installation as a secondary train control providing backup to the Alstom ATC CBTC.

■ **2009 Contract C31PV08752** — This involved the procurement of a Communications Based Train Control System to be installed along the wayside and in Toronto Rocket train sets. The new CBTC system was to upgrade the Line 1 YUS Subway system from Sheppard West to Finch Stations. The system envisioned would provide increases in passenger capacity by eliminating the service delays that occur from excessive train spacing based on the original 1960's-era technology, while also maintaining the safety standards expected in modern transit signal systems. This system would also greatly reduce the equipment required along the wayside and improve operational flexibility by allowing trains to operate in both direction on either track.

■ **2011 Contract C31PV08752** — This was awarded for additional CBTC equipment necessary to install CBTC train systems on Toronto Rocket train sets. In May 2010, an amendment to vehicle procurement (BTNA) contract was issued for an additional 21 Toronto Rockets (TR) to be supplied for the replacement of the 126 H6 Subway cars. This amendment to the contract was done to assure these trains sets would be capable of running the YUS Line using the CBTC system.

■ **2012 Contract C31PV11825** — This amendment to the Ansaldo wayside based signal system contract was to equip the remainder of YUS Line 1 not included in Contract C31PV07834. The contract goals included:

- The award of a contract to Ansaldo STS Canada Inc. (Ansaldo) for a Contract to Design & Supply a Signal System for YUS Line not included in previous contracts.
- Computer Based Interlocking (CBI) on an Engineering Test Track at Wilson Yard to support design and installation.
- The award of a contract to Ansaldo for a Contract to Design, Supply & Install a Signal System on the TYSSE.

■ **2013 Contract C31PV08752** — This contract change was issued January 2013 to Alstom to increase the supply of ATC equipment for Toronto Rocket subway trains from 60 to 70 trains.

■ **2015 Scope Changes to Ansaldo Contract C31PV08752 & Alstom Contract C31PV08752** — This extended Schedule of five years for Alstom ATC Contract completion includes: CBTC equipment for Toronto Rocket subway trains to increase the amount of equipped consists from 60 to 70 trains. Cancellation of Contract Change 16, issued to Ansaldo to Design and install wayside based ATC on Toronto York-Spadina Subway Extension (TYSSE). Supply of CBTC on-board parts for 10 additional subway train sets purchased from Bombardier. Adding Communications based Train Control to the YYSSE extension. Revisions to reduce the cost and scope of the secondary train control system. The assimilation of all train control technology under one vendor to reduce complexity and assured compatibility between the primary and secondary train control systems. An increase in the number of installation phases to minimize the scope and time of interruptions to the public. These changes and time extension required to complete them allowed YUS Line One to take full advantage of the CBTC train control system and all associated benefits of the technology.

This contract change divided Phase 2 into three parts — Phases 2A, 2B, and 2C — comprised of the original Phase 2 at Wilson Yard due to the need to resolve issues related to train control interfaces between the yard and the mainline.

In addition to the contract changes, TTC early project experience with passenger diversions resulted in the decision to divide Phase 3 into three parts — 3A, 3B, and 3C — to reduce the passenger impact of rail shutdowns and associated buss bridges between the St. George and Wellesley Stations.

## Executive Summary

The Transit Systems Engineering (TSE) team was retained by the Toronto Transit Commission in June 2018. TSE was tasked to review the status of the YUS Line One ATC Program being installed by both Alstom Transportation Information and Security Inc. and Thales Group.

Two significant and related Line 1 issues were to be reviewed by the TSE team:

1. TSE was to determine whether the capacity on the Yonge line can be expanded to meet the increasing passenger demand.
2. TSE would review the requirements of the new ATC CBTC and make recommendations that would mitigate performance, schedule and cost risks to overall project goals.

The TSE team consisted primarily of the following expert engineers:

— Mr. Robert A. MacDonald, who has accumulated more than 45 years in rapid transit signalling — including the operation, maintenance, design, testing and commissioning of Automatic Train Control Systems.

— Dr. Bjorn Conrad, one of the original founders and developers of the Transportation Decisions Systems OnTrack Train Simulation Software Suite. Mr. Conrad has more than 25 years of experience in the development and use of rail systems simulation software to analyze the technical advance of train operation scenarios using software.



— Dr. Nabil Ghaly, PE, president of Rail Transport Engineering, who has more than 30 years of experience in the operation, maintenance, design, evaluation and implementation of Automatic Train Control and high capacity communications systems.

— Also, assisting the team is Abhinav Durgapathi with two years of experience in Operations, Testing and Commissioning of a Communications Based Train Control System.

As can be demonstrated by the changes to the ATC contract from 2008 to 2014, a great deal of effort was expended by a dedicated team to assure this state-of-the-art train control system installation evolved to assure a final product capable of meeting the expectations of the latest ATC technology. The project's progress so far, and the operational use of the new system, indicate a project that has provided a reliable signal system installation based on a philosophy that minimizes impacts to the current customers. One of the key observations of the TSE team is the dedication and goal-oriented actions of the project management group, whose combined effort to date has resulted in successful Phases I and II project installations and commissioning.

The TSE team review indicates that the current implementation plan, including the revised budget and schedule, is reasonable based on the remaining scope of work. However, we have not seen evidence of a formal quantitative risk assessment that would indicate that the current budget and schedule do reflect the impact of all identified risks. It also should be noted that a quantitative risk assessment would identify appropriate risk mitigations, as well as opportunities that could benefit the project schedule and/or budget. However, the TSE team does not foresee unanticipated events beyond the identified risks that could adversely impact budget and/or schedule as long as TTC continues with the same project management team.

Over the last seventy years the goal of transit system designers has been to reduce the impact on passenger capacity caused by the signal system, while maintaining a design that does not compromise the traditional safety criteria. The ATC system known as CBTC is the latest and most efficient product to advance this goal. The application of this new and efficient signal system in an existing installation that was originally designed using a less robust technology will enable more throughput. CBTC technology will significantly improve conditions that make the legacy signal system a limitation to a higher capacity operation.

However, this latest improvement in technology must be tempered by the fact that other factors in the operation of a transit line may now become the restrictive influence in passenger throughput in 2026. These factors are unrelated to signal system operation and include adequate passenger and work trains to meet service projections, vehicle storage and maintenance facilities, traction power availability, terminal station turnback design, mid-line turnback scenarios and infrastructure design, passenger transfer station efficiencies, employee and passenger safety, schedule planning requirements, operator availability and maintenance practices.

Therefore, constant vigilance is required to identify and resolve issues in a timely manner.

These issues represent potential problems that constrain system throughput. It is recommended that they be identified, analyzed and solutions must be developed, approved and implemented before expected capacity increases can be realized. Ideally, these limiting factors must be defined and managed during the planning, installation and commissioning stages of the ATC systems. Any

conflicts discovered must be resolved in a timely manner, and funding sources must also be identified and prioritized. These activities should be completed in parallel with the process of installing the ATC system so that project goals can be realized.

Identification and resolution of problems can take the form of:

1. Operational simulations to assess projected passenger throughput requirements based on existing infrastructure, systems and vehicle performance parameters. Potential deficiencies can be identified, and solutions assessed.
2. Operational simulations to evaluate train criteria for the purpose of determining the number of trains needed to meet throughput, spare factor requirements and maintenance goals.
3. Planning that ensures effective management of passengers in order to realize timely travel of trains in crowded stations. Excess passenger loading times will restrict train throughput.
4. Defining a “concepts of operation” document as the basis for an Automatic Train Control (ATC) system that ensures effective and safe interface with operations management, including emergency procedures. The ATC system should support various operating scenarios capable of ensuring safe and reliable response under all operating circumstances.
5. Development of maintenance practices that do not interfere with train schedules and ensure the availability/reliability objectives.

Theoretical operational improvements and efficiency upgrades should be tested to determine the most effective methods for resolution and any associated deficiencies that might be caused in system recovery. Recommendations from correspondence with other more experienced system operators can be tested and incorporated into service planning simulation, training and documentation. The longer these actions are delayed, the more the impact on the final resolution of the ultimate goals.

The current leadership of the Toronto Transit Commission has recognized the need to address these problems and is currently assigning staff, identifying budget and schedule requirements, and developing procedures to resolve issues where possible. They are also in the process of identifying funding sources for those issues that will require additional investment. TTC is investigating the practices employed by other transit systems throughout the world whose experience can assist them in achieving a successful outcome. These positive and aggressive undertakings will be needed to experience timely and efficient application of this technology.

This report discusses the processes and issues related to the TTC design, installation, commissioning and operation of the Line 1 ATC and CBTC. The TSE team has reviewed project history and has interviewed many of the TTC departments affected and, as a result, provides the following:

CBTC is the technology most implemented after evaluating train control systems to increase passenger throughput for an existing alignment. Similar to other pre-CBTC technology, TTC's

system was designed to operate at a maximum headway of approximately thirty trains per hour per track. In a legacy system installation, the number of trains per hour cannot be easily increased. However, major infrastructure upgrades could be used to improve capacity in such systems. A capacity upgrade comparison of legacy systems and ATC CBTC implementation is included in the following summary:

1. The most effective methods for increasing capacity for legacy systems installations are extending the length of station platforms, increasing the number of vehicles to make longer trains and/or the addition of parallel tracks. Parallel arrivals and longer trains and station platforms would significantly improve capacity.
2. The use of modern ATC CBTC technology to allow trains to operate more frequently through stations. This can improve capacity by safely allowing more than thirty trains per hour through station platforms. This ATC system design would increase the number of trains moving through a station with limited or no changes to existing infrastructure.

Both solutions are costly options for capacity upgrades, but the expensive station and/or track changes required in Option 1 are significantly reduced and, in many cases, unnecessary in Option 2. Therefore, Option 2 is preferred since Option 1 could add significantly more cost, especially when evaluating existing subways installed under city alignments.

The design decisions of TTC during the preliminary project evaluation have seen several changes since inception, with a final decision to use the Alstom CBTC platform as the primary control system. Costs may have been avoided if a comprehensive assessment was undertaken during preliminary evaluation that measured and analyzed any limitations that affected the intended goals of the project. Furthermore, as discussed in this report, the implementation of CBTC technology does not eliminate all requirements for additional infrastructure and systems investment related to increases in passenger capacity, an issue with the potential to severely impact the objectives of the current project.

Two valuable tools in the initial design analysis and continuing system implementation process are the identification of risks associated with the ATC project and the software tools required for a comprehensive evaluation and proposed mitigation of these risks. The use of these tools in the process of implementing and completing an ATC system is considered by the TSE team to be important to the delivery of a successful project. A discussion of ATC Project Risks and Software Simulation associated with the Line 1 project are included in later sections of this report.

This paragraph outlines the TSE team evaluation of the major risks to the Line 1 ATC project schedule and budget as it relates to the successful delivery of project capacity goals. Based on the decision to divide Phase 3 into three parts and advancing Wilson Yard's implementation, the installation of the ATC system would appear to be on-schedule and on-budget to meet the revised delivery date of Q3 2021 at an overall cost of \$663M. However, the issues related to existing infrastructure upgrades, operational changes, organizational readiness and systems improvements needed to support the new ATC system are lagging and may not meet the 2026 demand. The TSE team has concluded that the TTC project team recently deployed to manage these activities will require assistance in the form of comprehensive risk evaluation, including quantitative risk

assessment, and the use of sophisticated software tools to evaluate all associated issues with Line 1. This undertaking is necessary to determine budget and schedule elements required to meet all project capacity goals.

## TSE Team Recommendations

The TSE team evaluation has determined that the goal of attaining high capacity passenger throughput at TTC has evolved into two equally important undertakings:

1. The installation of a modern Automatic Train Control System on TTC Line 1 between VMC and Finch.
2. The evaluation and, where required, resolution of any existing YUS Line 1 constraints that may affect the capacity goals of the new ATC system.

As previously stated, the performance of the project associated with the installation of a modern ATC system appears well managed and effective in accomplishing the tasks associated with the installation. The project team's effort in managing all the parameters that will realize the goals of installing and commissioning the ATC system is impressive. As such, the TSE Team recommends:

1. That the current management plan be kept in place for the duration of the project.
2. That emphasis be placed on assurances that the schedule critical paths activities (i.e. diversions, bus bridges, early closures, etc.) be closely monitored to make sure projected schedules are maintained and, when necessary, recovery plans are quickly developed and implemented.
3. That risks recommendations in this study be assessed and resolved in the process of managing project goals.

The TSE Team has observed less success in the TTC response to the need to manage issues not associated with the ATC project completion, and which have a detrimental effect on meeting the capacity goals of the communications based train control system for 2026 and beyond. The team discussion on risk has identified several areas where budget and schedule issues need to be resolved. When comparing the two efforts considered by the team to be of equal importance, it is clear the TTC emphasis has been on completing the ATC project installation in a timely manner with less focus and effort provided for the supporting infrastructure, systems and vehicle requirements of the new installation. The issues that are not related to CBTC implementation have been only recently assigned a dedicated project management team for this purpose.

The TSE team is of the opinion that the reason for this dilemma is the lack of critical information necessary for TTC management to identify issues regarding the overall long-term needs of the new system. Without this information their ability to address any restrictions that would affect the capacity requirements established for this project were limited.

It should be noted that CBTC is a new technology for which TTC had limited or no experience which when combined with inadequate information needed for management analysis reduced the efficiency of the review process. Therefore, the result is TTC did not appear to have a methodology to define the full requirements as well as associated budget and schedule during the preliminary phases of this project. This situation was unfortunate as there are currently methods for determining the issues needing resolution. The best tools for this purpose are the use of comprehensive risk analysis and sophisticated simulation software. As a result, the TSE Team provides the following recommendations:

1. Continue to provide a dedicated project management team to oversee the issues that will restrict effective use of improvements associated with the new ATC implementation.
2. Continue to develop a budget and schedule to implement additional scope items that are needed to meet capacity goals.
3. Continue to develop a budget and schedule that determines the additional cost and extended schedule that will be required to meet capacity goals.
4. TTC should consider a separate action that allows them to conduct operational evaluations using modern system simulation software. This process is needed to ensure an all-inclusive review of all project limitations.
5. TTC should consider performing a quantitative risk assessment of the remaining activities through the completion of the ATC Project. This effort should be based on the methodology advocated by the US Federal Transit Administration (FTA), and should encompass the following two parts:
  - a. **Risk Assessment**, which is based on the identification and evaluation of risks in terms of their likelihood of occurrence and their probable impact on budget and schedule.
  - b. **Risk Management**, which involves taking cost effective mitigations to reduce risks and to realize opportunities.

## Additional Observations and Recommendations

1. Develop a comprehensive management structure for large train control projects. If any future train control systems are planned, TTC should consider the need for a management structure dedicated to all elements needed to assure the expected goals of the project are met.
2. Development of a TTC action plan and specification documentation for an initial pre-project evaluation. The goal of this action plan is to identify the critical decision factors that could impede the intended performance goals. Included in this plan:
  - a. A technical requirement for implementing simulation software. The use of such a tool can assist the project team with analysis and evaluation of the full spectrum of issues that must be resolved for successful commissioning of an ATC system.
  - b. Conducting a comprehensive risk analysis to be updated at the beginning of the project and continued at regular intervals through to project completion.
3. Initiate a process for full system evaluation early in the project or ideally before the major project is bid. This allows project and TTC management as well as staff the ability to identify the initial issues in need of resolution. With this knowledge, the potential technology solutions can then be evaluated to determine the best selection for the intended purpose. Additionally, TTC can use this process to develop project-related technical documentation, budget needs and preliminary schedules required for procurement.
4. TTC should make every effort to contact and receive feedback from various Transit Agencies using Communications Based Train Control technology. Their experience and operational practices can greatly assist TTC as they work to provide the best solutions to achieve high capacity operation. TTC should consider organizing Peer Reviews during the remaining schedule for the ATC project.
5. TTC should seek and consider recommendations by CBTC experts to determine how the new system can be best utilized. Additionally, the development of “concepts of operation”, standard operating procedures, maintenance practices, and rule books are best undertaken with dedicated teams that have knowledge of both TTC operations and the ATC system.

## TSE Team Detailed Discussions

### Toronto Transit Commission Report–ATC Project Risks

The Transit Systems Engineering (TSE) Team met multiple times with TTC for discussions related to various aspects of the Line 1 ATC Program, including objectives, implementation status, schedule and budget, simulation analysis, etc. This Section of the TSE report focuses on the risk factors that could have an adverse impact on the schedule, budget and expected performance benefits of the ATC Program. TSE analyzed these risks in terms of the specific operational, budget and schedule impacts and the various factors that can cause or contribute to the risks. This analysis further identified the risk as being associated with the ATC Project Goals or the Line 1 Performance Goals as these two issues are addressed separately by TTC. As such, the TSE risk analysis is divided into two parts. Part I discusses the risks associated with the main objectives of the ATC Program, namely enhancing the capacity and service delivery for Line 1. Part II focuses on the implementation risks for Line 1 ATC Project. What follow is a summary of the risks identified by TSE.

## PART I

### Risk Analysis: Performance goals of the ATC Program (Line 1)

The main objective of the ATC Program is to enhance the capacity and performance of Line 1. This objective is necessary to relieve passenger crowding and meet ridership growth forecasts. The associated issues of these objectives are the completion of ATC installation and the mitigation of system and infrastructure problems that impact the performance goals of Line 1. During the last few months the TSE Team discussed this objective with TTC, and it has become apparent that significant risks exist regarding operational and performance benefits expected and their association with the implementation of CBTC technology. The following is a summary of this analysis:

#### 1. Failure to achieve throughput/headway objectives

##### — Potentially Affecting Schedule, Budget, and Performance

There are several factors that could limit the throughput/headway benefits expected from the implementation of the CBTC system in 2026. This issue is discussed in more details in the Section of the report that pertain to Line simulation. The following is a list of the factors discussed with TTC:

- a. Terminal operation and proposed mid-line turnback constraints,
- b. Structural design limitations
- c. Long passenger loading dwell times, especially at transfer stations

- d. An increase in ridership that puts pressure on service delivery, and its potential to extend further the station dwell times
- e. Additional fleet requirements
- f. Fleet support requirements for storage and maintenance
- g. Potential problems with a higher than expected onboard CBTC equipment failure
- h. Traction power limitations, TSE understands that the current traction power capacity in this Section is adequate for current service delivery. However, it is questionable if the power capacity in this Section can support service during recovery, wherein trains operates closer together
- i. Operational constraints imposed by ventilation requirements

## 2. Failure to enhance line operational flexibility

### — Potentially Affecting Performance

One of the benefits of CBTC Technology is the enhancement of operational flexibility using reverse traffic capabilities, and the enabling of flexible operation at interlockings. However, based on discussions with TTC, the TSE Team has identified several risk factors that could impact the potential operational flexibility benefits:

- a. While TTC's ATC system fully supports reverse running, TSE observed that the current service plan does not provide for its use. Further, a service plan for CBTC operation which takes full advantage of reverse running capabilities has not been devised. This may be explained by the requirement for TTC to operate at headways not exceeding 5 minutes even in off peak service. This would effectively restrict the use of reverse operations in significant sections of Line 1. TTC should leverage the reverse running capabilities by operating service at an extended headway and using the reverse running capability to support late night maintenance activities possibly in place of closures.
- b. TSE also observed that TTC has not identified a service plan for future operation with ATC (CBTC Technology). Without the details of a service plan, it is challenging to develop a plan for optimization of service delivery using mid-line turnback operation. A service plan can also be used to proactively identify any required modification in the track infrastructure.
- c. The current design for the CBTC system does not provide wayside signal protection for a failed ATC equipped train. This means that a failed train must operate under the protection of the operating rules and procedures until it is removed from the Main Line. Such manual operation, if it is frequent, would have an adverse impact on the operation flexibility and service delivery.
- d. The TTC team explained the planned operation for Wilson Yard and its criticality in supporting rush hour operation. The Yard includes a North and a South Hostlers for transitioning trains to the Main Line. TSE observed a potential limitation in yard configuration that could have an impact on operational flexibility. The issue is related to the locations of the discrimination area and wheel calibration zone. In the event a train fails to localize and/or calibrate (coming from the North Hostler), there is no place for it to move except to the Main Line. This could have an adverse impact on service delivery



and operational flexibility. TTC acknowledged this configuration issue and has indicated that the probability of occurrence of such event is very low.

### 3. Need to comply with existing procedures

#### — Potentially Affecting Performance

One of the topics discussed between TTC and TSE is related to existing procedures and to what extent they need to be reviewed and revised to minimize any impact on throughput. One of these existing procedures is the requirement to sweep trains at terminal stations. This requirement could increase the dwell time at terminal stations with potential impact on terminal capacity. A potential revision of this rule would restrict the “sweep” requirement to off-peak periods.

### 4. Failure to achieve a high level of availability/reliability for ATC equipment (Line 1 ATC Project)

#### — Potentially Affecting Schedule, Budget, and Performance

The current design approach for the ATC system with limited Auxiliary Wayside System (AWS) is based on the premise of high availability/reliability using redundancy. As such, if the performance of CBTC equipment does not meet the availability/reliability requirement, it will result in higher than anticipated reliance on manual operation with potential impact on service. Also, factors external to ATC (external failures or damage to CBTC equipment) could impact the availability of the ATC system. Further, there may be a budget risk associated with a need to initiate a contract with Alstom for maintenance activities, including software and data base.

### 5. Lack of funding to implement needed line enhancements

#### — Potentially Affecting Schedule, Budget, and Performance

TTC representatives discussed the various elements of the program and proposed schedule. One potential risk for program implementation is the availability of capital funds.

## PART II

### Risk Analysis - ATC Project

#### 1. Implementation Risks.

- a) TTC indicated that the ATC project has no schedule contingency left in project critical activities. There is a risk of schedule overrun in the event of a delay in one or more of the critical activities.
- b) The current project implementation plan is based on a predetermined number of steps, wherein each step has a defined scope of work and wherein each step requires Line Closure. There is a risk of the need for additional steps due (for example) to one or more additional software releases.
- c) As indicated above the project implementation plan is highly dependent on Line Closures. There is a risk of schedule delay in the event of cancellation of one or more closures. This will result in the cancellation of planned construction activities and could have a ripple cascade effect on remaining project activities. Cancellation could be due to operational issues or competition for track time from other high priority projects. The mitigation measure TTC has utilized for this risk is to assign the highest priority level to the ATC project closures.
- d) TTC Project Team need to have qualified resources. Based on the experience of the TSE Team, and as the ATC Project progresses to different project phases, it is critical that both the CBTC Supplier and the TTC Project Team have qualified resources. For example, as the project progresses to the testing and commissioning phase, it is essential that qualified resources are available to support this phase of the project. The lack of such could adversely impact project schedule.
- e) The TSE team has observed that the TTC Project Management Team has highly qualified resources and is very effective in managing the ATC Project. Loss of the experience and associated retention of TTC project management resources is critical to project success.
- f) During discussions with the TTC project team, it was indicated that one of the factors critical to project progress is to maximize the productive hours of work during week nights as well as during Line Closures. It is prudent for TTC to make every effort to maximize the productive hours of work. In discussion with TTC management early closures of sections of Line 1 were trialed in 2018 and will be implemented in 2019.
- g) Like other CBTC projects, one of the potential risks to the Line 1 ATC project is encountering field conditions that could impact the design or installation of CBTC equipment.
- h) Another risk that could have an impact on project schedule is a prolonged testing and commissioning period. Typical challenging activities include field integration testing and commissioning and performance of the Data Communication System (DCS).

## 2. Insufficient Organizational readiness

### — Potentially Affecting Schedule, Budget, and Performance

The ATC system that is currently being implemented on Line 1 is based on CBTC Technology with an Auxiliary Wayside System that is limited to train detection. This would represent a cultural change to all levels of the TTC Operating, Maintenance and Engineering Groups. As such, it is essential that TTC officials ensure that all levels of its organization are ready to operate and maintain the new ATC equipment. Insufficient organizational readiness could represent a risk to the ATC program schedule if additional time is needed to address organizational issues. TSE discussed this issue with TTC representatives, and at this point in time TSE is of the opinion that more work is needed to ensure an effective transition to ATC operation. In addition to the initiatives that TTC currently has in progress, TSE is setting forth the following elements for TTC's consideration when addressing the Insufficient Organizational Readiness risk:

- a) Based on the experience of the TSE Team, it is prudent to develop a structured plan with dedicated resources to identify, plan and oversee the execution of all the tasks necessary to ensure that the TTC Line 1 organization is ready to operate and maintain the ATC system.
- b) A critical element of Organizational Readiness is to implement comprehensive operating rules and procedures for ATC operation covering all operating modes, including degraded modes of operation. The Rules and Procedures should also address the movement and operation of work trains and maintenance vehicles.
- c) This effort also requires a review of the TTC Organization, especially the maintenance groups with focus on the maintenance responsibilities for onboard CBTC equipment, DCS and database.
- d) Similar to operating rules and procedures, it is recommended TTC develop comprehensive Maintenance Procedures based on maintenance approach that is compatible with the capabilities and skills of the maintenance organization. Maintenance procedures must be implemented in a manner that does not affect operational capacity. TTC should also conduct a business case review to determine the need for maintenance contracts with Alstom and the car supplier.
- e) It is also recommended that the Plan for Organizational Readiness address how knowledge will be transferred from the CBTC Supplier to all levels of the TTC Organization. Most likely, this would require training as well as comprehensive operating and maintenance manuals.

## 3. Operational constraints to ensure overall Line Safety

### — Potentially Affecting Schedule, Budget, and Performance

Another risk factor that could impact both ATC performance and project schedule is the need to address operational constraints to ensure overall line safety. Typically, these constraints are

mitigations to system hazards exported by the ATC supplier as part of its safety analysis. The overall safety case for Line 1 could impose operational constraints to mitigate hazards. One example would be operational constraints associated with the manual movement of trains. Further, constraints could be associated with limitations of system design. A proactive approach to analyze and address potential operational constraints is necessary to minimize this risk.

#### 4. Need to implement design changes

##### — Potentially Affecting Schedule, Budget, and Performance

One of the risk factors that could impact the implementation schedule of an ATC project is the potential for design changes. Typical project issues that could necessitate design modifications include:

- a) Design changes to address variances identified during each stage of testing
- b) New requirements/requests from operating/maintenance groups
- c) Changes to ensure compatibility with Line 1 operating environment

#### 5. Delay in procurement of additional trains

##### — Potentially Affecting Schedule, Budget, and Performance

In order to achieve the throughput and headway objectives for Line 1, TTC has plans for the procurement of additional trains, with delivery commencing in 2024. As such, one of the potential risks to achieve the ATC Program objectives is related to the procurement of additional trains. Such delay could be caused by a lack of funding or delivery delays related to the car purchase contract.

# Toronto Transit Commission Report

## ATC Project Simulation Analysis

Modern design of highly sophisticated transit Automatic Train Control such as the Communications Based Train Control system being installed on TTC Line 1 must include attention to a host of issues that may affect a successful implementation. This is especially relevant when applied to a replacement of existing signal system design originally utilized in a less dynamic train control environment. The reason is the more advanced train control system is specifically designed to allow significant increases in capacity with limited changes in infrastructure. Many past practices for capacity improvements that were expensive and time-consuming solutions can be reduced or eliminated — such as adding additional parallel tracks and extending station platforms lengths. However, this does not mean attention should not be paid to some of the basic requirement for the capacity increases. To move additional passengers will always mean the train fleet must also be increased with additional consideration for:

1. Traction power availability.
2. Train storage availability.
3. Heavy and light maintenance requirements.

The system architecture associated with moving trains in close proximity to each other also means that any delay in the train progress will serially affect the schedule of that train and any following trains. Consideration for any requirements of continuous and uninterrupted flow of trains is very important. Therefore, additional operations and safety analysis are required to be evaluated such as:

1. Operations practices.
2. Maintenance practices.
3. Passenger station flow
4. System safety requirements.

Also, of consideration is the difference in design of the original TTC signal system and the associated infrastructure. The normal design mantra for these expensive underground subway systems is to design infrastructure to assist the system in meeting its objective but not to spend needlessly on enhancement that cannot be utilized. The design of terminal stations, mid-line turnback's, track system and station location were implemented with a process that minimized cost while maintaining all capacity expectation of the original legacy system.

When implementing a new signal system on an existing infrastructure a designer must consider how these original limitations will affect the newer and more robust system capabilities. The modern method for performing these analyses is to use sophisticated software-based simulation programs to evaluate the performance of the existing architecture when used with the modern signal system being installed.

The following is a paper evaluating the TTC effort to date:

Many complex interrelated factors must be considered when attempting to increase the capacity of YUS Line 1. The timely operation of wayside control (with its associated supervisory system) is one important factor. Train speed and capacity (in terms of trains per hour and tradeoffs between them) are two others. The physical track geometry, particularly at terminals and midline turn backs, is another. Station-to-station proximity and the dwell times at stations represent additional constraints. One useful way to evaluate and visualize the impact of these constraints is to simulate the system with a tool that accurately emulates the system. Simulation experiments can focus on key areas of the system. And they can encompass complete system operations that considers a full spectrum of issues ranging from fleet size to the issue of loading and unloading train on the system and managing normal and degraded train operations during peak hours.

Currently a TTC simulation effort has been initiated for the purpose of analyzing the capabilities of the existing YUS Line 1. However, that effort has been hindered by several factors. For example, it does not incorporate all the physical characteristics of the system, such as vent separations, special work such as the midline turn back and crossovers, and the yard interfaces, including the yard leads. Additionally, the model does not incorporate representations of full schedule operations, specifications of vagaries in dwell and dispatch that must be considered. It also remains to be demonstrated that the model of the train control system, which approximates the Alstom's CBTC operation but is not designed to emulate it, is adequate for analysis purposes.<sup>1</sup>

The CBTC project team has performed some very useful, detailed analysis of the real time starter phase operations between Finch and Vaughan. The detailed data from that analysis can be used to perform validations of some important elements of the simulation including timings sequences that are important in interlocking that includes the time to process requests, move switches, align, lock and set routes permissive and the time at which trains clear an interlocking. But that work remains to be done.

For the purposes of analyzing capacity, the simulation should be operated with schedules that include loading the system out of the yard leads and from online storage and running full scale operations at least through a peak period subject to all existing physical constraints such as those mentioned above. Such simulations should be done with and without vagaries in dwells and dispatches. They should be done with schedules that reflect the margins that must be included in planned end-to-end runtimes. Sensitivity analysis can be carried out at various reduced headways to identify (1) the sustainable headways (2) the choke points of the system that are most constraining and (3) sustainable service quality. Such a simulation can provide the TTC with capacity targets as well as trade-offs that might be made between speed of operations and capacity, and with short turn operations vs. full operations to the end of line. The latter tradeoffs could involve train hours, fleet size and service reliability.

The CBTC implementation team's focus and commitment is on installing the Alstom control system. We recommend allocating the simulation effort to independent staff with a more system-wide charter. Such a team would provide the TTC with a tool for both determining the actual capacity limitations of the system with a fully operational CBTC system and guiding the TTC in making decisions regarding the cost/benefits of making complimentary improvements required to achieve capacity improvements.

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<sup>1</sup> We believe that the model's approximation may be acceptable but comments by Alstom and some specifications provided by them indicated that it will be important to perform stress tests to compare with actual field measured performance to verify adequacy. This could include comparison with planned close headway (trains interfering with one another) at Vaughan.