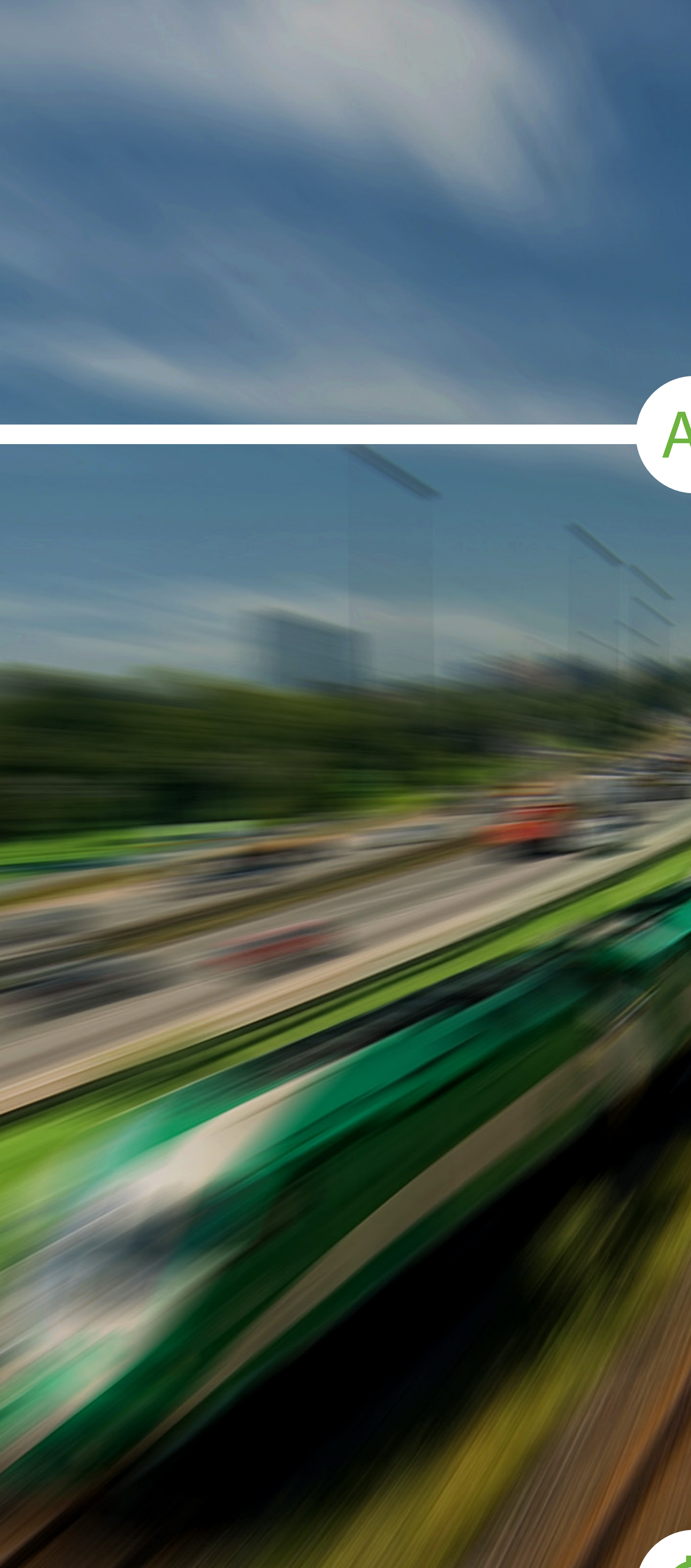

Appendix 7

Conceptual Design of Electrification System

December 2010

METROLINX

An agency of the Government of Ontario

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APPENDIX 7

Conceptual Design of Electrification System

December 2010

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EXECUTIVE SUMMARY

CONTEXT

Metrolinx operates a comprehensive transportation system of light rail transit, bus and commuter rail lines in the Greater Toronto and Hamilton Area (GTHA). The system includes the GO rail network which is an essential part of Metrolinx's service to the area commuters. GO Transit currently provides commuter rail service on seven corridors in the GTHA, using conventional diesel-electric locomotives and non-powered bi-level coaches in push-pull configuration.

In late 2008, Metrolinx published a Regional Transportation Plan – The Big Move – a multimodal vision for regional transportation to strengthen the economic, social and environmental sustainability of the Greater Toronto and Hamilton Area. The Big Move sets out a fast, frequent and expanded regional rapid transit network as a key element of the plan. The plan includes establishing Express Rail and Regional Rail services at speeds and frequencies that could be enhanced by system electrification.

ELECTRIFICATION STUDY

Metrolinx has initiated a study of the electrification of the entire GO Transit rail system as a future alternative to diesel trains now in service. The electrification study is examining how the future GO rail services will be powered – using electricity, enhanced diesel technology or a combination of the two – when these services are implemented in the future. The report assesses the advantages and disadvantages of a full range of technology options, including ac and dc powered systems and alternative system technologies and enhancements. The report includes the existing GO Transit network, the proposed extensions to St. Catharines, Kitchener/Waterloo, Allandale, Bloomington, Bowmanville, as well as the future Airport Rail Link (ARL).

POWER SUPPLY AND DISTRIBUTION SYSTEM TECHNOLOGY ASSESSMENT

A broad range of existing and future potential electrification system technologies that could be used to provide power to the future GO rail services were identified. The system technologies considered included dc electrification systems, ac electrification systems at commercial frequency, ac electrification systems at non-commercial frequency, combination of ac and dc electrification systems and alternative system technologies and enhancements.

A detailed assessment of the technologies was performed[1] and the autotransformer-fed system operating at 2x25 kV ac electrification voltage and commercial frequency of 60 Hz was selected and recommended for development of conceptual design and cost estimate of the GO system electrification. The chosen technology is fully compatible with the technology used by Agence Métropolitaine de Transport (AMT) for electrification of their Deux Montagnes commuter line in suburban Montreal. In the event that the entire Toronto-Montreal route is electrified in the future, VIA, freight and/or high speed trains will be able to operate along the corridor without conflicts.

[1] Power Supply and Distribution System Assessment for Metrolinx System Electrification, report prepared by LTK Engineering Services.

TRAIN OPERATION SIMULATION AND ELECTRIFICATION SYSTEM MODELING

A comprehensive computer-aided train operation simulation and electrical system load-flow modeling was performed for the operating schedule included in the Reference Case[2]. The trains consisted of 10 bi-level cars hauled by electric locomotives on all corridors, except the Airport Rail Link, where 2-car single-level electric multiple unit trains were modeled. The results of the modeling studies provided the performance of the rolling stock and the traction electrification system for evaluation of the conceptual design suitability and adequacy. Further, the report predicted power demands at each substation and system energy consumption for estimates of the electrification system operating costs.

CONCEPTUAL DESIGN DEVELOPMENT

Based on the train simulation system modeling studies, the conceptual design of the system was developed. Assuming full electrification of all the seven corridors and the Airport Rail link, the system can be supplied with power using seven (7) traction power substations, 17 autotransformer stations, and four (4) switching stations. In order to provide the substation transformers with sufficient power and to maintain high reliability of supply, the transformers will be connected to high voltage transmission network, 230 kV, of the local power utility Hydro One. In order to limit provision of costly high voltage transmission lines or cables, the traction power substations were located as close as possible to Hydro One substations. For redundancy purposes, each Metrolinx substation will include two equally rated traction power transformers. Power from the transformers to the power distribution system and eventually the trains, will be delivered via wayside switchgear arrangements required for control and protection of the overhead contact system (OCS).

[2] The “Reference Case” describes existing attributes and planned enhancements of GO’s rolling stock, rail infrastructure and services levels – as a basis for identifying and comparing rolling stock and electrification system technologies that could be used for future services.

1. INTRODUCTION

1.1. Purpose and Objective of the Report

Metrolinx is considering electrification of its GO transit system. All GO system corridors originate at Toronto Union Station and radiate out to the west, east, and north of Toronto. Including the planned expansions to Bowmanville, St. Catharines, Kitchener, Allendale, as well as the Airport Rail Link, the system is planned to expand to an ultimate network of 316 route miles or 508 route kilometres.

The objective of the report is to perform a conceptual system design based on a comprehensive computer-aided train operation simulation and electrical system load-flow report. The load-flow report takes into account all relevant rolling stock performance characteristics, track alignment infrastructure data, electrification system parameters and train operation data. Based on the fleet size and conceptual system design, capital costs are estimated. The operation and maintenance (O&M) costs are based on power demand requirement, energy consumption, the estimated workforce needed to operate and maintain the rolling stock and the electrification system and including estimated cost of materials and spare parts required.

The report includes the following:

- System operation modeling and load-flow simulation to identify the required number of substations, autotransformer stations, and switching stations for the preferred technology
- Identification of preliminary locations of the traction power substations, autotransformer stations, and the switching stations
- Determination of the required number and rating of power transformers in each facility
- Establishment of conductor sizes and materials for the overhead catenary system and the feeder system
- Calculation of substation power demands and energy consumption

Document Definitions and Glossary of Terms are presented in Appendix A.

1.2. Scope of the Report

The report will consider the following corridors for electrification as shown in Table 1-1.

Table 1-1 - Rail Corridors Considered for Electrification

Line	From	Via	To	Approximate Distance	
				(miles)	(km)
Lakeshore West	Toronto, Union Station	Hamilton Junction	Hamilton TH&B	39.9	64.2
			St. Catharines	71.2	114.6
Lakeshore East		Pickering	Bowmanville	42.9	69.0
Milton		Meadowvale	Milton	31.2	50.2
Georgetown		Georgetown	Kitchener	62.6	100.7
Barrie		Barrie South	Allandale	63.0	101.4
Richmond Hill		Richmond Hill	Bloomington	28.5	45.9
Stouffville		Kennedy	Lincolnville	31.1	50.0
Airport Rail Link		Airport Junction	Lester B. Pearson Airport	15.4	24.8

The Table shows the lengths of each individual route, with segments shared by two or more lines being reflected in each line. For example, both Lakeshore West lines, to Hamilton TH&B and to St. Catharines, include the length of the Union Station to Hamilton Junction segment. The table includes the existing GO network, and the proposed network expansions to St. Catharines, Kitchener, Allandale, Bloomington, Bowmanville, as well as the future Airport Rail Link.

1.3. Sources of Report Data

The report evaluations were based on data developed under separate efforts, including:

- Operations Analysis and Operating Plan Development, report prepared by CANAC, Inc.
- Network Option Evaluation Report, report prepared by SDG

Numerous photographs are presented throughout the report to illustrate the various technology options and electrification systems in service today. The photographs were taken by LTK employees.

1.4. Report Standards

The work in the report was performed in compliance with the following standards:

- CSA[3] C22.3 No. 8-M91 Railway Electrification Guidelines
- AREMA[4] Manual for Railway Engineering

1.5. Report Presentation

This report is presented in a single volume containing the main body of the report and Appendices. Further information on the electrification technologies can be found in the following companion reports:

Rolling Stock Technology Assessment for Metrolinx GO System Electrification. The report evaluates number of rolling stock technologies and concludes that the most suitable technologies for Metrolinx GO system electrification are the electric locomotive hauled trains, the electric multiple unit (EMU) trains, and the dual-mode locomotive hauled trains.

Power Supply and Distribution Systems Technology Assessment for Metrolinx GO System Electrification. The report evaluates number of electrification system technologies and concludes that the most suitable technology for Metrolinx Go system electrification is the 2x25 kV autotransformer system operating at commercial frequency of 60 Hz and supplying overhead contact system (OCS) consisting of catenary and feeder systems.

3 Canadian Standards Association

4 American Railway Engineering and Maintenance-of-Way Association

2. CONFIGURATION OF TYPICAL AUTOTRANSFORMER-FED ELECTRIFICATION SYSTEM

2.1. Basic System Definitions

Traction Electrification System (TES) provides electrical power to the trains by means of the traction power supply system, traction power distribution system, and traction power return system. In general, each system is comprised of the following:

- Traction Power Supply System - includes traction power substations located along the route at predetermined locations
- Traction Power Distribution System - consists of the OCS, along track feeder system, autotransformer stations and switching stations
- Traction Power Return System - comprised of the running rails, impedance bonds, cross-bonds, and the ground (earth) itself. In addition, the system is also equipped with static wires and grounding connections

The traction power supply system delivers power to the distribution system. The trains collect their propulsion power from the distribution system by means of pantographs and return the power to the substations via the rails and the traction power return system.

2.2. Autotransformer-Fed System Overview

A typical configuration of an autotransformer-fed (ATF) system is presented in Figure 2-1.

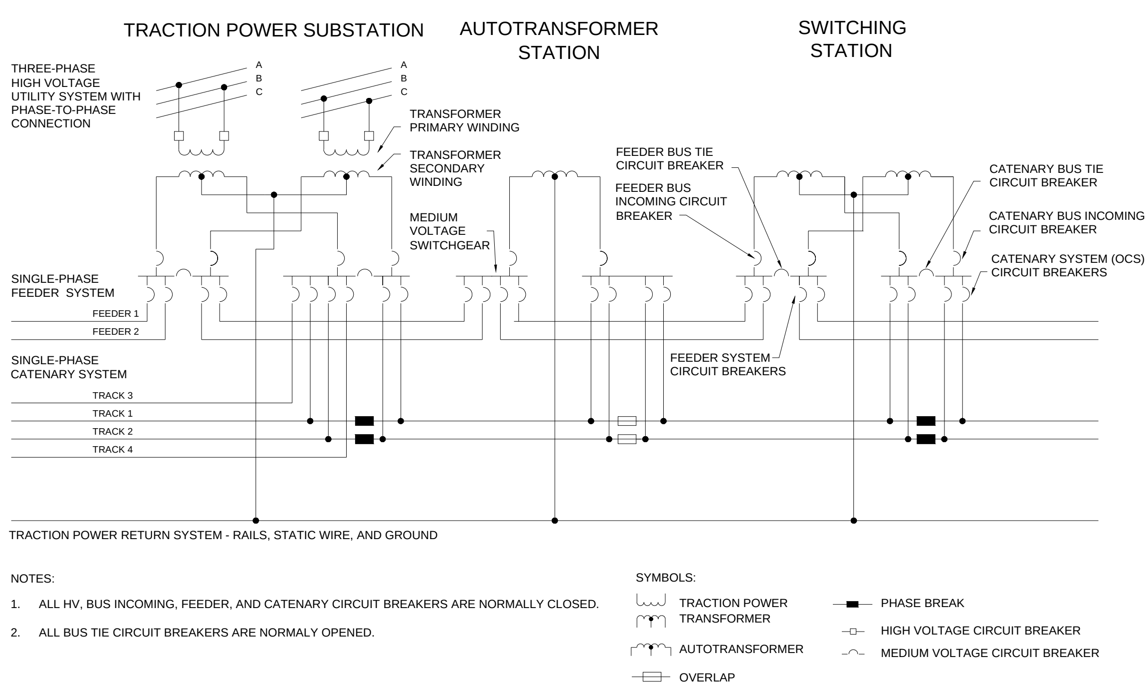

Figure 2-1 – Typical Configuration of AC Autotransformer-Fed Electrification System

The substation spacing depends on the rolling stock power demand, train consist size, train operation characteristics and the electrification system design. Typical substation spacing for the autotransformer-fed ac electrification system is approximately 50-60 km. Since the traction power substations are located at such wide spacing, substations will normally supply power to several trains at the same time, and relatively high power demand can be expected on the traction power transformers, typically rated 20 MVA to 40 MVA each. With substations at such long spacing and the traction power transformers feeding relatively high load, strong and highly reliable utility connections are required, typically at 115 kV or 230 kV input voltage.

Since the traction distribution system is single-phase, the traction power transformers are also single-phase with primary windings connected to only two phases of the local power utility three-phase transmission network. This connection will exert unequal loading on the each of the three phases, thereby creating a certain amount of unbalance in the utility system voltages and currents. In order to mitigate the effects of the unbalanced voltages and currents, the transformer primary winding connections should be alternated at successive transformers, for example, A-B, B-C, C-A, and so on. Such connections will help to balance the utility system somewhat, but will cause adjacent catenary sections to operate at different phases.

Modern autotransformer-fed systems operate at 2x12.5 kV ac or 2x25 kV[5] ac electrification voltages, with the 2x25 kV system being the world standard. The substation transformer secondary windings are wound with a center tap which is grounded and connected to the return system rails. For example, in a 2x25 kV autotransformer system, the transformer secondary winding is 50 kV and is connected to the feeder and the catenary circuits.

At regular intervals, 8-12 km apart, autotransformer stations are installed, typically with one or two autotransformers. The purpose of the autotransformers is to transform the 50 kV feeder-to-catenary voltage to 25 kV catenary-to-ground voltage. In this manner, the power is distributed along the system at 50 kV and the power is utilized by the trains at 25 kV. This is very advantageous, as the autotransformer-fed system can achieve substation spacing comparable to 50 kV direct-fed systems without the requirement for clearances necessary for electrification system operating at 50 kV.

At substations and at approximate mid-point between substations, phase breaks are installed in the catenary system to separate sections of catenary system operating at different phases. The feeder system is provided with a gap for the same reason. Adjacent to the catenary phase breaks and the feeder gaps, wayside switching stations are installed to enable switching operations of the catenary and feeder systems in the event of substation failure.

Power from the supply transformers and autotransformers is delivered to the catenary and feeder circuits via medium voltage switchgear installed in buildings or by outdoor, pole-mounted circuit breakers.

[5] It should be noted that for the 2x25 kV autotransformer-fed system the autotransformer voltage ratings are as follows: primary winding 50 kV (feeder-to-catenary), and secondary winding 25 kV (catenary-to-rail). Since the feeder-to-rail and catenary-to-rail voltages are both 25 kV, the system gained the name 2x25 kV. Because of almost universal acceptance of the name in the industry, the autotransformer-fed system will be referred to as 2x25 kV in this study. Similarly, a direct-fed system, being installed with catenary system only, will be referred to as 1x25 kV system.

2.3. Traction Power Supply System

Utility Power Supply

The traction power substations will receive electrical power from the local utility company, Hydro One, at high voltage of 230 kV. For economic reasons, the traction power substations should receive power directly from the power utility high voltage substations or transmission lines located in close proximity to the rail corridors.

Connections to the utility high voltage system is required to ensure optimal supply reliability and to limit voltage flicker, phase unbalance, and harmonic distortion that may result from the addition of the highly fluctuating, single-phase, and non-sinusoidal traction loads.

It is desirable to supply each traction power substation by two high voltage lines that are electrically as independent of each other as possible.

Substation Equipment

The substations will include all the necessary equipment to transform and control the ac voltage between the utility company and the traction power system voltage which is used by the rolling stock.

A typical traction power substation includes the following major items of electrical equipment:

- High voltage supply line termination structures
- High voltage circuit breakers and disconnect switches
- Traction power transformers
- Medium voltage circuit breakers or switchgear assemblies
- AC feeder supporting gantries and return cables
- Substation auxiliary power transformers
- Signal and communications power supply systems, if desired
- Substation control building enclosure housing protective devices, programmable logic controllers and supervisory control and data acquisition systems, instrumentation, indication, annunciation, lighting, temperature control system, and substation battery
- Busbars and bus connections
- Power cables, control cables, and low voltage auxiliary power wiring
- Insulation and grounding systems, raceways, conduits, ductbanks, and other miscellaneous equipment
- Substation ground mat
- Substation special equipment, if necessary

Due to the large electrical clearances required, high voltage equipment of traction power substations is typically installed outdoors. Each item of equipment is delivered to the site separately and installed on prepared foundations or footings.

Switchgear, protective relays and control equipment are normally installed in prefabricated or field constructed buildings. Optionally, the medium voltage circuit breakers may be installed outdoors.

High Voltage Circuit Breakers and Disconnect Switches

The function of the high voltage circuit breakers is to disconnect the traction power transformers from the utility system following a fault, severe overload condition, or for maintenance. Each circuit breaker should be equipped with disconnect switches to provide visible confirmation of isolation of the circuit breaker during maintenance.

Traction Power Transformers

The substation traction power transformers step-down the utility power from high voltage to distribution voltage. Normally, each substation is equipped with two equally-sized transformers, but one transformer substation can be acceptable in the event that real estate constraints exit. Each transformer should be rated to be capable of handling the entire substation load and to allow for continuous system feeding in the event of outage of one of the utility feeders, transformer, or other item of high voltage equipment.

The transformer primary winding is a simple single-phase winding. The secondary winding of each transformer is equipped with center point which is grounded and connected to track rails. For a 2x25 kV system the secondary voltage is 50 kV providing two 25 kV voltages suitable for supply of the feeder and catenary systems.

Medium Voltage Switchgear/Circuit Breakers

Each traction power substation includes a lineup of ac indoor switchgear or outdoor circuit breakers to distribute power to the feeder and catenary systems, auxiliary power supply transformers, and substation special equipment, if installed. In conjunction with the high voltage circuit breakers, the medium voltage circuit breakers also isolate the traction power transformers. The switchgear or circuit breakers should be configured to include main incoming circuit breakers, feeder and catenary busbars with bus-tie circuit breakers, and the appropriate number of feeder and catenary system circuit breakers.

Power to the overhead distribution system is supplied via feeder and catenary circuit breakers. The function of the circuit breakers is to protect the overhead distribution system against short circuits and to enable system outages for the purpose of equipment maintenance. It is recommended to equip each main track and feeding direction with its own dedicated circuit breaker. Thus, for a two-track system operating in the east-west (or north-south) directions, the following feeder and catenary circuit breakers would be required:

- Circuit breaker 1 - Track 1 east (or north)
- Circuit breaker 2 - Track 1 west (or south)
- Circuit breaker 3 - Track 2 east (or north)
- Circuit breaker 4 - Track 2 west (or south)

The substation and switching station feeder and catenary busbars need to be equipped with bus-tie circuit breakers. The bus-tie circuit breakers are normally open and are closed only when two adjacent sections of the distribution system need to be connected in the event of a traction power transformer or substation outage.

The substation auxiliary system can be protected by fuses or circuit breakers. The substation special equipment, such as phase balancing equipment, harmonic filters, or power factor correction equipment should be connected to the substation busbar via circuit breakers or circuit switchers.

Additionally, the use of a dedicated circuit breaker for the rolling stock maintenance facility is recommended.

Substation Special Equipment

In special circumstances, and depending on specific system and rolling stock design features, the traction power substations may also contain harmonic distortion filters, power factor correction equipment, and static VAr compensators (SVCs) as briefly described below:

- Harmonic Filters – to limit individual harmonic and total harmonic distortion at the point of common coupling of the traction power and utility equipment
- Power Factor Control Equipment – to control the power factor at the point of common coupling of the traction power and utility equipment
- Static VAr compensators – to limit the traction power substation unbalance caused to the power utility system, filter harmonics, and maintain bus voltage by supplying reactive power into or drawing reactive power from the system

The actual need for such equipment can be determined by performing a follow up report to evaluate the impact of traction power system loads onto the power utility system. Such report should determine busbar voltage unbalance and current unbalance in nearby generators. Further, the report should calculate individual and total harmonic distortion of voltage and current, especially in the event, that the power utility has capacitors and filters installed on the high voltage system. Finally, the load power factor should be calculated.

The results of the studies should be compared with limits previously agreed with the power supply utility company, and decision on any special equipment requirements can be made accordingly.

2.4. Traction Power Distribution System

Feeder/Catenary System

In the autotransformer-fed system, traction power from substations is distributed to trains by the overhead autotransformer feeder and catenary systems. The substations transformers utilize a center tapped secondary winding where the autotransformer feeder system is connected to one end of the substation transformer secondary winding and the catenary system is connected to the other end of the winding through medium voltage switchgear. The secondary winding’s center tap is tied to the rail/static wire/ground power return system.

For two track high-density train operation, two along-track feeders, one for each track, are normally provided for redundancy in the system.

Phase Breaks

As already mentioned, the primary windings of each traction power transformer are connected to only two phases of the power utility three-phase system. In order to mitigate the utility system unbalance, the two phase connections are rotated. For example, the first transformer can be connected to phases A & B, the second to phases B & C, the third to phases C & A, and so on for each successive transformer. Rotating the transformer connections causes the secondary windings of adjacent transformers to be out-of-phase. In order to electrically separate the sections of distribution system which are operating at different phases, phase breaks are installed in the overhead catenary system at the substations and at switching stations. The autotransformer feeders are also sectioned at the locations of phase breaks by using insulators.

Switching Stations

In order to provide for the autotransformer feeder and catenary system switching in the event of substation outages, switching stations are provided between each pair of adjacent substations. To facilitate the overhead system switching operations, each switching station is equipped with medium voltage indoor switchgear or outdoor circuit breakers. The circuit breakers are configured in two sections. The autotransformer feeder section includes circuit breakers on each side of the sectionalizing point and a bus-tie circuit breaker. Similarly, the catenary section includes circuit breakers on each side of the phase break and a bus-tie circuit breaker. The autotransformer feeder and catenary circuit breakers are normally closed and the bus-tie circuit breakers are normally open. The feeder and catenary circuit breakers of each track are intended to be arranged so they operate mechanically and electrically together. The purpose of the bus-tie circuit breakers is to connect the adjacent sections of the distribution system in the event of substation outage.

Autotransformer Stations

Autotransformer stations are an integral part of the autotransformer-fed system. Since substation to switching station spacing is often large, each section of the distribution system may be equipped with one or more autotransformer stations. The autotransformer stations are installed either between the substation and the switching station or between the substation and end of the line in order to improve the voltage profile along the system by transforming the feeder/catenary voltage to catenary/rail voltage using autotransformers. Further, the autotransformer stations parallel the catenary and feeder circuits of the two tracks and provide electrical sectioning points within the system.

Each autotransformer station is equipped with medium voltage indoor switchgear or outdoor circuit breakers configured in a similar arrangement as in the switching stations. However, since the autotransformer feeder and the catenary voltages on either side of the autotransformer stations are always of the same phase and magnitude, there is no need for bus-tie circuit breakers. For the same reason, overlaps or section insulators are used in autotransformer stations instead of phase breaks.

Benefits of Autotransformer Stations and Switching Stations

A key advantage of this arrangement is that the switchgear in the switching and the autotransformer stations enables sections of the distribution system to be disconnected following a fault or for routine maintenance. The switchgear is configured to permit paralleling of the overhead distribution system conductors in multiple track areas. The conductor paralleling decreases the effective system impedance between substations and trains which improves the train voltage profile along the system. The paralleling also provides for current sharing between conductors of adjacent tracks and improves system fault detection.

Autotransformers

In the autotransformer system, the catenary-rail voltage is delivered by the feeder-catenary distribution system via autotransformers. Autotransformers are installed at each autotransformer station and at each switching station to transform the feeder-to-catenary voltage to catenary-to-rail voltage. The autotransformer winding ratio must correspond to the distribution voltage (feeder-to-catenary) and the traction voltage (catenary-to-rail) ratio.

The autotransformer-fed system enables power to be distributed along the system at higher than the train utilization voltage. For example, in the 2x25 kV autotransformer system, power is distributed at 50 kV (feeder-to-catenary) while the trains operate at 25 kV (catenary-to-rail). This arrangement results in a system with lower voltage drop along the alignment than is possible with 25 kV direct-fed system, resulting in an improved train voltage profile along the line.

Similarly to the substation transformers, the autotransformers are constructed and tested in accordance with IEEE 57 series of standards. The autotransformer coils should be also provided with extra bracing to withstand pulsating radial and axial forces due to the highly fluctuating traction load.

2.5. Traction Power Return System

Return System Conductors

The traction power return system consists of the running rails, impedance bonds, cross-bonds, overhead static wires, return conductors, and the ground (earth) itself. Both running rails of each track serve as return conductors, except at special trackwork locations where electrical continuity is provided by jumper cables connected to the rails.

In order to enable both rails to carry the return current and to maintain the double rail signalling track circuits for broken rail protection commonly used by North American railroads, any existing dc track circuits must be changed to ac track circuits using a different frequency from the 60 Hz traction power system, for example 100 Hz.

Return System Continuity and Grounding

At locations requiring insulated rail joints, the electrical continuity of the return system is maintained by the use of impedance bonds. The running rails should be cross-bonded for traction power equalization through impedance bonds at every traction power substation and as required by the design of the signal and/or train control systems. The cross-bonds are periodically connected to the static wire which is used to connect the supporting structures of the feeder and catenary systems. The static wire is grounded at frequent intervals. The result, based on current division, is that, portions of the return current flow in the rails, the static wire, and the ground.

The purpose of this design is to reduce the effective return system resistance and provide as low an impedance return system as possible in order to limit voltage rise along the rails (rail-to-ground potentials), and to improve catenary fault detection by creating sufficiently high short-circuit currents.

Particular attention should be paid to return system grounding arrangements at, and in the vicinity of, passenger stations to avoid undesirable voltage rise between the station metallic structures, rails, and consequently, trains.

The cross-bond grounding must be coordinated with the signal system design.

2.6. Normal And Contingency System Operation

Continuity of Supply

The power supply, distribution, and return systems should be designed so that adequate propulsion power continues to be supplied to the system under normal and contingency operation. Therefore, electrical continuity must be provided in the distribution system from substations to switching stations under normal operating conditions and under single traction power transformer outage. Additionally, electrical continuity must be provided from substation-to-substation under full substation outage conditions.

At the substations, autotransformer stations, and switching stations, the distribution system continuity is provided by the normally closed feeder and catenary circuit breakers. In the event that a feeder or catenary circuit breaker needs to be opened for repair or maintenance, two approaches are possible:

- Provision of hand-operated or motor-operated outdoor or indoor type bypass disconnect switch
- Provision of a transfer bus and an additional circuit breaker which can substitute for any circuit breaker via the transfer bus

The distribution system should be sectionalized into electrical sections to limit the length of the track to be deenergized following a fault or for system maintenance. The sectioning can be performed at substations, autotransformer stations, and switching stations, as well as at interlockings where crossovers and turnouts are installed.

Normal Operation

During normal operation of the power system, i.e., when all major components of the system, such as substation transformers, feeders, and autotransformers, are in service, the system will maintain rated train operating performance during peak-hour traffic conditions. This includes providing full performance train voltage levels to allow simultaneous starting of trains.

Contingency Operation

Normally, each traction power transformer feeds its own section of system. During a substation transformer outage, continuity of supply to that section is achieved by closing of the substation feeder and catenary system bus-tie circuit breakers. The remaining substation transformer then feeds both sections of the system.

Each traction power transformer in a substation is recommended to be supplied by an independent, dedicated transmission line. In this event, an outage of entire substation is unlikely. Nevertheless, provision for such a contingency should be made in the system design. Following an outage of an entire substation, the neighbouring substations should maintain continuity of supply. Therefore, each substation must be capable of supplying its own section of the system as well as the adjacent sections previously supplied by the out-of-service substation. This is facilitated at switching stations. During a substation outage, the normally open switching station feeder and catenary bus-tie circuit breakers are closed, thus extending the supply areas of the healthy substations in operation.

When a substation at the end of the system is out-of-service, the end-of-the-line is supplied from the closest operating substation by closing bus-tie circuit breakers in the switching station and the outaged substation.

2.7. Autotransformer-Fed System Facilities

AC system substations have requirements for equipment that supports high voltage electrical input and medium voltage output. The requirements for electrical clearances dictate that most of the substation equipment be installed outdoors.

Typical 2x25 kV substation is shown in Figure 2-2 and typical 2x25 kV autotransformer station is shown in Figure 2-3. Both installations are from Amtrak's Northeast Corridor electrification system, New Haven, CT to Boston, MA.

Figure 2-2 - Typical 2x25 kV System Substation

Figure 2-3 - Typical 2x25 kV System Autotransformer Station

Visual impact of a typical two-track catenary and feeder system is illustrated in the Figure 2-4. At overlaps and at interlockings the visual impact is higher than shown.

Figure 2-4 – Typical Two-Track 2x25 kV OCS and Feeder System with Side Pole Construction

The OCS poles are installed at both sides of the track and are spaced approximately 55-60 m apart on tangent track, with the spacing decreasing progressively with decreasing radius of curves.

Visual impact of a typical multi-track catenary and feeder system is illustrated in the Figure 2-5. For multiple-track OCS and feeder system portal structures are used. The portal construction can be extended to accommodate practically any number of tracks. The portal spacing is comparable to the OCS pole spacing.

Figure 2-5- Typical Multi-Track 2x25 kV OCS and Feeder System with Portal Construction

3. TECHNICAL CHARACTERISTICS OF AC ELECTRIFICATION SYSTEMS

3.1. General

The electrification system includes the following impacts:

- Power Utility Impact on utility or customer systems
- Electromagnetic Field Impact on humans
- Electromagnetic Interference Impact on other equipment

3.2. Power Utility Impact

Power Demand Characteristics. Power demand of traction power supply systems is significantly different from power demand produced by the usual utility loads. Although there are exceptions, most of the utility loads are relatively slowly changing, well distributed amongst the three phases of transmission and distribution circuits, nearly sinusoidal, and typically with high power factor. Occurrence of short circuits is moderate especially on transmission circuits. As discussed below, the same cannot be said about the traction loads, as they are highly fluctuating, single-phase, contain harmonics, and the system is subject to higher occurrence of short circuits.

Power Fluctuation. Traction power demand is of a highly fluctuating nature. This is a result of abrupt, impulse-like changes in power requirements of trains as they accelerate and decelerate, as they encounter or leave track grades, and as they enter and leave distribution system feeding sections. The magnitude and frequency of the impulses increase during peak time (rush-hour) periods of operation as longer trains operate at shorter headways.

Phase-to-Phase Connections. AC electrification system traction loads are single-phase and are connected to a utility three-phase system phase-to-phase. The unequal phase loadings of the three phases cause the utility system currents to be unbalanced. The different currents in each phase cause unequal voltage drops in the three-phase utility network and this causes the utility voltages and currents to be unbalanced.

Harmonic Content. The train load on the electrification system substations consists of number of single-car and/or multi-car trains operating simultaneously on the system. The power electronics of the rolling stock propulsion and auxiliary systems generate harmonic currents. The harmonic currents generated by the rolling stock produce harmonic voltages along the traction power distribution system and inject harmonics into the utility power supply system. However, the harmonics of rolling stock equipped with modern propulsion systems using integrated gate bipolar transistor (IGBT) based propulsion converters are usually negligible and in many cases can be ignored.

If it is found necessary to lower the harmonic content, filtering equipment installed on-board the rolling stock often satisfies the relevant standards.

System Faults. Traction power distribution systems are subjected to faults and short circuits in a greater degree than utility power systems. This is mainly due to relatively low overhead system clearances, which are often further reduced under bridges and in tunnels, and due to a relatively large number of support insulators used per kilometre of the system.

Power Factor. Low power factor has been a concern in the past when rolling stock was equipped with thyristor-controlled propulsion equipment. Today, modern rolling stock is invariably utilizing propulsion systems with IGBT-based four-quadrant converters which can be designed to operate with power factor approaching unity.

Power Demand Impact. The traction load is likely to have some effect on the utility power supply system and, in most onerous cases, on other adjacent systems and subsystems. The power demand fluctuation may cause a voltage flicker at utility busbars. This flicker may cause customer light flickering and may affect the operation of some electronic equipment. Also, the fluctuating currents flowing in the traction power supply equipment can cause pulsating forces which can be of significant magnitude, and therefore, can be potentially harmful to substation equipment.

The voltage and current phase unbalance causes flow of negative sequence current in the rotors of rotating machinery and may increase heating of utility generators and utility customer motors.

The rolling stock injects harmonic currents into the traction power distribution and return systems where they are combined with any existing harmonics of the power utility system. The harmonic currents produce voltage drops at harmonic frequencies at the utility busbars, and in turn, the distorted busbar voltages produce harmonic currents in the bus-connected equipment. The harmonics may cause malfunction of some electronic equipment, EMI into wayside equipment, increased equipment heating and, in severe cases, resonance of the utility system. As already mentioned, modern propulsion systems equipped with integrated gate bi-polar thyristor converters exhibit very low harmonics.

Due to OCS impedance, rolling stock operating with low power factors causes voltage drop in the OCS resistance and reactance. By comparison, modern rolling stock with power factor close to unity causes voltage drops mainly in the OCS resistance while the reactive voltage drop is significantly reduced. Since the OCS reactance is typically three to four times larger than the resistance, a significant reduction in voltage drop can be achieved and the traction power substations can be located further apart.

The short circuit current may cause EMI into wayside equipment, voltage dip at utility busbars, and pulsating forces in substation equipment.

In general, the impact of modern traction electrification system and the vehicle propulsion equipment it supplies on the power utility system is relatively minor, and remedial measures are seldom required. However, corrective equipment, in the form of phase balancing equipment, harmonic filters, and power factor correction equipment, is available, should it be required in a particular situation.

3.3. Electromagnetic Field Impact[6]

Electromagnetic Fields (EMF). Flow of ac power produces two types of fields, electric fields and magnetic fields. Both, electric and magnetic fields are present in electric rolling stock, in electrical substations, and along an electrified railroad.

EMF Studies. Numerous epidemiological studies and comprehensive reviews have evaluated magnetic field exposure and risk of cancer in children[7,8]. Since the two most common cancers in children are

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6 This section has been prepared using information from National Cancer Institute (NCI) website www.cancer.gov and from World Health Organization (WHO) website www.who.int.

7 A. Ahlbom, E. Cardis, A. Green, M. Linet, D. Savitz, A. Swerdlow, Review of the Epidemiologic Literature on EMF and Health, Environmental Health Perspectives 2001, 109(6), 911–933.

8 World Health Organization, International Agency for Research on Cancer, Volume 80: Non-ionizing radiation, Part 1, Static and Extremely Low-frequency (ELF) Electric and Magnetic Fields. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2000, Lyon, France.

leukemia and brain tumours, most of the research has focused on these two types. A report in 1979 pointed to a possible association between living near electric power lines and childhood leukemia[9]. Among more recent studies, findings have been mixed. Some studies have found an association between electromagnetic fields and cancer, others have not.

Currently, researchers conclude that there is limited evidence that magnetic fields from power lines cause childhood leukemia, and that there is inadequate evidence that these magnetic fields cause other cancers in children. Researchers have not found a consistent relationship between magnetic fields from power lines or appliances and childhood brain tumours.

EMF Limits. A number of national and international organizations have formulated guidelines establishing limits for occupational and residential EMF exposure. The exposure limits for EMF fields were developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), a non-governmental organization formally recognized by the World Health Organization (WHO), following reviews of all the peer-reviewed scientific literature, including thermal and non-thermal effects. The standards are based on evaluations of biological effects that have been established to have health consequences. The main conclusion from the WHO reviews is that EMF exposures below the limits recommended in the ICNIRP international guidelines do not appear to have any known consequence on health.

In Canada there are no national standards for occupational and residential exposure to EMF. Health Canada, the department of the government of Canada, issued a Guideline document in 1999 which is enforced through the federal and provincial regulations and standards.

In USA, the American Conference of Governmental Industrial Hygienists (ACGIH) publishes recommended occupational exposure limits. Further, the Federal Communications Commission (FCC) and the Institute of Electrical and Electronics Engineers (IEEE) publish their own standards.

Both, Canada and USA have been taking part in the International EMF Project coordinated by WHO. The Project's missions include provision of coordinated international response to concerns about possible health effects due to EMF exposure and to facilitate development of internationally acceptable standards for EMF exposure.

Measurements Along Electrified Railroad. Electric Research & Management, Inc. (ERM) performed a survey to quantify the levels of extremely low frequency (ELF, 3-3,000 Hz) electric and magnetic fields (EMF) and radio-frequency (RF, 300 kHz to 50 GHz) electric fields near electric facilities along Amtrak's Northeast Corridor (NEC) between New Haven, CT, and Boston, MA. This work was sponsored by the Federal Railroad Administration (FRA) and contracted to ERM with oversight by the Volpe National Transportation Systems Center.

According to EMR[10], the maximum ELF electric and magnetic field readings were compared with exposure limits in the American Conference of Industrial Hygienists (ACGIH) and Institute of Electrical and Electronic Engineers (IEEE) C95.6 standards[11]. None of the limits were exceeded.

9 N. Wertheimer, E. Leeper, Electrical Wiring Configurations and Childhood Cancer, American Journal of Epidemiology 1979, 109(3), 273–284.

10 DOT/FRA/RDV-06/01, EMF Monitoring on Amtrak's Northeast Corridor: Post-Electrification Measurements and Analysis, October 2006.

11 IEEE C95.6, Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields 0 To 3 kHz.

All radio frequency readings were logged directly as a percentage of the occupational FCC standard. None of the readings were greater than 3 % of this standard. Thus, all readings were also less than 3 % of the IEEE C95.1[12] and ACGIH occupational limits. Because the general public limits are lower than the occupational by factor of 2.2, the electric field limits for the general public were similarly never exceeded.

3.4. Electromagnetic Interference Impact

General. In the direct-fed system all traction current is flowing to the train along the entire substation-to-switching station OCS length. Similarly, the current travels back to the substation along the entire return system length. The current in the catenary may induce electromagnetic fields in nearby signal and communication circuits and cause interference. The return current in the rails may cause an undesirable voltage rise. Increased potentials along the rails cause increased voltages between rolling stock and platform, with possible discomfort for passengers boarding and alighting trains.

In the autotransformer-fed system, the major portion of catenary and return currents flow between the much closer-spaced autotransformer stations or between an autotransformer station and a switching station, often in opposite directions. Also, the catenary and feeder conductors are much closer to each other than the OCS and rail in the direct-fed system. Therefore, the induction effects are lower and the potential rise along the rails is lower in the autotransformer-fed system than in the direct center-fed system.

Depending on the train position along the autotransformer system, the current in the feeder may flow in the opposite direction than the current in the catenary. In this event, certain electromagnetic field cancelation occurs. This field cancelation mitigates, to some degree, the effects of electromagnetic interference on other wayside equipment as well as communications and signalling circuits.

The induction effects occur at fundamental and harmonic frequencies. The effects of induced magnetic fields on humans should be considered during electrification system design. Testing both inside the vehicle and at passenger boarding platforms should be verified per European standards EN50061 and DIN VDE 0848, part 4. The limit for dc field exposure is 1 mT. The limit for ac fields is 500 µT from 1 Hz to 7.5 Hz, falling linearly on a log plot to 3.75 µT at 1 kHz and then flat to 30 kHz.

EMI/EMC Plan. EMI and Electromagnetic Compatibility (EMC) Plans should be developed for the rolling stock and the wayside communications and signal systems during preliminary design stage of any electrification project. All susceptible systems should be identified and characterized. Preliminary specifications for Conducted, Induced and Radiated EMI should be developed. Although not applicable at present, provisions for Cab Signal Interference (CSI) and PTC equipment installed on the rolling stock should be included as directed by Metrolinx. Emission limits curves should be developed for all potential generators of EMI. The limits curves should be sufficiently lower than the susceptibility limits to provide a comfortable margin of safety.

Limits for the individual subsystems that comprise the vehicle must be established in advance of building the vehicle to have assurance that overall vehicle and train limits are met during manufacture. Subsequently, prototype laboratory EMC testing should be performed during manufacture for all critical systems and for verification of emission limits by measurement during field testing.

12 IEEE C95.1, Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

Conducted EMI. Conducted emissions can be produced by the wayside traction supply equipment and the rolling stock. Care must be taken during the design phase of each to prevent generation of harmonic currents that could cause interference to the wayside track signal, communications system and the public power grid. These currents flow in the OCS, through the vehicle and return to the substation via the running rails. The conducted EMI testing only applies to vehicles that use external power from catenary. Self-powered vehicles, such as diesel locomotives, are exempt from this requirement.

Induced EMI. Induced interference results from high-powered electrical equipment on the vehicle inducing harmonic currents in a loop directly under the vehicle. The loop consists of the two inner axles and the running rails between them. When the vehicle pass over impedance bonds or signal connection points, interference is possible. Mitigation starts in the design phase with good EMI avoidance techniques. Laboratory testing is done in the prototype stage to verify the design. Final wayside field testing is done to verify the emission limits.

Radiated EMI. Radiated interference can be generated from the vehicle and radiate through space similar to a radio transmitter. Mitigation methods must be taken in the design phase. The established limits should specify the frequency range and measuring distance and should be based on broadband EMI measured in dBµV/m/MHz. The goal is to avoid destructive interference with railroad communications, signal and public radio and TV reception. Testing, including a frequency scan, should be performed on the wayside with appropriate antennae and RF spectrum analyzer. Testing should be carried out in at least three phases:

- Phase 1 - Base Case – performed prior to electrification commencement
- Phase 2 - After electrification is completed with the line energized and without trains
- Phase 3 - Line energized with a train operating in full acceleration and braking modes

Cab Signal Interference and Positive Train Control. As provisions for possible future CSI and PTC systems, appropriate noise rejecting cab signal track receivers must be applied to rolling stock equipped with ac propulsion systems. The verification test is done onboard the vehicle by measuring the EMI at the output of these track receivers. Excessive Cab Signal Interference could result in cab signal reliability or safety problems. It should be noted that CSI is a separate item from conducted and radiated EMI, and is often forgotten by foreign vehicle suppliers who are not familiar with cab signal systems in North America.

Existing Wayside Signals. The design and operation of existing wayside signals, including grade crossing warning devices should be reviewed to determine if changes are required in order to achieve EMC with electrified territory to avoid subsequent operational problems.

Traction Power Substations. Testing is recommended in the substations to verify the harmonics injected back into the power utility grid are within IEEE Std. 519 limits. This testing should be performed on the wayside at the substation. This is a power quality issue.

4. ROLLING STOCK SIMULATION AND ELECTRIFICATION SYSTEM MODELING METHODOLOGY

4.1. Procedure

The computer load-flow report simulations are performed in the following steps:

- Development of report criteria
- Development of rolling stock performance characteristics
- Data collection, including:
  - Route alignment gradients, speed restriction, and passenger station locations
  - Rolling stock physical and performance characteristics
  - Train operation data, including the train consist sizes, schedules, routes, and passenger station dwell times
  - Electrical network data, substations, paralleling stations, switching stations, OCS, and power utility network
- Conversion of collected data into computer input data
- Trip duration computer runs and development of string charts
- Analysis of trip duration and string chart results
- Collection of electrical power utility parameters
- Conversion of electrical data into computer input data
- Electrical system computer runs, including:
  - All equipment in-service scenarios
  - Contingency conditions such as substations out-of-service
- Analysis of electrical output results. The analysis includes the following calculations:
  - Derivation of train voltage profile along each system route
  - Calculation of feeder and catenary system currents
  - Determination of substation and autotransformer power demands
  - Determination of substation power demands and energy consumptions

Based on the analysis of the electrical network results, the proposed electrification system conceptual design is verified.

To develop a conceptual design of the electrification system, a comprehensive computer-aided train operation and electrical system load-flow modeling and simulation is performed. Following are the assumptions in the model.

4.2. Modeling Features

To develop a conceptual design of the electrification system, a comprehensive computer-aided train operation and electrical system load-flow modeling and simulation is performed. The modeling was performed with the following features:

- Train Operation. The Reference Case train schedule was used in the system modeling with train consisting of ten (10) coaches hauled by one (1) electric locomotive.
- Maximum Performance. All trains are modeled to operate at maximum acceleration rate, maximum deceleration rate and up to the maximum authorized speed.
- System Modeled in Its Entirety. Since it is possible that some substation may supply more than one route and some switching stations and autotransformer stations may be serving more than one route, it is necessary to model the system in its entirety. Modeling of the system route-by-route would give unrealistic results.

All corridors are included in the simulation, with the entire OCS network supplied by appropriately spaced and rated substations, switching stations, and autotransformer stations.

4.3. Evaluations Performed

Detailed evaluation of the following results is performed:

- Voltage profiles along all electrified corridors. This is the most important set of results, as the voltage available to the train directly affects its performance. Unless the minimum train voltages are above minimum specified values, the system design, such as substation locations, will need to be modified.
- Current flows in the feeders and OCS. The currents in the feeder and OCS are used to define the switchgear rating, calculate the conductor temperatures, and verify adequacy of OCS conductor sizes.
- Power demands and energy consumption at each traction power substation. The substation power demands are used to determine continuous and overload ratings of major substation equipment. Energy consumption is used to estimate possible energy savings due to regeneration of rolling stock. Also, this data is used for estimating the power utility demand and energy charges.

Based on the simulations, adequacy of the conceptual system design is verified. The design is modified and rechecked in iterative fashion, as necessary. The system modifications may include change in substation or autotransformer station locations, adding an additional substations or autotransformer stations, or modifying rating of transformers.

4.4. Computer Simulation Software Used

The train operations and load-flow simulations were performed using computer software TrainOps Version 14. The software was developed by LTK Engineering Services (LTK) specifically to perform traction power studies and is a comprehensive software tool used for design and analysis of both dc and ac traction power systems. TrainOps was developed by identifying key elements which exist in other traction power simulators. These elements were improved where necessary (i.e. train dispatch file) and combined with a highly accurate method for modeling vehicle performance and power/voltage/current requirements into one comprehensive tool. The program is written in C++ and is Microsoft Windows-based with many user definable features, including customizable vehicle performance parameters.

LTK's traction vehicle/electrical system simulation software is unique in the industry in several respects. The performance of each train in the model is dynamically determined by the continuously varying voltage at the trains during the simulation, as occurs in the real world. Therefore, the program accurately models the tractive effort and current curves for the desired vehicle and automatically adjusts these curves as the traction power voltage varies along the traction power distribution system. This software also allows the simulator to model very accurately modern ac drive systems which include automatic, voltage dependent current or tractive effort limitations or adjustments, including detailed modeling of vehicle regeneration.

The TrainOps model can represent one or more "routes" on which trains run. A route consists of one or more track segments on which the trains will operate under different operational criteria such as headway, train length, acceleration, deceleration and speed limits. In general, trains on each route operate independently of other routes in the model, except for the voltage dependency mentioned earlier. Any electrical connections between the route power supplies or distribution systems feeding more than one route are correctly represented.

The program produces a wide array of color graphical outputs, which aid in the analysis of the traction power system by visually displaying the data rather than printing the data in tabular form. The output charts and graphs include the following:

- Train tractive effort and current vs. speed
- Train speed vs. time and distance
- String charts for each route
- Train voltage profile for each route
- Substation average power over pre-defined time intervals for each substation
- Substation instantaneous power for each substation
- Substation energy consumption for each substation
- Feeder/catenary RMS currents

Other important features include multi-route simulation and per-train scheduling. There is no limit to the number of routes, or train types. All output is graphical and is produced directly by the program without external software or manual effort. The simulator uses modern equation solution methods (i.e. spare matrix techniques and direct inversion of matrixes), is very fast and accurate, and very large and complex models can be simulated with ease.

The TrainOps software uses a dynamic performance algorithm for adjusting the trains' performance based on the instantaneous system electrical loading where most other simulators assume a fixed performance value irrelevant of actual train voltage. TrainOps uses "snapshots" at one second intervals to increment the calculations of vehicle performance and the system electrical load. TrainOps uses the train's actual voltage and its corresponding current to determine the load on the traction power system. As these values change, the available tractive effort is recalculated and applied to the performance of the train to determine the trains' current requirements. This is performed individually for each train on the system at each snapshot. The calculations are modified each time there is a change to the system, and consequently, train locations vary slightly from run to run due to actual performance associated with each train's actual train voltage. Therefore, each train on the system affects all other trains on the system and vice versa.

Each train's performance is individually calculated based on local conditions and the subsequent location of each train updated. The electrical system is then re-evaluated through a matrix calculation. The result is a more accurate representation of system performance under actual conditions as individual train performance is dependent on both the traction power system and other trains on the system. Train performance may appear to vary run to run, but this is actually representative of total system dynamics that are seen in service.

The simulation output is dependent on operating assumptions such as system population which is determined by headway, train consist, and train departure scheduling. The results presented in this report represent only one possible combination of such operating assumptions. Variable operator behaviour, dwell times, passenger loads, and weather or track conditions, along with potential train bunching and special events trains will change actual system performance. Design standards were developed for minimum train voltage to try to allow for real-world performance and operation anomalies since there is no practical way to simulate every possible scenario or situation.

Further details on the TrainOps system modeling software are presented in Appendix B.

5. REPORT CRITERIA

5.1. General

The following criteria are developed for the report:

- System voltages, nominal, maximum, minimum, and emergency minimum, to evaluate the system substation, autotransformer station and switching station locations, and the train performance
- Conductor currents and their effect on the distribution system conductor temperatures
- Power demands to develop transformer and autotransformer continuous and overload ratings

5.2. System Voltages And Train Performance

Industry Practice

The suitability of the selected locations for traction power substation, switching station, and autotransformer locations is verified by determining the train voltage drop profile along the system. In a traction power system, comprising of the utility network, substation equipment, feeders, catenary conductors, and rails, every train on the system should have adequate voltage at the pantograph to achieve desired performance of its propulsion system. The adequate voltage levels are defined by the American Railway Engineering and Maintenance-of-Way Association[13] (AREMA) recommendations.

The AREMA Manual for Railway Engineering defines the following standard voltages:

- Nominal Operating Voltage. Voltage measured at the pantograph of a train located at the substation feed point while full rated power is being drawn from the appropriate substation transformer or transformers if connected in parallel, 25 kV for the Metrolinx system.
- Normal Upper Voltage Limit. Voltage measured at the pantograph of a train located at the substation feed point with no traction power being drawn from the appropriate substation transformer or transformers, if connected in parallel. The Normal Upper Voltage Limit is 110% of the Nominal Operating Voltage, 27.5 kV for the Metrolinx system.
- Normal Lower Voltage Limit. Voltage measured at the pantograph of a train located at the point of maximum voltage drop with the OCS functioning for normal design conditions, assuming no substation outage and rated continuous power being developed by the rolling stock. The Normal Lower Voltage Limit is 80% of the Nominal Operating Voltage, 20 kV for the Metrolinx system.
- Emergency Minimum Operating Voltage. Voltage measured at the pantograph of a train operating under emergency conditions, such as a substation outage, loss of one or more transformers at a substation, or utility supply problems. Rated vehicle power and performance is not available, but reduced operation is possible, assuming that on-board logic automatically degrades the vehicle performance. The Emergency Minimum Operating Voltage Limit is 70% of the Nominal Operating Voltage, 17.5 kV for the Metrolinx system. As per the American Railway Engineering and

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[13] AREMA, Manual for Railway Engineering, Chapter 33, Electrical Energy Utilization, Part 3, Recommended Voltages, published in 2006.

Maintenance-of-Way Association recommendations, this limit applies to vehicle design only and is not to be used as a criterion for the traction power system design.

Metrolinx System Voltages

Taking into account the AREMA recommendations, the traction power supply and distribution system voltage levels for the Metrolinx 2x25 kV autotransformer-fed system, as developed for this report, are shown in Table 5-1.

Table 5-1 - 2x25 kV Autotransformer-Fed System Voltages

System	Location		Voltage (kV)	Voltage (p. u.)
Traction Power Supply System	Traction Power Substation Input Voltage		230	1.00
	Traction Power Substation Normal Upper Output Voltage Limit	Feeder-to-Catenary	55.0	1.10
		Catenary-to-Rails	27.5	1.10
	Traction Power Substation No-Load Output Voltage	Feeder-to-Catenary	52.5	1.05
		Catenary-to-Rails	26.25	1.05
	Traction Power Substation Nominal Output Voltage	Feeder-to-Catenary	50.0	1.00
		Catenary-to-Rails	25.0	1.00
Traction Power Distribution System	Normal Lower Voltage Limit for All Systems in Service	Catenary-to-Rails	20.0	0.80
	Emergency Minimum Operating Voltage for Outage Conditions	Catenary-to-Rails	17.5	0.70

Use of the Voltage Criteria in the Report

The nominal traction power supply system voltages were used in the computer simulations and the distribution system voltages along the various lines were calculated and compared to the values presented in the above table.

The Normal Lower Voltage Limit was used as criterion in evaluation of the simulated system performance. For computer runs simulating the all equipment in-service condition (i.e. all substations, switching stations, autotransformer stations, traction power transformers, feeders, and autotransformers in-service), the lowest train voltage along any of the three corridors during rush-hour operation should not fall below the Normal Lower Voltage Limit.

Under system outage conditions, the lowest train voltage along any of the three corridors during rush-hour operation should not fall below the Emergency Minimum Operating Voltage for Outage Conditions.

5.3. Conductor Currents And Temperatures

As already mentioned, traction power demand is highly fluctuating, and consequently, the currents in the system conductors are correspondingly fluctuating. The temperatures of the overhead conductors will vary in accordance with such current variation, and will depend on the conductor size, material, and environmental conditions.

The highest currents and temperatures in the distribution system conductors occur in the catenary and feeder conductors adjacent to the traction power substations. In order to prevent overheating and annealing of the feeder and catenary system conductors, it is always recommended to check the conductor temperatures during a design stage of a project. The conductor temperatures should be calculated using a transient method[14] and plotted versus time over the rush-hour interval.

Such detailed evaluation is not in the scope of the report. In order to evaluate the suitability of the conductors used in the report, the calculated load current root-mean-square (RMS) values are compared with the estimated ampacities of the distribution system conductors.

The distribution system conductors considered for the Metrolinx commuter system in this report and their ampacities are shown in Table 5-2.

Table 5-2 – Configuration and Ampacity of Typical 2x25 kV Traction Power Distribution System

Conductor	Number of Conductors per Track	Size (kcmil or A.W.G.)	Material	Approximate Ampacity (A)	Total Approximate Ampacity (A)
Feeder Wire	1[15]	556.5	ACSR	730	730
Messenger Wire	1	4/0	H. D. Copper	480	870
Contact Wire	1	4/0	H. D. Copper	390	

The ampacity of the feeder and messenger wires were obtained from the Westinghouse Reference Book[16]. The ampacity of the contact wire was obtained from the AREMA Manual[17]. In the above mentioned references, the ampacities were calculated based on the following conditions:

- Ambient air temperature 25°C

14 T. Kneschke, Overhead Conductor Selection Based on Transient Current and Temperature Analysis for Better Traction Electrification System Economics, IEEE Catalog Number 03CH37424, 2003 IEEE/ASME Joint Rail Conference, Chicago, IL.

15 For single-track and two-track systems one feeder per track is used. For higher number of tracks, only two feeders are required.

16 Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, published in 1964.

17 AREMA, Manual for Railway Engineering, Chapter 33, Electrical Energy Utilization, Part 4, Railroad Electrification Systems, published in 2006.

- Conditions Sunny
- Conductor operating temperature, copper 75°C
- Conductor operating temperature, alloys and ACSR 100°C
- Emissivity 0.5
- Wind velocity 0.61 m/s
- Frequency 60 Hz
- Contact wire wear 30% (70% of the conductor original cross-section area remains)

The actual conductor ampacities can be expected to be somewhat lower in Toronto, especially in the summer, when the daily maximum ambient temperature is just over 26°C and can reach 40°C under extreme conditions.

5.4. Power Demands and Transformer Ratings

Power Demand Characteristics

Traction power substations experience highly fluctuating loading due to the abrupt, impulse-like changes in power requirements of trains as they accelerate, decelerate, or as they encounter or leave track grades. The magnitude and frequency of the impulses increase during peak power demand time periods, since longer trains are likely to operate at shorter headways. Therefore the power demand also fluctuates in the same manner as the load. The rush hour period occurs twice a day, in the morning and in the afternoon, and the maximum power demands usually occur during this time. For traction power substations to supply this load cycle, the substation equipment must have sufficient continuous and overload power ratings as recommended by the AREMA guidelines[18].

Transformer and Autotransformer Ratings

Traction power system simulations were performed for the peak demand rush-hour period in order to determine the power ratings of the transformers and autotransformers. In order to determine the traction power transformer continuous ratings, the maximum power demand for each substation was averaged over 2-hour, 1-hour, 15-minute and 1-minute time intervals. Power utilities typically require a power demand value based on a particular time period, usually corresponding to the billing interval (e.g. 15-minute average). The results of the report provide these values based on the prescribed headway and consist for each route. The continuous and overload power ratings were assigned to the respective power demand averages are shown in Table 5-3.

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18 AREMA, Manual for Railway Engineering, Chapter 33, Electrical Energy Utilization, Part 6, Power Supply and Distribution Requirements for Railroad Electrification Systems, published in 2006.

Table 5-3 – Continuous and Overload Rating of Traction Power Transformers and Autotransformers

Demand Period	**Traction Power Transformer and Autotransformer ONAN[19] Continuous and Overload Ratings (% of Rated Power)**
2 Hours	100, Continuous Rating
1 Hour	150
15 Minutes	200
1 Minute	250

Based on the simulations predicted power demands, the ratings of the transformers and autotransformers can be defined.

19 Oil Natural Air Natural transformer cooling method.

6. REPORT INPUT DATA

6.1. Data Collection

The data for the electrification system modeling and simulation includes data in the following major groups:

- Rolling stock data
- Track alignment data
- Electrification system data
- Operations data

The data is discussed in more detail in the following sections.

6.2. Rolling Stock Data

The most onerous rolling stock operation, as far as the power demand is concerned, was selected for the system modeling. The highest power demand on the system substations would be caused by a fleet of trains composed of EMU units. The proposed GO vehicle data were input into the TrainOps model, and included the following data:

- Mechanical characteristics, including the car empty, design, and rotating weight, axle count, and cross-sectional area
- Electrical characteristics, including the car nominal, maximum, and minimum operating voltages, and auxiliary (hotel) power
- Propulsion system data, including the car tractive effort, power factor, electrical and mechanical efficiencies, and the maximum acceleration rate
- Braking system data, including the maximum deceleration rate

The rolling stock input data are presented in Appendix C.

6.3. Track Alignment Data

The track alignment data were received from CANAC and include the following:

- Route gradients with respect to milepost
- Track speed restriction along each route
- Locations of passenger stations

The system track alignment data including the gradients, speed restriction and passenger station locations were obtained from a report titled Operations Analysis and Operating Plan Development, prepared as a part of the Metrolinx electrification report by CANAC, Inc.

6.4. Electrification System Data

Data used for the electric network simulations include the following:

- Equivalent impedance of the utility system at the point of common coupling, i.e. the substation traction power transformer connection point
- Traction power substation transformer impedances
- Autotransformer impedances
- Impedances of the traction power distribution and return systems between substations, switching station, and autotransformer stations

A simplified schematic diagram of the proposed Metrolinx GO system to be electrified is shown in Figure 6-1.

The electrification system input data are presented in Appendix D.

6.5. Operations Data

The operation data used in the electrical network simulations were received from CANAC and include the following:

- Train timetable, including departure location and departure time for each train
- Operating time data including the time of simulation start and finish, and the power simulation time interval

The morning rush-hour operation usually exhibits higher traffic densities than the evening rush-hour. This is due to the fact that in the morning, commuters are making an effort to reach their work places in a limited time frame, while in the evening, some commuters may not return immediately after working hours and may stay in the city for education, entertainment and other purposes. Therefore, the report was performed for the more onerous morning rush-hour traffic density.

The system operations data including the train timetable were obtained from a report titled Operations Analysis and Operating Plan Development, prepared as a part of the Metrolinx electrification report by CANAC, Inc.

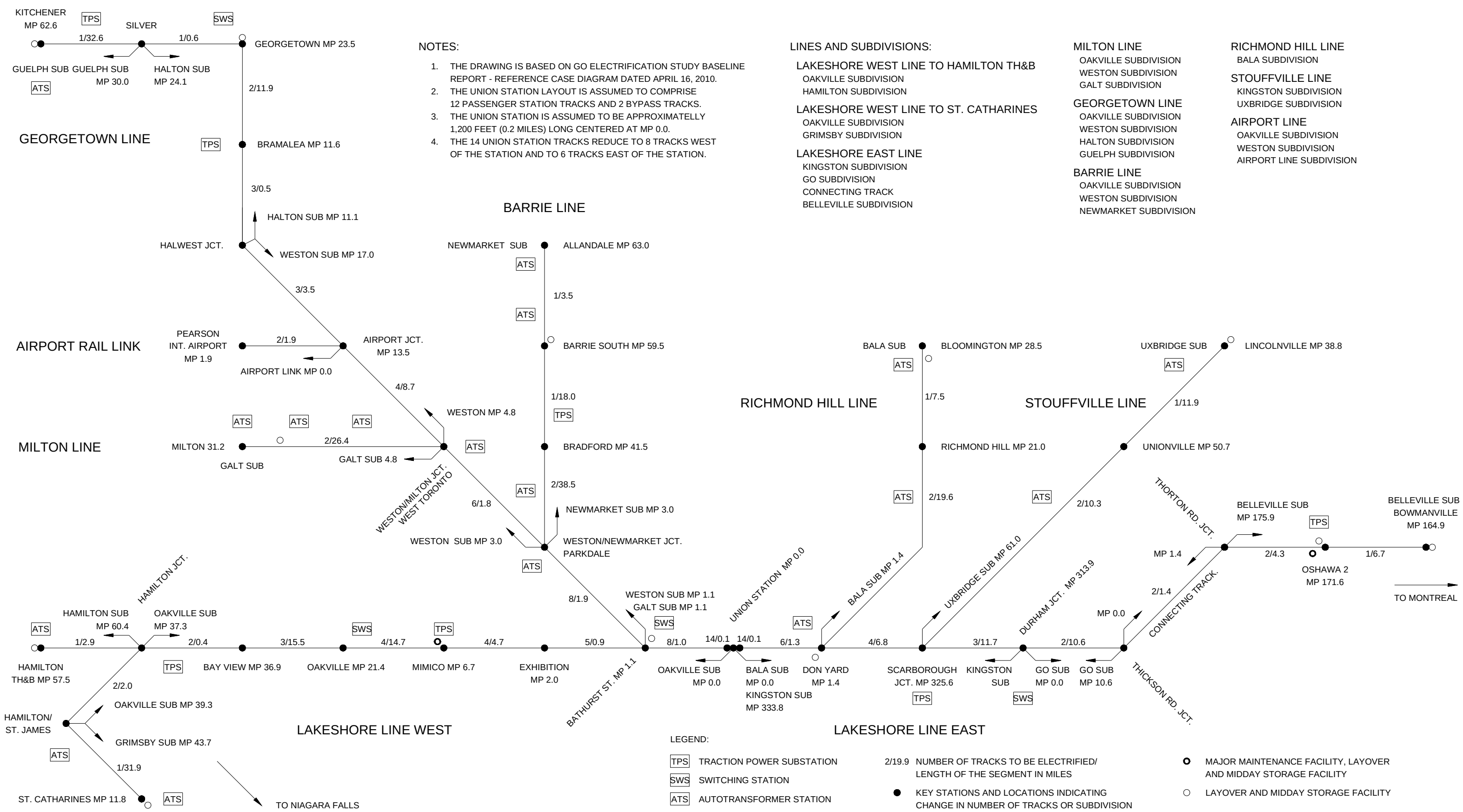


Figure 6-1 - Simplified Schematic Diagram of the Proposed Metrolinx GO System Lines to be Electrified

7. ELECTRIFICATION SYSTEM MODELING RESULTS

7.1. System Voltages

The train voltage profiles, as measured between pantograph and running rail, were calculated against time for morning rush-hour traffic. The calculations were performed for all commuter rail lines under normal operating conditions with all electrical equipment in service. The minimum voltages for each corridor are shown in the Table 7-1 for all substations in service condition.

Table 7-1 – Minimum System Voltages – All Systems in Service

System Condition	Minimum Voltage (kV)								
	Lakeshore Line West		Lakeshore Line East	Milton Line	George-town Line	Barrie Line	Richmond Hill Line	Stouff-ville Line	Airport Rail Link
	TH&B	St. Catharines							
All Systems In Service	24,527	24,527	24,944	24,079	24,703	24,443	24,616	25,021	24,766

The results show that the minimum voltage in each corridor is above the Normal Lower Voltage Limit of 20 kV as defined voltage criteria.

7.2. Conductor Currents

Normally, conductor temperatures vs. time are derived on transient basis using the one-second output from the computer load-flow simulations. However, since the RMS currents were well below the ampacity of the overhead system conductors, as shown in Tables 7-2 and 7-3, and annealing of the conductors is highly unlikely, the predicted conductor temperatures were not calculated.

Table 7-2 - Conductor Ampacities and Maximum Feeder RMS Currents – All Systems in Service

Location	Feeder/Direction	Approximate Ampacity (A)	Maximum 15 Minute RMS Current (A)
Dixie Road Substation	Feeder West	730	17
			17
	Feeder East		114
			114

Table 7-3 - Conductor Ampacities and Maximum Feeder RMS Currents – All Systems in Service

Location	Catenary/Direction	Approximate Ampacity (A)	Maximum 15 Minute RMS Current (A)
Burlington Substation	Catenary 1 - West	870	158
	Catenary 2 - West		95
	Catenary 3 - West		93
	Catenary 1 - East		251
	Catenary 2 - East		148
	Catenary 3 - East		164

7.3. Substation Power Demands

The substation transformer power demand for the system substations are shown in the following Tables. In order to define the transformer continuous and overload ratings, the one-second power demands were averaged over 1-minute, 15-minute, 1-hour, and 2-hour time intervals, as shown in Table 7-4. For the power utility billing interval of 1-hour, the 1-hour average power factor is also given.

Table 7-4 - Substation Transformer Average Power Demands (MVA) – All Systems in Service

Substations	Transformer	1-Minute Average Power Demand (MVA)	15-Minute Average Power Demand (MVA)	1-Hour Average		2-Hour Average Power Demand (MVA)
				Power Demand (MVA)	Power Factor (p. u.)	
Mimico	T-1	17.4	11.8	9.8	0.95	7.6
	T-2	14.3	6.3	5.6	0.96	4.7
Burlington West	T-1	15.1	8.0	5.6	0.95	4.5
	T-2	24.9	12.5	10.6	0.95	8.0
Scarborough	T-1	23.2	17.1	13.4	0.95	12.5
	T-2	23.8	15.4	14.5	0.95	12.3
Oshawa	T-1	13.9	8.6	6.4	0.96	5.2
	T-2	10.6	5.0	3.7	0.95	2.8
Dixie Road	T-1	9.3	4.0	3.0	0.96	3.0
	T-2	29.5	19.5	16.9	0.94	16.2
Guelph	T-1	6.7	3.7	2.5	0.96	2.2
	T-2	7.3	5.0	3.3	0.95	3.0
New Market	T-1	11.6	6.8	5.2	0.95	4.6
	T-2	15.1	10.2	7.3	0.95	7.1

The predicted power demands resulted in selecting 2x30 MVA transformer power rating for Dixie Road and Scarborough substations and 2x20 MVA power rating for all other substations.

7.4. Autotransformer And Switching Station Power Demands

The power demands averaged over 2-hour time interval for autotransformer stations are shown in the Table 7-5. Since the autotransformers are connected in parallel, the power demand in each autotransformer will be the same and one half of the number shown.

Table 7-5 – Autotransformer Power Demands – Autotransformer Stations – All Systems in Service

Autotransformer Stations	Autotransformers	2-Hour Average Power Demand (MVA)
Hamilton TH&B ATS	AT-1 and AT-2	0.6
Grimsby ATS	AT-1 and AT-2	0.7
St. Catharines ATS	AT-1 and AT-2	0.3
Cooksville ATS	AT-1 and AT-2	2.2
Meadowvale ATS	AT-1 and AT-2	2.0
Milton ATS	AT-1 and AT-2	0.9
Carlton ATS	AT-1 and AT-2	1.8
Woodbine ATS	AT-1 and AT-2	1.9
Kitchener ATS	AT-1 and AT-2	0.9
Maple ATS	AT-1 and AT-2	2.7
Gilford ATS	AT-1 and AT-2	1.1
Allandale ATS	AT-1 and AT-2	0.8
Old Cummer ATS	AT-1 and AT-2	2.3
Bloomington ATS	AT-1 and AT-2	0.7
Unionville ATS	AT-1 and AT-2	2.3
Lincolnville ATS	AT-1 and AT-2	1.2
Don Yard ATS	AT-1 and AT-2	1.7

The power demands indicate that a standard continuous autotransformer power rating of 5 MVA is adequate.

The power demands averaged over 2-hour time interval for autotransformers located in the switching station are shown in the Table 7-6. Since each autotransformer is connected to a different feeding section, the power demands in the autotransformers are different.

Table 7-6 – Autotransformer Power Demands – Switching Stations – All Systems in Service

Switching Stations	Autotransformers	2-Hour Average Power Demand (MVA)
Bathurst SWS	AT-1	1.4
	AT-2	0.8
	AT-3	1.1
	AT-4	0.7
Oakville SWS	AT-1	2.3
	AT-2	1.7
Durham Jct. SWS	AT-1	1.8
	AT-2	1.6
Georgetown SWS	AT-1	1.3
	AT-2	0.9

The power demands indicate that a standard continuous autotransformer power rating of 5 MVA is adequate.

7.5. Presentation Of Modeling Results

The voltage profiles along the lines, substation transformer power demands, autotransformer power demands and catenary currents are presented in graphical form in Appendix E.

8. CONCEPTUAL DESIGN OF ELECTRIFICATION SYSTEM

8.1. General

The traction electrification system equipment should be designed for a minimum functional life expectancy of thirty (30) years. All traction electrification system equipment must be designed to maintain sufficient voltage levels at the rolling stock current collection devices without overloading and overheating of any of the system equipment.

The design must take into account the effects of the highly fluctuating pattern of traction current, the harmonic content of the traction loads, the phase-to-phase utility connections, and frequent distribution system faults, to ensure minimal impact on the power supply utility system and wayside equipment.

The overall system insulation needs to be coordinated to ensure that the voltage surges caused by lightning strikes to the system and circuit breaker switching operations do not damage the system equipment. The traction electrification system design must be compatible with the other systems, including the signal, communication, and fare collection systems, and must not cause electromagnetic interference affecting the wayside systems.

Based on the traction power system report results, a conceptual design of the traction power supply and distribution systems have been developed. For electrification of the Metrolinx commuter rail lines, the autotransformer-fed (ATF) system has been selected. The system will operate at 2x25 kV electrification voltages, at the commercial frequency of 60 Hz.

Preliminary locations of the traction power substations, the autotransformer stations, and the switching stations were identified in consultation with Hydro One and Metrolinx. The report results confirm that the locations of the power supply and distribution system facilities are suitable and enable to define ratings of major items of equipment.

8.2. Basic Design Principles

For a satisfactory system design, the following basic conditions should be satisfied even under normal conditions with all equipment in service and contingency operating scenarios with equipment outage:

- Voltage along the distribution system should not drop below the Normal Lower Voltage Limit with all systems in service.
- Voltage along the overhead distribution system should not drop below the Emergency Minimum Operating Voltage under equipment outage conditions.
- Substation locations should result in uniform loading of transformers to the extent possible to permit selection of standard rating of equipment.
- The traction power supply equipment should not be overloaded beyond the defined load-cycle causing excessive temperature rise of equipment and premature equipment failure.
- The maximum temperature of the distribution system conductors should not exceed the permissible value to minimize the possibility of annealing of distribution system conductors.
- The negative return system should be designed to ensure that the running rail-to-ground voltages are maintained within acceptable limits to prevent creation of irritating or unsafe vehicle-to-platform potentials.

The above conditions apply to the ultimate traffic density along each corridor to be electrified.

8.3. Traction Power Supply System

Substation Locations and Power Utility Interface

The traction power substation will be connected to the high voltage transmission system operating at 230 kV. Connections to the utility high voltage lines are required to ensure an adequate and highly reliable power supply with low susceptibility to phase unbalance, harmonic distortion, and voltage flicker that may result from the addition of traction load.

Discussions were held with the local power utility, Hydro One, supplying high voltage power to the Toronto area. The purpose of the discussions was to identify locations of high voltage transmission lines and substations adjacent to the GO transit network that would be suitable as primary supplies to the traction power substations.

Table 8-1 shows the conceptual locations of traction power substations (TPSs) and Hydro One supply substations.

Table 8-1 – Location of Traction Power Substations

GO System Line	Metrolinx Substations	Hydro One Substations	Voltage (kV)	Note
Lakeshore West Line	Mimico	Horner	230	Traction power substation would be near Hydro One substation.
	Burlington West	Cumberland	230	Traction power substation would be near Hydro One substation.
Lakeshore East Line	Scarborough	Warden	230	The substation would also supply Richmond Hill and Stouffville lines. Approximately 1.5 mile of transmission line or cable will be required.
	Oshawa	Thornton	230	Approximately one mile of 230 kV transmission line or cable will be required.
Georgetown Line	Dixie Road	Bramalea	230	Approximately ¾ mile of 230 kV transmission line or cable will be required.
	Guelph	Campbell	230	Approximately 1.5 miles of transmission line or cable will be required.

GO System Line	Metrolinx Substations	Hydro One Substations	Voltage (kV)	Note
Barrie Line	Newmarket	Armitage	230	Substation will supply the entire Barrie line. Approximately two spans of transmission line will be required.

Hydro One confirmed sufficient thermal capacity of the supply circuits at all sites. The power supply at Armitage substation is currently limited and should improve by 2011 when the peaking York Energy Center generating plant comes on line.

In order to limit construction cost, the traction power substations were located along the railroad as close as possible to the Hydro One substations or transmission lines. Any required connections between the Hydro One substations and the traction power system substations will be in the form of overhead transmission lines or underground cables. The selection of the type of connection will depend on the location of the substations and the corresponding environmental impact.

Autotransformer Station and Switching Stations

Table 8-2 shows the number of autotransformer stations (ATSs) and switching stations (SWSs) per line.

Table 8-2 – Location of Autotransformer and Switching Stations

GO System Line	Autotransformer and Switching Station Name
Lakeshore West Line	Bathurst SWS
	Oakville SWS
	Hamilton TH&B ATS
	Grimsby ATS
	St. Catharines ATS
Lakeshore East Line	Don Yard ATS
	Durham Junction SWS
Milton Line	Cooksville ATS
	Meadowvale ATS
	Milton ATS
Georgetown Line	Carlton Park ATS
	Woodbine ATS
	Georgetown SWS
	Kitchener ATS
Barrie Line	Maple ATS
	Gilford Street ATS
	Allandale ATS
Richmond Hill Line	Old Cummer ATS
	Bloomington ATS
Stouffville Line	Unionville ATS
	Lincolnville ATS

High Voltage Circuit Breakers and Disconnect Switches

Selection of high (primary) voltage circuit breakers, disconnect switches and protective equipment is governed by the circuit voltage level and short circuit fault level existing at the particular electrical power utility supply. The high voltage supply arrangement and protection should be designed in accordance with the power utility practices and should be reviewed by the power utility. The high voltage circuit breakers and disconnect switches should be designed, tested and installed in accordance with relevant Canadian and IEEE C37 series of standards.

Traction Power Transformers

The transformer primary windings will be connected phase-to-phase to the transmission line system facilities owned and operated by Hydro One. In order to limit the system unbalance, the transformer primary winding phase connections should be rotated among the phases. Considering the loadings of the substation transformers, one possible set of transformer connections, to aid in balancing the load within the Hydro One system, is shown in Table 8-3.

Table 8-3 – Possible Traction Power Substation Phase Connections

Substations	Transformer	Suggested Phase Connection Schedule	
Mimico	T-1	A	B
	T-2	B	C
Burlington West	T-1	C	A
	T-2	A	B
Scarborough	T-1	B	C
	T-2	C	A
Oshawa	T-1	A	B
	T-2	B	C
Dixie Road	T-1	C	A
	T-2	A	B
Guelph	T-1	B	C
	T-2	C	A
New Market	T-1	A	B
	T-2	B	C

Final selection of the transformer phase connection should be made during preliminary design with Hydro One consultation.

Based on the load-flow modeling, it is proposed is that each substation be equipped with two 25 MVA continuously-rated single-phase traction power transformers. This rating will allow for substation outage conditions, future increase in traffic density, and for unusual operating conditions, such as train bunching.

The transformer primary winding will be single-phase and will match the power utility incoming voltage of 230 kV. The transformer secondary winding will be rated at 50 kV nominal voltage and will feed the feeder and catenary distribution systems. The secondary windings will be center-tapped, with the tap solidly grounded and connected to the traction power return system. Consequently, this arrangement will result in the feeder-to-rail and a catenary to rail systems that operate at a 25 kV nominal voltage with the feeder-to-catenary system that operates at 50 kV nominal voltage.

The substation transformers should be designed, constructed and tested in accordance with relevant Canadian and IEEE 57 series of standards. The transformer coils should be provided with extra bracing to withstand pulsating radial and axial forces due to the highly fluctuating traction load.

Medium Voltage Switchgear

The OCS is susceptible to frequent short circuit faults and, therefore, switchgear with vacuum or sulphur hexafluoride (SF_6) circuit breakers is recommended. The circuit breakers should be capable of several hundred operations at short circuit current levels and several thousand operations at rated current levels. The medium voltage switchgear should be designed, constructed and tested in accordance with relevant Canadian and IEEE C37 series of standards.

Whenever voltage rating permits, metal-clad switchgear assemblies with horizontal draw-out circuit breakers are recommended. The switchgear should be located in a Control Building and installed in dead-front, floor-mounted, free-standing cubicles. Indoor, fixed, metal-enclosed switchgear or outdoor, pole-mounted circuit breakers are recommended alternatives to the metal-clad, draw-out circuit breaker type switchgear.

Control Building

The Control Building can be either metal, prefabricated building, or a masonry building. The building houses the station SCADA equipment, control equipment, metering equipment, the station ac and dc auxiliary power supply including ac and dc panelboards, battery and one or two battery chargers. As already mentioned, the building can also house the medium voltage switchgear.

Real Estate Requirements

Traction power substations have requirements for equipment that operates at high voltage electrical input and medium voltage output. Requirements for electrical clearances dictate that most of the traction power substation equipment be installed outdoors. Typical substation for 1x25 kV direct-fed or 2x25 kV autotransformer-fed systems would require an area of approximately 45 m x 100 m (150 ft x 300 ft). In areas where suitable real estate is not available, but a sufficiently wire railroad right-of-way exists, investigation can be conducted to accommodate a “long and narrow” substation design requiring approximately 25 m x 150 m (75 ft x 500 ft) of real estate, as shown in Figure 8-1. In this configuration, a space for Static VAr Compensator (SVC) equipment has been allocated. The SVC equipment is used to improve voltage profile, reduce unbalance, and mitigate harmonic distortion at the utility power supply busbar.

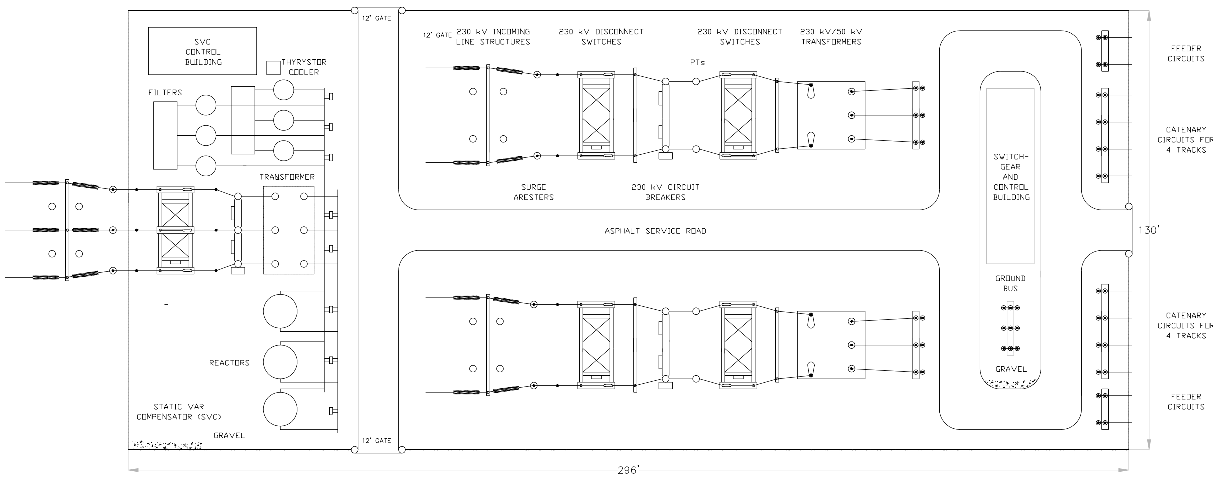


Figure 8-1 - Typical Traction Power Substation Equipment Layout

Typical switching station or autotransformer station would require an area of approximately 20 m x 35 m (60 ft x 120 ft), as shown in Figure 8-2.

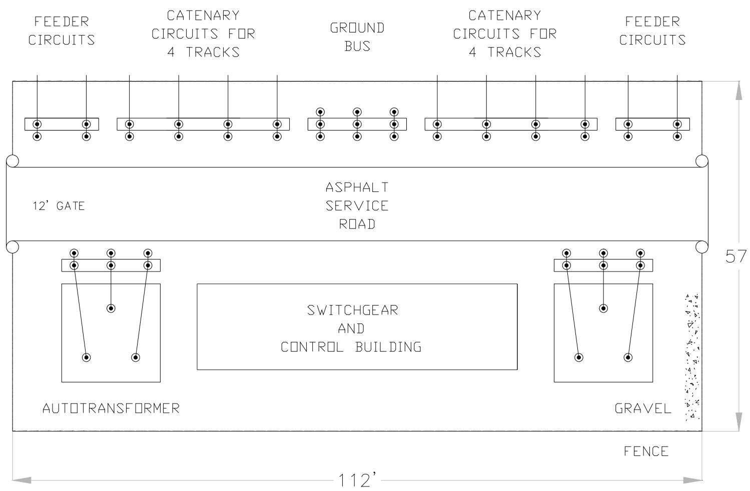


Figure 8-2 - Typical Autotransformer Station Equipment Layout

Each substation will be build on land either owned by Metrolinx or purchased by Metrolinx, as there is no space that can be made available in the Hydro One substations.

The autotransformer stations and switching stations can most likely be built within the railroad right-of-way to avoid purchase of the required real estate.

8.4. Overhead Contact System

Modern OCS Configuration

The OCS consists of messenger and contact wires which are supported from poles, portals, cross-spans, head-spans, bridge supports and tunnel supports, as required. The contact wire, which is required to be installed at a constant height with respect to the track, is suspended from the messenger wire by the means of hangers. Since the messenger wire assumes the natural profile of a catenary curve[20], the hangers need to be designed and fabricated at different lengths to maintain the contact wire level profile, as shown in Figure 8-3.

[20]Catenary is the curve that is assumed by a freely hanging conductor, chain or rope when supported at its ends and acted on only by its own weight.

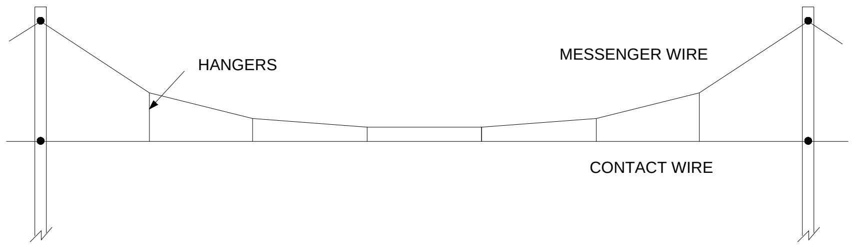


Figure 8-3 – Catenary System[21]

Since messenger and contact wires are delivered form suppliers on reels containing lengths of approximately 1.6 km (1 mile) of wire, the OCS needs to be constructed in a series of sections, so called tension lengths. A tension length is an individual physical segment of OCS wiring and includes the conductors, weight-tensioning equipment, and anchoring devices.

The weight-tensioned systems of modern OCS design allow the overhead system to adjust to temperature changes and to maintain constant wire tension. Without the weight-tensioned equipment, the conductors could become too taut on cold winter days and exhibit excessive sag during hot summer days limiting the maximum speed of train operation. The weight tensioning system employs a system of pulleys and balance weights at each end of each tension section to allow the messenger and contact wires to respond to thermal changes while maintaining a constant tension. Further, in modern systems, the contact wire is pulled in and pushed off the centerline of track, or “staggered”, at supports, as shown in Figure 8-4. The stagger, typically ±6” to ±10”, intentionally displaces the contact wire from the centerline of the track. Without this stagger the contact wire would wear a grove at the center of the pantograph carbon. When stagger is employed, the contact wire uniformly sweeps the width of the pantograph carbon as the vehicle travels along the alignment, thus eliminating localised pantograph wear.

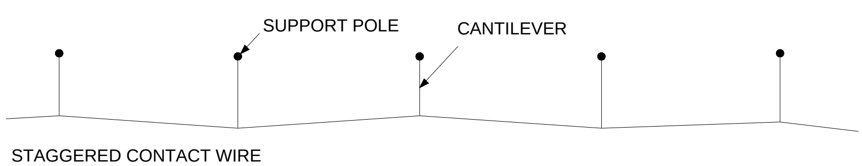


Figure 8-4 - Staggered Contact Wire

In the auto-tensioned or weight-tensioned systems, the cantilevers are hinged and move (or swing) along track as the messenger and contact wires expand and contract due to ambient and conductor temperature changes. As the cantilevers swing, they change the position of the contact wire relative to the track centerline. In order avoid the conductor displacement becoming excessive at extreme conductor temperatures, half tension sections are limited in length to 0.8 kilometres.

21 The purpose of the OCS diagrams is to illustrate design concepts and placement of equipment. The diagrams are not to scale.

To prevent the whole conductor assembly from moving along the track, especially on gradients, the center of each tension length is held stationary by a mid-point anchor, as shown in Figure 8-5, which creates two half tension sections.

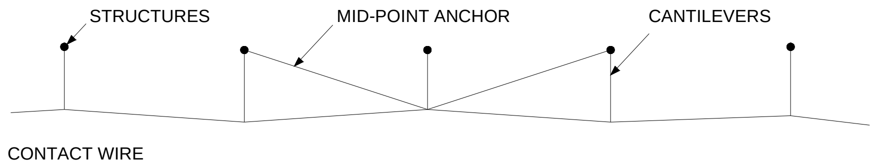


Figure 8-5 - Principle of Mid-Point Anchor

At the ends of each tension length, one set of conductors is taken out-of-running and a balance weight assembly is applied. The other set of conductors, also connected to a balance weight assembly, is taken in-running. The out-of-running conductors and the in-running conductors are installed side by side, at the same height, for one span, the so called overlap span, shown in Figure 8-6. The overlap span ensures the pantograph smoothly transitions from one tension length to the other.

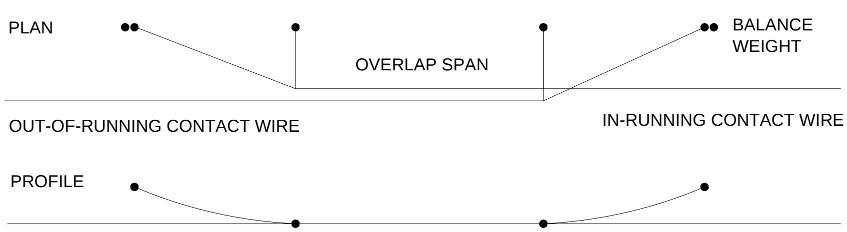


Figure 8-6 - Principle of Overlap

Along a particular section of track, it is necessary to build multiple tension lengths, the ends of which overlap each other to form a continuous OCS. In an effort to reduce costs associated with providing overhead contact system wiring overlaps, the length of tension lengths can be maximized, subject to the constrains discussed above, by careful selection of the design parameters.

Basic OCS Design Principles

The fundamental task in design of the OCS is the selection of support structure spacing along tangent and curved track, and messenger and contact conductor tensions. The challenge is to optimise the selection of both of these parameters so that most economic design is achieved while the vehicle pantograph does not leave the contact wire under the most onerous conditions of operation.

Basically, in order to ensure continuous current collection the designer needs to consider the movements of two mechanical systems, the rolling stock and the OCS.

The movement of the rolling stock traveling along the alignment is caused by the following factors:

- Track alignment tolerances, gauge, vertical, horizontal, and cross-level
- Vehicle roll
- Vehicle lateral displacement
- Pantograph sway
- Track curvature

The movement of the OCS, and the contact wire in particular, from the design location is caused by the following factors:

- Conductor blow-off due to wind loading taking into account ice loading
- Conductor displacement due to movement of hinged cantilevers swinging as the conductor length changes due to temperature variation
- Conductor stagger effect – where the stagger at two adjacent structures is not the same, the maximum wire deflection is not mid-span and additional wire offset needs to be taken into account
- Pole deflection due to imposed wind loads
- Erection tolerances of the OCS

Considering the most onerous operating conditions, both systems can be moving in the opposite directions. The designer needs to select appropriate combination of structure spacing and conductor tensions to ensure that the contact wire does not loose contact with the pantograph. The OCS design is further complicated by the overall design philosophy. Although the worst condition of each parameter should be considered, some designers assume that the worst condition in all parameters does not occur at the exactly same time. This assumption invariably leads to more economical OCS design and should be supported by design and operation experience in similar environments and sound engineering judgement.

OCS Design

The longer the spacing between structures, generally, the more cost effective design will result. However, such design needs to be balanced by the likely requirement for higher conductor tensions which will be needed to limit the higher conductor blow-off. The larger conductor tensions may result in more robust tensioning equipment and higher structure foundation costs.

While the final design of an OCS is best performed based on accurate survey of right-of-way, design cost saving methods can be applied during the early and less detailed preliminary design phases. For example, using mathematized alignment data obtained from an aerial survey, preliminary overhead contact system wiring layouts can be prepared. The effort should concentrate on minimizing the pole and portal structure count as the real means of reducing capital and maintenance costs, as well as reducing visual intrusion.

To further reduce pole count and cost, center-pole construction should be considered where possible and practical for two-track electrification. However, portal structures will be necessary in multiple-track areas. Clearly, maximum possible span lengths on tangent sections of track and on curves should be used.

Overhead System Conductors

The traction power substations will distribute power along the system route by the feeder and overhead contact systems. The traction power distribution system considered in the report consists of the following conductors:

- Feeder Conductor, 556.5 kcmil, Aluminum Cable Steel Reinforced (ACSR) Wire
- Messenger Conductor, 4/0 A.W.G., Stranded Hard-Drawn (H. D.) Copper Wire
- Contact Conductor, 4/0 A.W.G., Grooved H. D. Copper Wire

The report demonstrates that this, or similar, configuration of the distribution system would be suitable for electrification of the Metrolinx corridors, as it would be capable to carry the envisioned load currents for both normal and contingency operations. The conductor configuration of the overhead feeder and catenary systems should be coordinated with the traction power system design team.

During the design phase of the OCS, an optional choice for the contact wire is to use a larger 300 kcmil grooved contact wire in preference to the smaller 4/0 AWG wire. This choice would yield the following advantages:

- The larger contact wire can be installed at a higher tension. The higher tension reduces blow off of the contact wire, permitting longer spans on both tangent and curved track, thus reducing the structure count and costs, speeding installation, and reducing maintenance costs for supports.
- The larger contact wire reduces system impedance and improves voltage profile along the system.
- The larger contact wire allows for greater wear, and increases time for contact wire replacement.

A 300 kcmil conductor is used by Amtrak on the New Haven, CT to Boston, MA electrification and has been selected for the Caltrain system electrification.

Wiring an Operating Railway

The process of adding electrification to an already operating commuter rail system should take the following factors into consideration:

- The schedule for major track upgrades should show completion before OCS installation begins.
- A program for routine field surveys and onsite inspections (walk-outs) should be established to coordinate OCS foundations with other systems disciplines and new civil/structural work.
- A track possession pattern must be developed to allow for OCS activities, foundation installation, steel erection, as well as conductor running and adjustments. These activities could require reverse train operation on revenue tracks between crossovers during off-peak times.
- Styles of OCS structures and supports should facilitate future incremental addition of wiring in multi-track sections of route.
- Electrification circuit sectionalizing should be compatible with the current methods of providing maintenance and emergency track outages.

- Electrification safety aspects should be added to the existing on-track safety rules for both Metrolinx and other railroad users.
- Practices for safety grounding and bonding of metallic objects near or above tracks should be developed. This should be coordinated with the signalling system design and design of wayside electrical facilities.
- Cost effective measures should be developed to protect public from accessing and vandalizing the new electrical equipment.

Clearance Requirements

Horizontal Clearance. Standard minimum horizontal clearance is 2.6 m (8'-6") between the face of the catenary structure and the centerline of nearest track on tangent sections. The distance will be suitably increased on the curves.

Realignment of the existing tracks is not generally required for installation of the catenary structures. Poles between the tracks can be provided if adequate track centers are available and if such design is acceptable from the mechanical independence of the OCS.

Normal Minimum Vertical Clearances. The overhead clearance required for electrification at 25 kV and electrification voltage is shown below. The Normal Minimum clearances were developed based on recommendations by American Railway Engineering and Maintenance-of-Way Association (AREMA)[22]. Figure 8-7 presents the clearances that need to be considered in developing the Normal Minimum clearances for electrification.

[22] AREMA, Manual for Railway Engineering, Chapter 33, Electrical Energy Utilization, Part 2, Clearances, published in 2009.

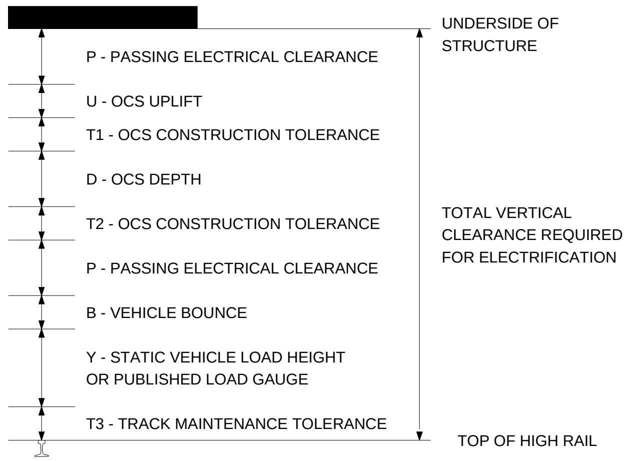


Figure 8-7 – AREMA-Recommended Diagram for Determination of Total Vertical Clearance Required for Electrification

Table 8-4 presents development of the Normal Minimum Total Vertical Clearances required for electrification at 25 kV voltage.

Table 8-4 – Normal Minimum and Absolute Minimum Catenary System Vertical Clearances Required for 25 kV Electrification Without and With Allowance for Flash Screen

Clearance	Symbol, Refer to Fig. 8-7	Normal Minimum (mm)
Passing Electrical Clearance	P	205
OCS Uplift	U	50
OCS Construction and Maintenance Tolerance	T_1	25
OCS Depth	D	155
OCS Construction and Maintenance Tolerance	T_2	25
Passing Electrical Clearance	P	205
Vehicle Bounce	B	65
Static Vehicle Load Height (Load Gauge)[23]	Y	6,248
Track Maintenance Tolerance	T_3	40
Total Vertical Clearance Required for Electrification (mm)		7,018
Total Vertical Clearance Required for Electrification (m)		7.02

Where the vertical space is limited, the 25 kV feeder is routed to the side of OCS, away from the vehicle.

Flash Screens and Weather Screens. Flash screens, also called arc screens, are required at all overpasses with concrete soffits closer than 1,220 mm (4 feet) to the OCS. The flash screens prevent electrical flashover (arcing) from the energized parts of the OCS to the bridge structure. The flash screens may be as wide as the pantograph, or marginally wider, and need to be installed for the full track length of the bridge beneath the concrete. Two solutions are possible:

- Aluminum or stainless steel flash screen mounted on the underside of the bridge and grounded to the electrification system ground

23 For static vehicle load gauge, double stack freight car height of 20’6” was assumed. In the event that the vehicle load gauge increases in the future, significant cost impact may be expected.

- Insulating material, such as glastic, flash screen mounted to the underside of the bridge

In the event that the Union Station smoke ducts are renovated, it may be possible to manufacture the flash protection as a part of the new smoke ducts.

Fibreglass weather screens may be used on bridges to prevent water seeping through the bridge construction joints and onto the catenary system. Such water seepage may form icicles which in turn may cause a flashover.

Decision on which approach should be used for the flash screens and which bridges will receive weather shields should be made by the OCS designer during detail design. Either approach should require less than 25 mm of vertical space, which is accommodated in the track maintenance tolerance and OCS construction and maintenance tolerances.

Pantograph Clearance. In addition to providing for the vertical clearance requirements, it is necessary to provide the space required for the pantograph, the so called, pantograph clearance envelope (PCE). The PCE is only an issue when the soffit of the overpass or tunnel is not in parallel with the track surface above the swath of the pantograph, namely, when the soffit is arched. In these cases the PCE could determine the maximum pantograph operating height and hence the required contact wire height. Should the contact wire height required per the above Tables (sum of symbols T3+Y+B+P+T2), be higher than the maximum height at which the pantograph can safely operate, there will be need for an additional review of means to provide the required clearances.

Evaluation. For each location the recorded clearance, supplied by Metrolinx, was compared to the required clearance[24]. Where the required clearance exceeded the recorded clearance, the additional clearance required was calculated. Based on this evaluation, required civil modifications, to raise the structure or lower the track, have been determined, and the associated cost of civil modifications estimated.

Should Metrolinx electrify the GO network with overhead catenary system and VIA chose to stay with its current diesel locomotive fleet, no compatibility issues with VIA train operation are envisaged. VIA trains' loading gauge is expected to fit easily within the cross-sectional profiles of 25 kV commercial ac electrification arrangements.

Freight train loading gauge compatibility is, of course, a concern with GO network electrification. There are numerous North American precedents for freight operation in both third rail and OCS, including freight operations on Amtrak, NJ Transit, MNR, LIRR and the SEPTA. However, clearances are limited and no North American OCS electrification supports the typical 7 meter, (23 feet), clearance envelope required for double-stack freight train operation.

[24] GO Electrification Study – Baseline Report

It is necessary to compare the required clearances with the actual, recorded, clearances available along the alignment. The next phase of the report should investigate the GO line-specific and site-specific electrification loading gauge issues, including:

- Present freight clearances,
- Statutory requirements to maintain current freight clearances,
- Statutory requirements not to preclude future freight clearances that support double stack container trains and other high clearance rolling stock,
- Commercial requirements of the freight carriers and the possibility that some or all GO lines' freight clearances can be limited to conventional Association of American Railroads (AAR) Plate "C" or Plate "F" clearances more typical of boxcar, tank car, gondola, hopper and flat car traffic.

Typical OCS Equipment Construction

Conceptual drawings are presented to illustrate typical arrangements of various OCS constructions. The drawings are not to scale and their purpose is to illustrate relative placement of typical OCS equipment.

Figure 8-8 shows a typical two-track OCS arrangement with side pole construction.

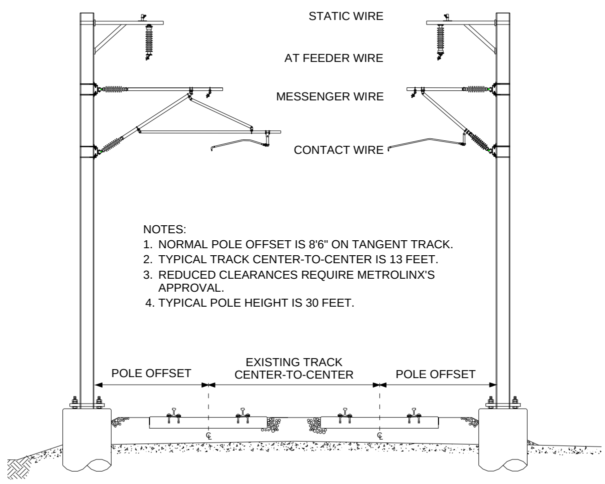


Figure 8-8 – Typical Two-Track OCS Arrangement with Side Pole Construction

Figure 8-9 shows a typical two-track OCS arrangement with center pole construction.

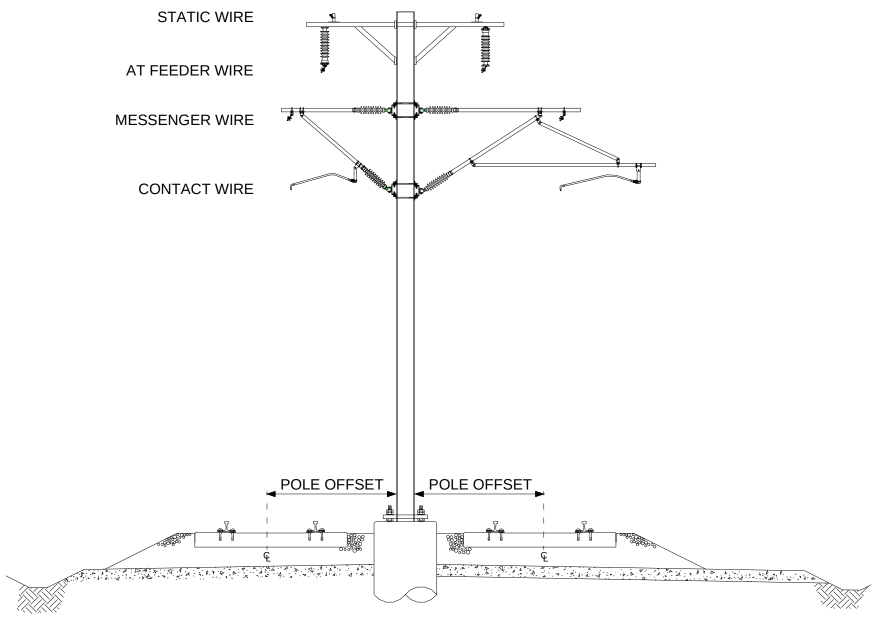


Figure 8-9 – Typical Two-Track OCS Arrangement with Center Pole Construction

Figure 8-10 shows a typical three-track OCS arrangement with portal construction. This concept can be extended to practically any number of tracks.

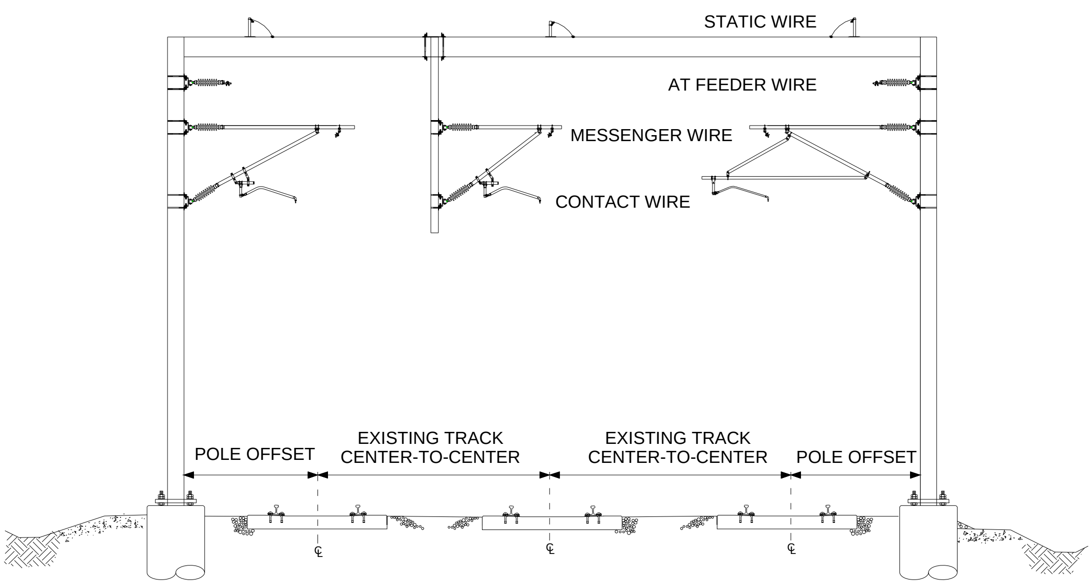


Figure 8-10 – Typical Three-Track OCS Arrangement with Portal Construction

Figure 8-11 shows a typical two-track OCS arrangement with headspan construction. Although considered by many to be more environmentally acceptable than portal construction, technically, a single wire breakage in the headspan construction renders all tracks inoperable.

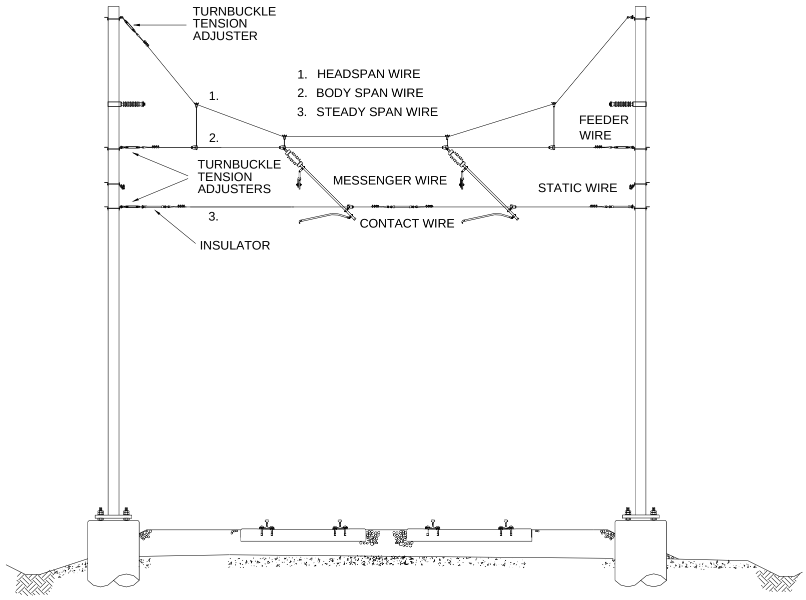


Figure 8-11 – Typical Two-Track OCS Arrangement with Headspan Construction

Figure 8-12 shows a typical shop building contact wire supports.

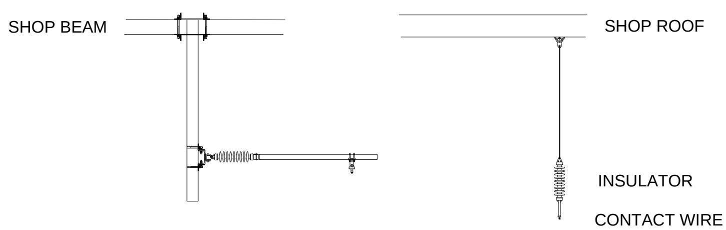


Figure 8-12 - Typical Shop Building Supports

8.5. Traction Power Return System

The traction power return system consists of the running rails, impedance bonds, cross-bonds, overhead static wire, and the ground itself. The traction power return system considered in the report utilized the following configuration:

- Static Conductor, 336.4 kcmil ACSR Wire
- Running Rails, 132 RE

The static wire should be installed on the distribution system supporting structures effectively connecting the OCS structures to each other and to the ground. For the return system to operate at its optimal level and to limit rail-to-ground potentials, it is required to cross-bond the running rails at impedance bonds, and to periodically connect the impedance bonds to the static wire/supporting structure system, as well as to the substation, autotransformer station, and switching station ground grids.

This design allows for portions of the return current to flow in the rails, static wire, and the ground. The purpose of this arrangement is to provide as low an impedance return system as possible in order to limit voltage rise on the running rails (rail-to-ground potentials) and to improve catenary fault detection by facilitating sufficiently high short-circuit currents.

8.6. System Protection

Transformer and Autotransformer Protection

Each traction power transformer and autotransformer is recommended to be equipped with phase and ground fault overcurrent relay and a differential relay. It is recommended that the traction power supply substation overcurrent protection is fully coordinated with the power utility protection.

Two stage winding over-temperature relay should be also provided. The relay should be designed to provide an alarm at lower excess temperature level and to open the medium voltage circuit breakers at higher excess temperature. A two-stage sudden pressure relay for internal transformer faults should initiate an alarm for gas accumulation and trip out the transformer in the event of an oil surge.

Catenary and Feeder Protection

The catenary and feeder system protection should be implemented in each substation, autotransformer station and switching station switchgear. The systems can experience high peak load currents and low fault currents which can be comparable in magnitude. This precludes effective use of overcurrent type protection, as overcurrent relaying cannot distinguish between the high load currents and low fault currents.

The most feasible solution for catenary and feeder protection is the use of distance relaying. This form of protection is comparatively simple to apply, is of high speed class, and provides primary and back up protection inherent in a single scheme. The distance relays measure impedance along the protected line and are arranged to operate for faults between the relay locations. The reach of the distance relays is usually divided into three protection zones, thus enabling time discrimination for faults in different line sections. Modern relays have completely independent and adjustable resistive and reactive reach settings and are capable of operating with forward and backward reach.

Faults occurring in the Zone 1 (the closest to the relay) are recommended to be cleared with no intentional time delay. Zones 2 and 3 (beyond Zone 1) have adjustable time delays and train start detection feature using current, voltage and phase rate of rise (di/dt, dv/dt, and dϕ/dt) to trigger conditions to prevent the distance relay operation under train accelerating current. Further, it is recommended that the relays be equipped with circular and polygonal tripping characteristic with independently adjustable line resistance, line reactance, and “load blinding” settings to prevent the relay operation on train load.

A high proportion of catenary and feeder faults will clear once the circuit breaker is opened and the air in the fault location is de-ionized. Depending on the railroad operating practices, use of an auto-reclosing operating device can be considered. The auto-reclosing feature will reclose the circuit breaker after an interval of 3 to 15 seconds, if not manually overridden. In the case of persistent faults, the circuit breaker will latch out on the second or third opening.

In addition to distance relaying, consideration should also be given to two-stage backup overcurrent protection activated in case of voltage transformer failure, thermal overload protection which prevents the system conductors from overheating and possible annealing, and a fault locator unit capable of indicating fault distance from the relay. In order to accelerate the fault clearance, and in special circumstances, where sufficiently high short circuit currents are not available to clear remote faults, transfer trip of remote circuit breakers using pilot wire or fibre optic communication can be considered.

Overvoltage Protection

It is recommended to provide comprehensive overvoltage protection to protect the traction power supply system and its components from overvoltages caused by lightning strikes or switching surges. The protective equipment should include appropriately rated surge arresters and transient voltage surge suppressors. The grounding connections of these devices should be as short as possible and without unnecessary bends in the grounding wires. Recommended standards for application of surge protection include IEEE C62 Surge Protection Standards Collection, Underwriters Laboratories' UL 96A, National Fire Protection Agency's NFPA 780, and Lightning Protection Institute's LPI 175.

Protective Relay Immunity

The electrification system protection must be immune to system harmonics and must ensure full discrimination of protective devices. The protection must also provide a complete back up in the case of breaker or relay failure and be inoperative under inrush of magnetizing current to autotransformers and rolling stock on-board transformers.

8.7. Supervisory Control And Data Acquisition System

Each traction power supply substation, autotransformer station and switching station should be controlled locally from a Human Machine Interface (HMI) unit. The HMI should be equipped with a high resolution color CRT touch screen and programmed to show the electrical facility one-line diagram including all major equipment.

Remote control, monitoring and telemetering of the traction power supply substations, autotransformer stations switching stations, and wayside motor-operated disconnect switches used for system sectioning should be provided. The use of a computer-based Supervisory Control and Data Acquisition (SCADA) system is recommended. In the Control Center, the SCADA system should be equipped with one or more color visual display units which may be supplemented with modular or rear projection screens.

As a minimum, the SCADA/HMI system should incorporate the following local and remote control, monitoring and telemetering features:

- Closing and opening operations of all circuit breakers and motor-operated disconnect switches
- Control of electrical lockout relays
- Status indication of all circuit breakers, disconnect switches and grounding switches

- Status indication of protective relaying, ac auxiliary power equipment and dc auxiliary power equipment including the station battery and battery charger
- Status indication of communication system
- Enable/disable automatic reclosing of circuit breakers
- Metering of substation power demand and energy consumption
- Maximum demand prediction
- Recording of maintenance clearance permits and maintenance status
- Work permit, power removal and out of service equipment tagging
- Catenary power removal coordination with railroad operations and track blocking
- Annunciation of circuit breaker tripping and low substation voltages
- Annunciation of facility intrusion and smoke/fire alarms
- Sequence of events recording
- Voice communication

It is also recommended that the selection and de-selection of equipment and control command transmittal be performed from the computer keyboards and touch screens. In order to facilitate SCADA system maintenance, software changes, and to avoid disruption of service due to failures, duplication of the SCADA system is recommended either at the railroad Control Center or at a remote location.

8.8. System Grounding And Bonding

General

In order to provide a safe system for the general traveling public and to provide safe environment for the system maintainers, various components of traction electrification system are required to be bonded and grounded. The purpose for equipment grounding and bonding is to limit the magnitude of potentials to which a person or persons could be exposed to safe levels. Elevated potentials can occur during short circuits caused by insulation failures, OCS, transmission or distribution line conductor breakages, electromagnetic interference and accidental contact of non-energized equipment with live equipment, such as when a fence connected to an overpass falls on energized OCS equipment underneath, or birds and rodents accidentally bridge the electrical clearance gap. In general, it is recommended that all OCS components, grade crossings, pedestrian crossings, structures, buildings, and fences adjacent to the electrified tracks be grounded and bonded in accordance with Railway Electrification Guidelines CSA C22.3 No. 8-M91 published by Canadian Standards Association.

Traction Power Supply Substations, Autotransformer Stations and Switching Stations

Each traction power supply substation, autotransformer station and switching station is provided with ground grid. The ground grid is a mesh of copper wires exothermically welded at each cross and tee. In order to achieve a low overall grid resistance, the wire mesh is supplemented by ground rods. The depth, size of the individual meshes, number and type of ground rods required, and the extent of the ground grid can be determined by following the calculation methods and procedures published in IEEE Std. 80[25]. The general design principle is to install the grid conductors sufficiently close to each other and provide the grid with sufficient number of ground rods, so that, in the event of short circuit in the facility, the step and touch potentials do not exceed permissible limits.

All metal equipment in each facility should be bonded to the ground grid. This equipment includes supporting steel structures, metal housings, and electrical equipment within the metal housings, outdoor circuit breakers, power transformers, switchgear cubicles, surge arresters, transient voltage suppressers, lighting poles, and the facility fence.

Traction Power Return System

Signalling system requires the running rails to be divided into electrically separate sections, so-called track circuits, by insulated rail joints. In order to enable the traction power return current to bypass the insulated rail joints on its way back to the substation, impedance bonds are connected to the rails to span the joints. The impedance bonds do not allow the signalling circuit currents to pass, but allow the traction return current to pass.

Some impedance bonds are installed with connection only to the rails, some bonds are cross-bonded (connected) to bonds serving other tracks in multiple-track territories, and some impedance bonds are cross-bonded and grounded. The purpose behind bonding and grounding of the bonds is to limit the return circuit impedance and prevent excessive rise of rail-to-ground voltages. At substations the cross-bonds are connected to the substation ground grid.

The locations of cross-bonds and grounded cross-bonds is critical for satisfactory operation of the signalling system, and therefore, the bonding and grounding design should be developed in close collaboration between signalling and electrical power engineering staff.

Overhead Contact System

Along the open route, the OCS poles are bonded to a static wire. The static wire is a conductor attached to each pole or portal structure and is grounded at locations of grounded cross-bonds. In multiple-track territories multiple static wires may be provided.

At locations of manually-operated disconnect switches an individual ground mat is provided under each switch operating handle to protect the operator of the switch.

Passenger Stations and Platforms

In order to prevent voltage difference between the station platforms and rolling stock body, which may be noticed by boarding and alighting passengers, all station steelwork is bonded and connected to a ground wire which is connected to impedance cross-bonds in the vicinity of the station.

25 IEEE Guide for Safety in AC Substation Grounding

Fences, Bridges, Fuel Tanks and Other Utilities

Long fences paralleling the tracks should be periodically grounded to ground rods. Typically, a ground rod should be installed every 300 m to 1,000 m (1,000 feet to 3,000 feet), depending on the fence proximity to the tracks, in accordance with CSA C22.3 No. 8-M91.

Bridges, fuel tanks, and other utilities crossing the railroad should be equipped with ground wire grounded with ground rods on each side of the railroad, in accordance with CSA C22.3 No. 8-M91. Utility pipelines attached to the bridges should be bonded and connected to the bridge ground wires. Such installation should be reviewed by the facility owner to ensure compliance with the owner requirements.

8.9. Overall System Arrangement And Equipment Ratings

The Metrolinx system is proposed to be supplied by 7 substations, 17 autotransformer stations, and 4 switching stations as shown in Table 8-5. The Table shows the proposed number and rating of the traction power transformers and autotransformers, as well as the total power capability for each substation, autotransformer station, and switching station.

Table 8-5 - Traction Power System Facilities Proposed for the Metrolinx GO Electrification System

Line	Substations	Autotransformer Stations	Switching Stations	Number of Transformers	Transformer Rating (MVA)	Total Station Capability (MVA)
Lakeshore West Line to TH&B			Bathurst St.	4	5	20
	Mimico			2	20	40
			Oakville	2	5	10
	Burlington West			2	20	40
		Hamilton TH&B		2	5	10
Lakeshore West Line to St. Catharines		Grimsby		2	5	10
		St. Catharines		2	5	10
Lakeshore East Line		Don Yard		2	5	10
	Scarborough			2	30	60
			Durham	2	5	10

	Oshawa			2	20	10
Milton Line		Carlton Pk.		2	5	10
		Cooksville		2	5	10
		Meadowvale		2	5	10
		Milton		2	5	10
Georgetown Line		Woodbine		2	5	10
	Dixie Road			2	30	60
			Georgetow n	2	5	10
	Guelph			2	20	40
		Kitchener		2	5	10
Barrie Line		Maple		2	5	10
	New Market			2	20	40
		Gilford St.		2	5	10
		Allandale		2	5	10
Richmond Hill Line		Old Cummer		2	5	10
		Bloomington		2	5	10
Stouffville Line		Unionville		2	5	10
		Lincolnville		2	5	10

Preliminary locations of substations, autotransformer stations and switching stations as well as the conceptual single-line diagram of the electrification system are shown in Figure 8-13.

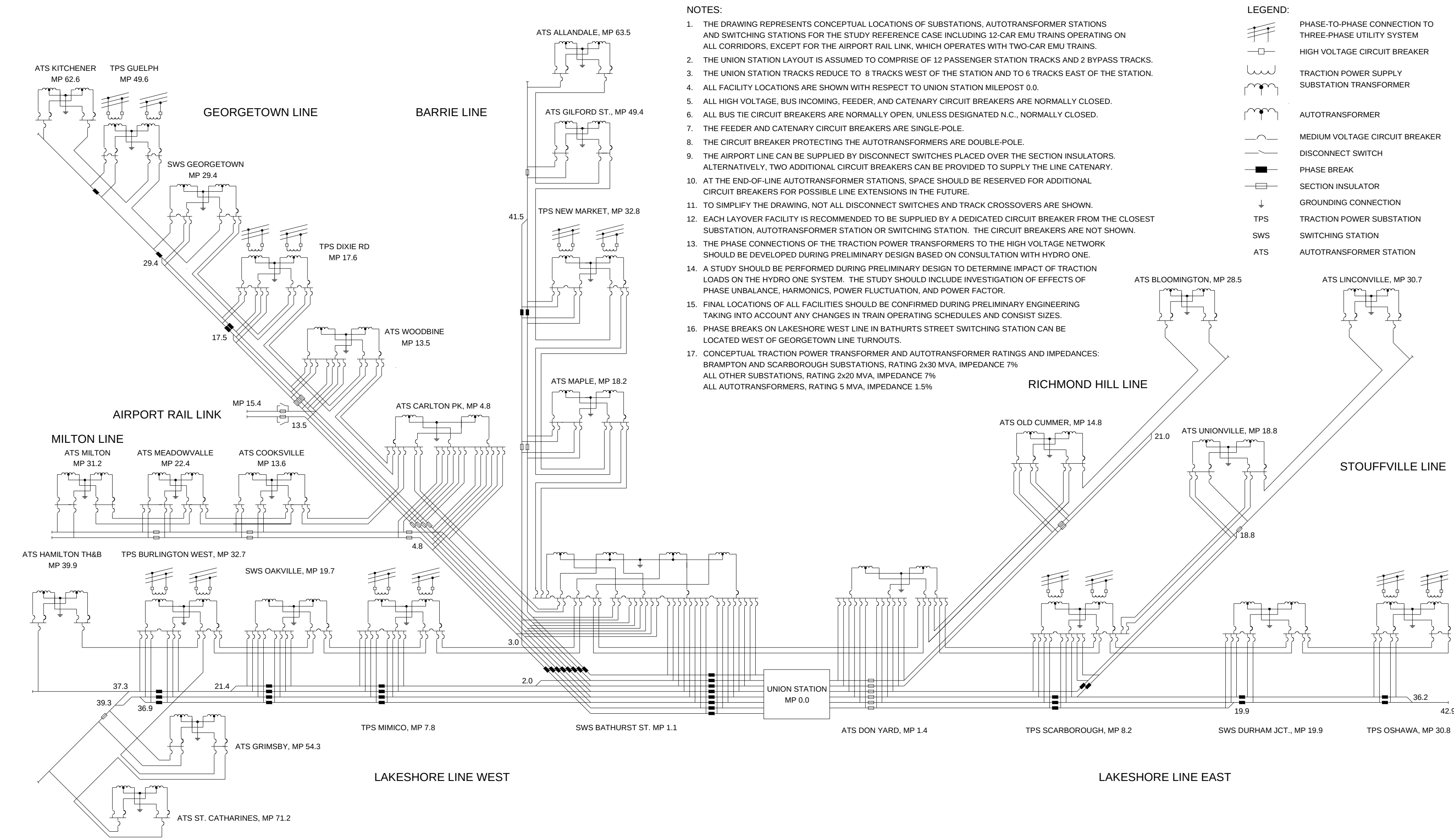


Figure 8-13 – Conceptual One-Line Diagram of the Electrification System

8.10. Normal And Emergency Operation

Normal Operation

During normal operation of the power system, i.e., when all equipment, including substations, is in service, each traction power transformer feeds its own section of track. A section of track in this context is defined as follows:

- A section extending from the traction power substation transformer to the end of the system
- A section extending from the traction power substation transformer to the switching station

Using the above definitions, the Metrolinx Lakeshore Line West, for example, has the following sections:

- Section 1 – Horner substation to Bathurst St. switching station
- Section 2 – Horner substation to Oakville switching station
- Section 3 – Burlington substation to Oakville switching station
- Section 4 – Burlington substation to end of the line at Hamilton and St. Catharines

Transformer Outage

Two transformers are installed in Horner and Burlington substations. For example, following a transformer outage at Horner substation, continuity of power supply to the Sections 1 and 2 is achieved by closing of the feeder and catenary bus-tie circuit breakers at that substation. The substation transformer remaining in-service then feeds both sections of the system. Similar switching would occur at Burlington substation to maintain continuity of power supply to Sections 3 and 4.

Substation Outage

In the event of an entire substation failure, continuity of power supply would be provided by the remaining in-service substation. For example, should Horner substation fail, Burlington substation Transformer T2 must be capable of supplying its own Section 3, as well as Sections 1 and 2 normally fed by Horner substation, as described above. Similarly, should Burlington substation fail, the Horner substation traction power Transformer T1 would supply Sections 2, 3, and 4.

This switching is facilitated by the switching station and the out-of-service substation. The normally open switching station feeder and catenary bus-tie circuit breakers and the normally open bus-tie circuit breakers in the out-of-service substation would be closed to extend feeding of the in service substation transformer to the required sections of the system.

In order to prevent accidental closing of the bus-tie circuit breakers and connecting two out-of-phase buses, the bus-tie circuit breaker operation is interlocked. The interlocking circuit allows the bus-tie circuit breakers to close only when one of the buses is de-energized (the busbar voltage is monitored by potential transformers) and the associated circuit breaker feeding the deenergized busbar is open. The interlocking prevents the bus-tie circuit breakers to close when both buses are energized.

9. EVALUATION OF SHORT LIST OF OPTIONS

9.1. Short List Of Options

The high level evaluation identified the following short list of options:

- Option 1 – Georgetown Line and Airport Rail Link
- Option 2 – Lakeshore Lines, East and West (up to Hamilton St. James)
- Option 3 – Georgetown Line, Airport Link and Lakeshore Lines, East and West (up to Hamilton St. James)
- Option 11 – Georgetown Line, Lakeshore Lines, East and West (Hamilton St. James), and Milton Line
- Option 15 – Georgetown Line, Lakeshore Lines, East and West (up to Hamilton St. James), Milton Line and Barrie Line
- Option 18 – Entire Network (up to Hamilton TH&B and St. Catharines on Lakeshore West line)

The rolling stock, substation, autotransformer station, and switching station requirements for each option are identified in the following sections. All rolling stock quantities include spares. The number of tracks to be electrified is presented in Sections 6 and 8.

9.2. Option 1 - Electrification Of The Georgetown Line

The Option 1 provides for electrification of the Georgetown and Airport Rail Link. The rolling stock, substation, autotransformer station, and switching station requirements are identified in Table 9-1.

Table 9-1 – Rolling Stock and Traction Power System Facilities Required for Electrification of Georgetown Line

<table>
<tr><th>Line</th><th>Locomotives</th><th>Coaches</th><th>Cab Cars</th><th>Substations</th><th>Autotransformer Stations</th><th>Switching Stations</th></tr>
<tr><td>Lakeshore West Line to Hamilton St. James</td><td rowspan="2">17</td><td rowspan="2">131</td><td rowspan="2">18</td><td></td><td></td><td>Bathurst St.</td></tr>
<tr><td>Georgetown Line to Kitchener</td><td>Dixie Road
Guelph</td><td>Carlton Park
Woodbine
Kitchener</td><td>Georgetown</td></tr>
</table>

In addition to the above rolling stock quantities, 12 EMUs are required to serve the Airport Rail Link.

One track of Lakeshore West Line is required to be equipped with OCS to provide access for the electric trains to the Willowbrook maintenance facility.

9.3. Option 2 - Electrification Of The Lakeshore East And West Lines

The rolling stock, substation, autotransformer station, and switching station requirements for Option 2 are identified in Table 9-2.

Table 9-2 - Rolling Stock and Traction Power System Facilities Required for Electrification of Lakeshore East and West Lines

<table>
<tr><th>Line</th><th>Locomotives</th><th>Coaches</th><th>Cab Cars</th><th>Substations</th><th>Autotransformer Stations</th><th>Switching Stations</th></tr>
<tr><td>Lakeshore West Line to Hamilton St. James</td><td rowspan="2">44</td><td rowspan="2">358</td><td rowspan="2">46</td><td>Mimico
Burlington West</td><td></td><td>Bathurst St.
Oakville</td></tr>
<tr><td>Lakeshore East Line to Bowmanville</td><td>Scarborough
Oshawa</td><td>Don Yard</td><td>Durham</td></tr>
</table>

In addition to the above rolling stock quantities, 12 DMUs are required to serve the Airport Rail Link.

9.4. Option 3 – Electrification Of The Georgetown And Lakeshore East And West Lines

The rolling stock, substation, autotransformer station, and switching station requirements for Option 3 are identified in Table 9-3.

Table 9-3 - Rolling Stock and Traction Power System Facilities Required for Electrification of the Georgetown and Lakeshore East and West Lines

<table>
<tr><th>Line</th><th>Locomotives</th><th>Coaches</th><th>Cab Cars</th><th>Substations</th><th>Autotransformer Stations</th><th>Switching Stations</th></tr>
<tr><td>Lakeshore West Line to St. James</td><td rowspan="3">60</td><td rowspan="3">488</td><td rowspan="3">63</td><td>Mimico
Burlington West</td><td></td><td>Bathurst St.
Oakville</td></tr>
<tr><td>Lakeshore East Line to Bowmanville</td><td>Scarborough
Oshawa</td><td>Don Yard</td><td>Durham</td></tr>
<tr><td>Georgetown Line to Kitchener</td><td>Dixie Road
Guelph</td><td>Carlton Park
Woodbine
Kitchener</td><td>Georgetown</td></tr>
</table>

In addition to the above rolling stock quantities, 12 EMUs are required to serve the Airport Rail Link.

9.5. Option 11 - Electrification Of The Georgetown, Lakeshore East And West, And Milton Lines

The rolling stock, substation, autotransformer station, and switching station requirements for Option 11 are identified in Table 9-4.

Table 9-4 - Rolling Stock and Traction Power System Facilities Required for Electrification of Georgetown, Lakeshore East and West, and Milton Lines

Line	Locomotives	Coaches	Cab Cars	Substations	Autotransformer Stations	Switching Stations
Lakeshore West Line to St. James	73	595	76	Mimico Burlington West		Bathurst St. Oakville
Lakeshore East Line to Bowmanville				Scarborough Oshawa	Don Yard	Durham
Milton Line to Milton					Cooksville Meadowvale Milton	
Georgetown Line to Kitchener				Dixie Road Guelph	Carlton Park Woodbine Kitchener	Georgetown

In addition to the above rolling stock quantities, 12 EMUs are required to serve the Airport Rail Link.

9.6. Option 15 - Electrification Of The Georgetown, Lakeshore East And West, Milton And Barrie Lines

The rolling stock, substation, autotransformer station, and switching station requirements for Option 15 are identified in Table 9-5.

Table 9-5 - Rolling Stock and Traction Power System Facilities Required for Electrification of Georgetown, Lakeshore East and West, Milton and Barrie Lines

Line	Locomotives	Coaches	Cab Cars	Substations	Autotransformer Stations	Switching Stations
Lakeshore West Line to St. James				Mimico Burlington West		Bathurst St. Oakville
Lakeshore East Line to Bowmanville				Scarborough Oshawa	Don Yard	Durham
Milton Line to Milton	81	666	84		Cooksville Meadowvale Milton	
Georgetown Line to Kitchener				Dixie Road Guelph	Carlton Park Woodbine Kitchener	Georgetown
Barrie Line to Allandale				New Market	Maple Gilford St. Allandale	

In addition to the above rolling stock quantities, 12 EMUs are required to serve the Airport Rail Link.

9.7. Option 18 - Electrification Of The Entire Network

The electrification of all corridors includes Hamilton TH&B and St. Catharines sections on Lakeshore West line, as well as electrification of the Richmond Hill and Lincolnville lines. The rolling stock, substation, autotransformer station, and switching station requirements for Option 18 are identified in Section 8 and presented in Table 9-6.

Table 9-6 - Rolling Stock and Traction Power System Facilities Required for Electrification of the Entire Metrolinx GO System

Line	Locomotives	Coaches	Cab Cars	Substations	Autotransformer Stations	Switching Stations
Lakeshore West Line to TH&B Lakeshore West Line to St. Catharines Lakeshore East Line Milton Line Georgetown Line Barrie Line Richmond Hill Line Stouffville Line	107	888	112	Mimico Burlington West Scarborough Oshawa Dixie Road Guelph New Market	Hamilton TH&B Grimsby St. Catharines Don Yard Carlton Pk. Cooksville Meadowvale Milton Woodbine Kitchener Maple Gilford St. Allandale Old Cummer Bloomington Unionville Lincolnville	Bathurst St. Oakville Durham Georgetown

In addition to the above rolling stock quantities, 12 EMUs are required to serve the Airport Rail Link.

10. FINDINGS AND CONCLUSIONS

The load-flow simulation results show that the conceptual traction electrification system design of the Metrolinx system is in compliance with the accepted industry practices. Specifically:

- The train voltages are well above the minimum design values.
- Change in substation, autotransformer station, and switching station locations may be made for operational requirements and due to real estate availability. Changes in facility locations will not materially impact the minimum system voltages.
- Substation locations in proximity to Hydro One's high voltage transmission lines and substations in order to limit cost of additional connecting transmission circuits.
- Location of substations, autotransformer stations, and switching stations to enable the system to operate during normal and contingency conditions.
- Substation transformer and autotransformer ratings were selected to provide sufficient power to the system.
- Catenary and feeder currents are well below the overhead feeder and catenary system conductor thermal capabilities.

The traction electrification system is designed to support the ultimate future system operation during normal and contingency conditions.

The preferred rolling stock technology for the system is the electric locomotive hauled train with ten (10) coaches, except for the Airport Rail Link where train consists of two single-level multiple units will be used.

APPENDIX 7A - DOCUMENT DEFINITIONS AND GLOSSARY OF TERMS

Term	Definition
A	
Autotransformer-Fed System	Electrification system consisting of substations feeding along-track feeder and catenary systems. The feeder-to-catenary voltage is stepped-down to catenary-to-rail voltage at autotransformer stations and switching stations located along the system by the means of autotransformers. Since the feeder-to-catenary voltage is typically two to three times the catenary-to-rail voltage, longer substation spacing can be achieved than for a direct-fed system not using autotransformers.
Autotransformer Station	Station with one or more autotransformers used for transforming the feeder-to-catenary voltage to catenary-to-rail voltage. Autotransformer stations contain circuit breakers or switchgear line ups and effectively parallel the feeder and catenary circuits. Feeder and catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop.
C	
Cab Car	A passenger carrying railcar that also has a control stand from which a trained operator can control the propulsion and braking of the train consist.
Catenary System	Overhead power distribution system providing traction power to electric locomotives and EMU cars.
Catenary System Supporting Structures	Poles, towers, bridges, or other stationary structures used for supporting a catenary system including foundations, anchors, guys, braces, and similar reinforcing attachments.
Center-Fed System	Electrification system in which substations feed sections of catenary at their center to minimize catenary voltage drop. In the event that the center-fed system operates at commercial frequency, the system substations would have one or two single-phase traction power transformers connected phase-to-phase to the three-phase power utility network.
Conceptual Design	A generalized plan describing design requirements and used as a guide to preliminary design.

Term	Definition
Coach Car	A passenger carrying railcar without an operator's control cab. A coach car is typically simpler than a cab car.
Contact Wire	Conductor in contact with pantograph used by locomotives and EMU cars to collect train power requirements. The conductor is suspended from messenger or auxiliary messenger by the means of hangers and contact wire clamps.
Cross-bonds	Connections between impedance bonds to reduce effective resistance of the traction power return system and to return the currents back to the substation.
D	
Direct-Fed System	Electrification system consisting of substations feeding a catenary system.
Distribution	Delivery of power from transmission system to end-use customers at voltages greater than 110 V and less than 69 kV.
E	
Electric Multiple-Unit	A railroad car equipped with its own electrical propulsion system, braking system, and auxiliary devices.
Electric Traction	A means for propulsion of railroad vehicles whereby power is provided by electrical energy transmitted from a remote source through a traction power distribution system.
Electrification System	Facilities and structures required to provide electrical power to the trains.
F	
Final Design	A design stage during which final specifications, contract drawings, schedules, and cost estimates are prepared for a specific construction project.
Fluctuation of Power Demand	Train power demand has a highly fluctuating pattern due to frequent train acceleration and deceleration, and due to sudden changes in track gradient. Consequently, the traction power substations have correspondingly fluctuating power demand on the power supply utility system.
Fundamental Frequency	The fundamental frequency is the first harmonic.

Term	Definition
Component	
G	
Grounded Equipment	Equipment connected to the conducting mass of the earth via ground rods, grounding grid, or both, to ensure an immediate discharge of electrical potential without danger.
H	
Harmonics	Voltages and currents at frequencies other than the fundamental system frequency. Harmonics are caused by non-linear circuit components such as diodes, thyristors and transistors.
Harmonic Distortion	Voltage and current waveform distortion due to the harmonic currents generated by non-linear equipment, such as power electronics-controlled equipment on board the rolling stock or in substations.
I	
Impedance Bond	An iron-core coil of low resistance and relatively high reactance used to confine signalling current to its own track circuit and to provide a continuous path for the traction return current around insulated joints to substation.
Independent Electricity System Operator (IESO)	The Independent Electricity System Operator (IESO) is a government agency responsible for the day-to-day operation of Ontario's electrical system.
Insulated Gate Bi-polar Transistor (IGBT)	A semiconductor device acting as an electronic switch capable of switching current on and off with greater efficiency and lower harmonics than thyristor.
M	
Messenger Wire	Upper wire in a catenary system from which the contact wire is suspended by means of hangers.
Milepost	An identifier for a given location along a railroad line. Mileposts may or may not be located exactly one mile apart and may not be sequentially numbered.
Multiple-Unit	A railroad car equipped with its own propulsion system, braking system, and auxiliary devices.
P	

Term	Definition
Pantograph	Locomotive or EMU collector of traction power from overhead catenary system.
Pantograph Head	Uppermost part of the pantograph fitted with the current collector which slides on the bottom of contact wire.
Paralleling Station	Stations containing circuit breakers or switchgear line ups used for paralleling of traction power distribution system circuits. Catenary paralleling achieves better current sharing between the conductors, lowers the effective impedance between substations and trains, and results in lower voltage drop.
Phase Break System	System consisting of on-board and wayside equipment enabling locomotives or EMU cars automatic, or “on the fly”, negotiation of phase breaks by ramping propulsion power down on approach and ramping propulsion power up upon crossing the phase break.
Phase-to-Phase Connection	Traction power transformers of ac electrified rail systems operating at commercial frequency receive power input from high voltage utility system. The transformers are connected between two conductors (phases) of the three-conductor (three-phase) power utility system. Such phase-to-phase connection results in unequal phase loading and causes a certain level of unbalance in the utility system.
Power Demand Analysis and Load-Flow Report	A computer-aided report using specially written computer program to calculate the combined performance of the traction power supply and traction power distribution systems with operating trains. The report results include catenary system voltages, catenary system currents, substation power demand requirements and substation energy consumption.
Power Factor	Ratio of useful (real) power to total (apparent) power. Power factor is dependent on the rolling stock propulsion system design. With conventional propulsion systems using thyristor-controlled rectifiers and dc traction motors, the power factor is low at low trains speeds and improves as the speed increases. Using modern IGBT-based propulsion systems with ac motors, a power factor close to unity can be maintained throughout the speed range.
Preliminary Design	A design stage at which specifications and drawings clearly show all major design elements and define requirements for final design. Design calculations are substantially complete, cost estimates are detailed to an extent compatible with the level of design, and a preliminary construction sequence schedules are prepared.

Term	Definition
Prime Mover	The core source of tractive power on a non-electrified railcar. For a diesel locomotive, the prime mover is traditionally a single large diesel engine. More modern designs, including DMUs, tend to use several medium sized diesel engines to create the traction power. A fuel cell can also be a prime mover.
S	
Simple Catenary System	A system of messenger wire supporting a contact wire by the means of hangers. The system is suitable for medium speed to high-speed applications.
Single Contact Wire System	A system of single contact wire without messenger or auxiliary messenger wire. The system is suitable for tramway system, yard, and shop applications.
Static VAr Compensator	Equipment used to improve voltage profile, reduce unbalance, and mitigate harmonic distortion at the utility power supply busbar.
Station Dwell Time	That amount of time during which a train is stopped to open and close doors and receive and/or discharge passengers.
Substation	Traction power supply facility. Typical traction power substation includes power utility interface equipment; disconnect switches, circuit breakers, traction power transformers, switchgear, control equipment, and auxiliary system. Special equipment, such as harmonic filters, power factor control equipment or static VAr compensators may be installed in substations, as required.
Switching Station	Stations containing circuit breakers or switchgear line up used for switching section of distribution system during substation outage conditions and for paralleling distribution system circuits.
T	
Thyristor	A semiconductor device acting as an electronic switch capable of switching current on and off.
Track Circuit	An electrical circuit formed by the running rails of the track. The purpose of the track circuit is to detect the presence of rolling stock on a given section of track when the track circuit is short-circuited by wheels and axles.
Traction Electrification System	Traction power supply, traction power distribution, and traction power return systems.

Term	Definition
Traction Motor	An electric motor that directly drives one or more axles to propel a railcar along the tracks.
Traction Power Distribution System	Overhead catenary system, overhead trolley system or contact rail system. Each may be accompanied by along track overhead or underground feeders.
Traction Power Return System	Rails, impedance bonds, cross-bonds, earth, and in the case of ac electrification, also static wire.
Traction Power Supply System	Traction power substations located at predetermined spacing along the route.
Transmission	Delivery of power at a voltage of 69 kV or higher from generating plants across interconnected high voltage facilities to points where the power enters distribution system.
U	
Unbalance	Voltage and current unbalance occurs when a three-phase system supplies a phase-to-phase load. The utility system voltage and current unbalance can be limited by alternating substation transformer primary connections to different phases of the utility power system, e.g., A-B, B-C, C-A, A-B, and so on.
V	
Voltage Flicker	Mathematically, the voltage flicker is defined as a change in voltage divided by the voltage, and is usually expressed in percent.
A	
A	Ampere
AAR	Association of American Railroads
A, B, C	Designation of Three-Phases of Utility Power System
ac	Alternating Current
AMT	Agence Métropolitaine de Transport
APS	Alimentation Par Sol
APTA	American Public Transit Association

Term	Definition
AREMA	American Railway Engineering and Maintenance-of-Way Association
AT	Autotransformer
ATF	Autotransformer-Fed
ATS	Autotransformer Station
AW0	Empty Car Operating Weight, Filled with Consumables
AW1	AW0 Weight Plus Full Seated Passenger Load And Train Crew
AW2	AW1 Weight Plus Standees at 4 per square meter of Available Floor Space (One Passenger per 2.7 sq. ft.). Structural Mean Fatigue Load, Propulsion and Dynamic Braking Performance Load.
AW3	AW1 Weight Plus Standees at 6 per square meter of Available Floor Space (One Passenger per 1.8 sq. ft.). Friction Braking Performance Load.
AW4	Either 105% of AW3 or AW1 Weight Plus Standees at 8 per square meter of Available Floor Space (One Passenger per 1.35 sq. ft.). Structural Design Load, not Contemplated For Revenue Operation.
B	
BE	Braking Effort
C	
C	Capacitance
CEPA	Canadian Environmental Protection Act
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations (United States)
cmil	Circular mil
CN	Canadian National Railway
CNG	Compressed Natural Gas
CO	Carbon Monoxide

Term	Definition
CP	Canadian Pacific Railway
CSA	Canadian Standards Association
CSI	Cab Signal Interference
D	
dB	Decibel
dBµV/m/MHz	Decibel Microvolt per Meter per Megahertz, Unit for Measurement of Electric Field Strength
dc	Direct Current
DEMU	Diesel-Electric Multiple Unit
DF	Direct-Fed
DMU	Diesel Multiple Unit
DMMU	Dual-Mode Multiple Unit
E	
EC	Environment Canada
EIS	Environmental Impact Statement
Eff	Efficiency
ELF	Extremely Low Frequency
EMF	Electromagnetic Fields
EMI	Electromagnetic Interference or Electromagnetic Induction
EMR	Electromagnetic Radiation
EMU	Electric Multiple Unit
EPA	Environmental Protection Agency (United States)
ESI	Electrostatic Interference or Electrostatic Induction
F	

Term	Definition
FCC	Federal Communications Commission (United States)
FRA	Federal Railroad Administration (United States)
G	
G	Giga, 10^9
g/bhp-h	Grams/Brake Horsepower-Hour
H	
HC	Hydrocarbons
HDMU	Hybrid Diesel Multiple Unit
HEP	Head-End Power
HMI	Human Machine Interface
hp	Horsepower
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
I	
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IESO	Independent Electricity System Operator
IGBT	Insulated Gate Bi-Polar Transistor
IPT	Inductive Power Transfer
J	
j	Complex Number Operator
K	
k	kilo, 10^3

Term	Definition
kA	Kiloampere
kcmil	Kilo Circular Mil
kV	Kilovolt
kVA	Kilovolt-Ampere
kVAr	Kilovolt-Ampere Reactive
kW	Kilowatt
kWh	Kilowatt-Hour
kWh/ckm	Kilowatt-Hour per Car-Kilometre
kWh/cm	Kilowatt-Hour per Car-Mile
L	
L	Inductance
ICNIRP	International Commission on Non-Ionizing Radiation Protection
LHC	Locomotive-Hauled Coaches
LNG	Liquefied Natural Gas
LV	Low Voltage
M	
M	Mega, 10^{6}
µ	micro, 10^{-6}
m	mili, 10^{-3}
Maglev	Magnetic Levitation
MHz	Megahertz
MP	Milepost
MPI	Motive Power Industries

Term	Definition
MU	Multiple-Unit
MV	Medium Voltage
MVA	Megavolt-Ampere
MVAr	Megavolt Ampere Reactive
MW	Megawatt
MWh	Megawatt-Hour
N	
N. C.	Normally Closed
NMHC	Non-Methane Hydrocarbons
N. O.	Normally Opened
NO_x	Nitrogen Oxides
O	
O&M	Operation and Maintenance
OCS	Overhead Contact System
ONAN	Oil Natural Air Natural Transformer Cooling Method
P	
PCE	Pantograph Clearance Envelope
PM	Particulate Matter
PM10	Particulate Matter Less than 10 Microns in Diameter
PTC	Positive Train Control
p. u.	Per Unit
R	
R	Resistance

Term	Definition
RF	Radio Frequency
RLC	Resistive-Inductive-Capacitive
ROW	Right-of-Way
RR	Railroad
S	
SVC	Static VAr Compensator
SWS	Switching Station
T	
T	Tesla, Transformer
TE	Tractive Effort
TES	Traction Electrification System
TH&B	Toronto, Hamilton and Buffalo
TPS	Traction Power Substation, Traction Power Supply
V	
V	Volt
V ac	Volts, Alternating Current
V dc	Volts, Direct Current
W	
WHO	World Health Organization
X	
X	Reactance
Xfrm	Transformer
Z	

Term	Definition
Z	Impedance

APPENDIX 7B - SYSTEM MODELING SOFTWARE

General

To develop conceptual system design and determine the electrification system cost and power demand and energy consumption cost, a comprehensive modeling of the traction power system and of the underlying train operations is performed. For the performance of the modeling, state-of-the-art simulation software, the TrainOps™ developed by LTK, is used

The difference between TrainOps and conventional software packages is in the fundamental modeling of the traction electrification system and its interaction with the train propulsion system, as described below.

Limitations of Conventional Software

Conventional simulation packages perform traction power system studies in two steps. In the first step, a Train Performance Calculator (TPC) run is performed for each train operating along the railroad route at fixed voltage, taking into account the train data, track gradients, speed restrictions, and passenger station stopping pattern. This simulation yields a fixed power profile as a function of train location and station-to-station operating time for each train consist along the given route. Subsequently, in the second step, the fixed train power profiles form input to the electrical network simulator.

The conventional software train power demand profiles are static, voltage-independent, and represent an unconstrained electrical load requirement. This is not a realistic representation of system operation, as the performance of every train on the system is constrained and influenced by the voltage variation of the overhead contact system (OCS) caused by the train itself as well as by other trains operating on the system. Because the train power demand is always constrained by the voltage at the OCS, performing the simulations with unconstrained power demands yields unrealistically high and significantly conservative results. Based on such results, a designer may recommend capital expenditures that may not be needed.

Advantages of TrainOps

In order to obtain an accurate and realistic representation of the Metrolinx power system, it is essential that the traction power system simulations be performed using software that permits dynamic modeling of the electric train operation and the performance of the traction power system. This includes dynamic simulation of the interaction between the trains and the power system as conditions change along the alignment.

Voltage variation at the pantograph affects train performance. When the voltage decreases, the acceleration, and, therefore, the simulated velocity and location of the train are altered. Conversely, when the system presents high voltage to the train, the rolling stock can accelerate at full rate and reach the maximum operating speed in shorter time.

In TrainOps, the change in OCS voltage at the train is reflected in a change of vehicle tractive effort and propulsion power demand. The change in vehicle propulsion demand results in a corresponding change of the traction power system loading. It is important to include this vehicle-to-traction power system interaction into the power simulations.

TrainOps models the electrification system-train interaction completely dynamically, again as happens in the real world. Each train has an influence on other trains and vice versa. For example, TrainOps can demonstrate schedule delays caused by low voltages, which is not possible when using conventional software, as these programs' TPCs produce fixed power profiles and station-to-station running times. Similarly, TrainOps can demonstrate the impacts on the traction power system of a line blockage and the ability of the system to support the restarting of multiple "stacked" trains.

Benefits of Using TrainOps

From the foregoing description it is clear that the conventional software would overstate the OCS voltages and currents, as well as the substation power demands. This means that in comparison with TrainOps, voltages would be lower, and OCS currents and substation power demands would be higher, sometimes unrealistically so.

The new generation software developed by LTK corrects the conventional simplifications by simulating the rolling stock and the traction power infrastructure as one system. Every train, even two identical trains operating on the same alignment and with the same passenger station stopping pattern, will experience different performance, as performance of each train is influenced, to greater or lesser degree, by the performance of the other trains on the system.

This argument is illustrated in the two voltage profile output results from TrainOps presented here for a nominal 25 kV ac electrification. The first voltage profile in Figure B-1 represents trains operating with voltage independent tractive effort and unconstrained power demand. The results show voltages below 20 kV, the normal minimum operating voltage. Based on this result, a case could be made for power system augmentation.

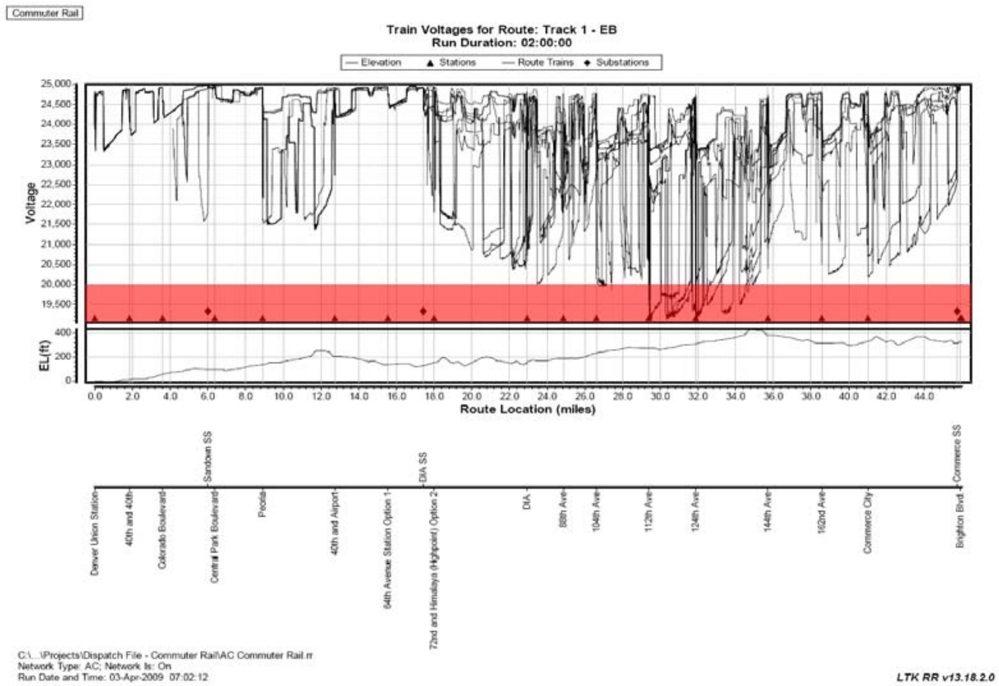


Figure B-1 – Voltage Profile Along the Line Using Rolling Stock with Voltage Independent Tractive Effort

However, as the next voltage profile in Figure B-2 shows, when the simulation realistically includes the tractive effort as a function of voltage, the system, in fact, still operates within the normal minimum voltage.

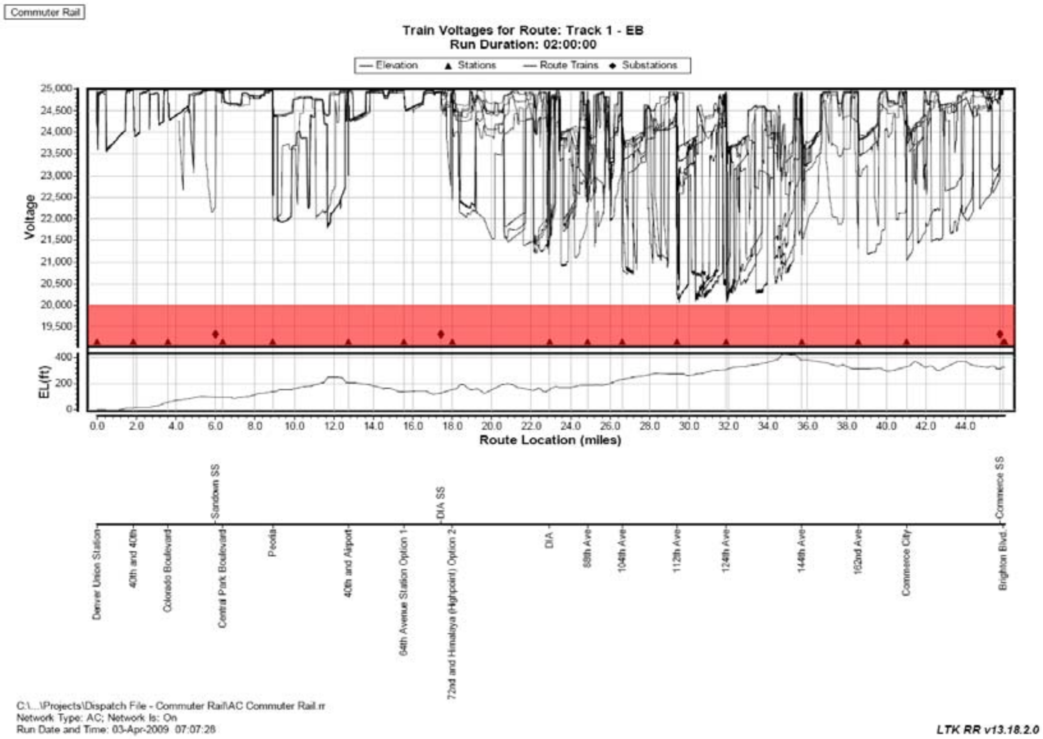


Figure B-2 – Voltage Profile Along the Line Using Rolling Stock with Voltage Dependent Tractive Effort

APPENDIX 7C - PERFORMANCE CHARACTERISTICS OF ROLLING STOCK

GENERAL

The Tables and Figures in this Appendix present typical performance characteristics for the rolling stock options considered in the report. The data is used for operations modeling and for traction power system simulation. Performance data may change as Metrolinx refines their studies and starts to target specific rolling stock models.

All data has been normalized to single vehicle units. This data thus represents the performance of single locomotives. LHC consist performance will vary as coach cars are added and trailing tonnage increases. Data are also representative of single EMUs and DMUs. Performance is not expected to change as additional EMUs or DMUs are added to the consists. EMUs and DMUs are traditionally sold in married pairs, making train lengths even numbers of vehicles.

ELECTRIC ROLLING STOCK

Table 7C-1 – Power Car Definitions

Parameter	**Unit**	**Electric Locomotive**	**Bi-Level Electric Multiple Unit**	**Single-Level Electric Multiple Unit**	**Dual-Mode Locomotive (Electric Mode)**
Nominal Power Rating	hp	7,100	1,214	1,650	5,900
Maximum Initial Tractive Effort	lbs	72,250	13,489	17,750	71,000
Maximum Continuous Tractive Effort	lbs	72,250	13,489	17,750	71,000
Electrical Efficiency (Nominal)	%	94	93	93	94
Auxiliary Power, Maximum Supply	kW	1000	80	90	880
Electrical Aux Power from Prop Sys	kW	0	0	0	0
Electrical Aux Power not from Prop Sys	kW	1000	80	90	880
Propulsion Sys Power after Elec Aux	hp	7,100	1,214	1,650	5,900
Mechanical Aux Efficiency (Nominal)	%	96	96	96	96
Mech Aux Power from Prop Sys	hp	0	0	0	0
Propulsion Sys Power after Mech Aux	hp	7,100	1,214	1,650	5,900

Parameter	Unit	Electric Locomotive	Bi-Level Electric Multiple Unit	Single-Level Electric Multiple Unit	Dual-Mode Locomotive (Electric Mode)
Mechanical Prop Efficiency (Nominal)	%	95	95	95	95
Net Drive Train Efficiency (Nominal)	%	89.3	88.4	88.4	89.3
Net Propulsion System Power	hp	6,340	1,073	1,458	5,269
Weight, Empty, AW0	lbs	198,400	121,254	145,000	288,000
Weight, Loaded, AW2	lbs	198,400	157,389	176,020	288,000
Rotating Weight	lbs	19,800	16,500	14,500	28,800
Length	ft	62’ 8”	85’ 0”	85’ 0”	71’ 6”
Width	ft	10’ 6”	9’ 5”	10’ 6”	10’ 10”
Height	ft	14’ 11”	15’ 1”	14’ 6”	14’ 4”
Frontal Area	sq-ft	145	127	130	145
Number of Axles	-	4	4	4	4
Number of Powered Axles	-	4	2	4	4
Weight on Driven Axles	lbs	49,600	33,620	36,250	72,000
Train Resistance to Motion	lbs	Davis Eq.	Davis Eq.	Davis Eq.	Davis Eq.
Acceleration, Nominal Limit	mph/s	2.5	2.4	2.4	2.5
Deceleration, Full Service Braking	mph/s	2	2.67	2.5	2
Maximum Speed	mph	110	90	90	110
Propulsion System Power Factor	p. u.	0.98	0.98	0.98	0.98
Auxiliary System Power Factor	p. u.	0.85	0.85	0.85	0.85
Design Voltage	kV	30	30	30	30
Run/Base Voltage	kV	25	25	25	25

Parameter	Unit	Electric Locomotive	Bi-Level Electric Multiple Unit	Single-Level Electric Multiple Unit	Dual-Mode Locomotive (Electric Mode)
Maximum Braking Voltage	kV	29	29	29	29
Rheostat Voltage Range	V	50	50	50	50
Line Filter Resistance	Ω	0.025	0.025	0.025	0.025
Maximum Dynamic Brake Power	kW	1,200	770	900	1,200
Maximum Dynamic Brake Force	lbs	34,000	10,397	15,000	34,000
Maximum Dynamic Braking Speed	mph	110	90	90	110
Minimum Dynamic Braking Speed	mph	6	6	6	6
Regeneration Power Limit	%	100	100	100	100
Traction Motor Type	-	AC	AC	AC	AC
Propulsion System Type	-	AC Inverter Drive	AC Inverter Drive	AC Inverter Drive	AC Inverter Drive

Table 7C-2 –Consist Definitions

Parameter	Unit	Electric Locomotive, 10-Car Trainset	Bi-Level EMU, 12-Car Trainset	Single-Level EMU, 2-Car Trainset	Dual-Mode Locomotive (Electric Mode), 10-Car Trainset
Number of Powered Units	-	1	12	2	1
Number of Nonpowered Units	-	10	0	0	10
Weight, Empty, AW0	lbs	122,000			122,000
Weight, Loaded, AW2	lbs	162,920			162,920
Rotating Weight	lbs	13,000			13,000
Length	ft	85’ 0”			85’ 0”
Width	ft	9’ 10”			9’ 10”
Height	ft	15’ 11”			15’ 11”
Frontal Area	sq-ft	150			150
Weight of Consist, AW0	lbs	1,418,400	1,455,049	290,000	1,508,000
Weight of Consist, AW2	lbs	1,827,600	1,888,669	352,040	1,917,200
Acceleration Weight of Consist, AW0	lbs	1,568,200	1,653,049	319,000	1,666,800
Acceleration Weight of Consist, AW2	lbs	1,977,400	2,086,669	381,040	2,076,000
Acceleration at 25 mph, AW2	mphps	0.802	1.702	2.044	0.750
Acceleration at 25 mph, AW2	m/s2	0.358	0.761	0.914	0.335
Power-to-Weight, AW2	hp/ton	6.94	13.63	16.56	5.50
Power-to-Weight, Accel, AW2	hp/ton	6.41	12.34	15.30	5.08

Table 7C-3 – Tractive Effort Limits at Various Voltages for AC Inverter Drives

Voltage	Magnitude (kV)	Electric Propulsion
		TE , % of Nominal
Normal Maximum	27.5	100% (disconnected above 27.5 kV
Nominal	25	100%, 20.0 kV ≤ V ≤ 27.5 kV
Normal Minimum	20	(V – 17.5)/(20.0 – 17.5)%, 17.5 kV ≤ V ≤ 20.0 kV
Emergency Minimum	17.5	0% (disconnected below 17.5 kV

Table 7C-4 – Electric Locomotive, 10-Car Trainset, (Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	72,250	0	0.0	0.802	0.364
2	72,250	385	5.4	0.802	0.364
4	72,250	771	10.9	0.802	0.364
6	72,250	1,156	16.3	0.802	0.364
8	72,250	1,541	21.7	0.802	0.364
10	72,250	1,927	27.1	0.802	0.364
12	72,250	2,312	32.6	0.802	0.364
14	72,250	2,697	38.0	0.802	0.364
16	72,250	3,083	43.4	0.802	0.364
18	72,250	3,468	48.8	0.802	0.364
20	72,250	3,853	54.3	0.802	0.364
22	72,250	4,239	59.7	0.802	0.364
24	72,250	4,624	65.1	0.802	0.364
26	72,250	5,009	70.6	0.802	0.364
28	72,250	5,395	76.0	0.802	0.364
30	72,250	5,780	81.4	0.802	0.364
32	72,250	6,165	86.8	0.802	0.364
34	69,930	6,340	89.3	0.776	0.352
36	66,045	6,340	89.3	0.733	0.333
38	62,569	6,340	89.3	0.694	0.315
40	59,440	6,340	89.3	0.659	0.300
42	56,610	6,340	89.3	0.628	0.285

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
44	54,037	6,340	89.3	0.599	0.272
46	51,687	6,340	89.3	0.573	0.261
48	49,534	6,340	89.3	0.550	0.250
50	47,552	6,340	89.3	0.528	0.240
52	45,723	6,340	89.3	0.507	0.230
54	44,030	6,340	89.3	0.488	0.222
56	42,457	6,340	89.3	0.471	0.214
58	40,993	6,340	89.3	0.455	0.207
60	39,627	6,340	89.3	0.440	0.200
62	38,349	6,340	89.3	0.425	0.193
64	37,150	6,340	89.3	0.412	0.187
66	36,024	6,340	89.3	0.400	0.182
68	34,965	6,340	89.3	0.388	0.176
70	33,966	6,340	89.3	0.377	0.171
72	33,022	6,340	89.3	0.366	0.166
74	32,130	6,340	89.3	0.356	0.162
76	31,284	6,340	89.3	0.347	0.158
78	30,482	6,340	89.3	0.338	0.154
80	29,720	6,340	89.3	0.330	0.150
82	28,995	6,340	89.3	0.322	0.146
84	28,305	6,340	89.3	0.314	0.143
86	27,647	6,340	89.3	0.307	0.139

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
88	27,018	6,340	89.3	0.300	0.136
90	26,418	6,340	89.3	0.293	0.133
92	25,844	6,340	89.3	0.287	0.130
94	25,294	6,340	89.3	0.281	0.127
96	24,767	6,340	89.3	0.275	0.125
98	24,261	6,340	89.3	0.269	0.122
100	23,776	6,340	89.3	0.264	0.120

Table 7C-5 – Electric Locomotive, 10-Car Trainset, (Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	0	0.000	0.000
2	0	0	0	0.000	0.000
4	0	0	0	0.000	0.000
6	-34,000	544	362	-0.377	0.171
8	-34,000	725	483	-0.377	0.171
10	-34,000	907	604	-0.377	0.171
12	-34,000	1,088	725	-0.377	0.171
14	-34,000	1,269	845	-0.377	0.171
16	-34,000	1,451	966	-0.377	0.171
18	-33,525	1,609	1,072	-0.372	0.169
20	-30,173	1,609	1,072	-0.335	0.152

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
22	-27,430	1,609	1,072	-0.304	0.138
24	-25,144	1,609	1,072	-0.279	0.127
26	-23,210	1,609	1,072	-0.257	0.117
28	-21,552	1,609	1,072	-0.239	0.109
30	-20,115	1,609	1,072	-0.223	0.101
32	-18,858	1,609	1,072	-0.209	0.095
34	-17,749	1,609	1,072	-0.197	0.089
36	-16,763	1,609	1,072	-0.186	0.084
38	-15,880	1,609	1,072	-0.176	0.080
40	-15,086	1,609	1,072	-0.167	0.076
42	-14,368	1,609	1,072	-0.159	0.072
44	-13,715	1,609	1,072	-0.152	0.069
46	-13,118	1,609	1,072	-0.146	0.066
48	-12,572	1,609	1,072	-0.139	0.063
50	-12,069	1,609	1,072	-0.134	0.061
52	-11,605	1,609	1,072	-0.129	0.058
54	-11,175	1,609	1,072	-0.124	0.056
56	-10,776	1,609	1,072	-0.120	0.054
58	-10,404	1,609	1,072	-0.115	0.052
60	-10,058	1,609	1,072	-0.112	0.051
62	-9,733	1,609	1,072	-0.108	0.049
64	-9,429	1,609	1,072	-0.105	0.048

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
66	-9,143	1,609	1,072	-0.101	0.046
68	-8,874	1,609	1,072	-0.098	0.045
70	-8,621	1,609	1,072	-0.096	0.043
72	-8,381	1,609	1,072	-0.093	0.042
74	-8,155	1,609	1,072	-0.090	0.041
76	-7,940	1,609	1,072	-0.088	0.040
78	-7,737	1,609	1,072	-0.086	0.039
80	-7,543	1,609	1,072	-0.084	0.038
82	-7,359	1,609	1,072	-0.082	0.037
84	-7,184	1,609	1,072	-0.080	0.036
86	-7,017	1,609	1,072	-0.078	0.035
88	-6,857	1,609	1,072	-0.076	0.035
90	-6,705	1,609	1,072	-0.074	0.034
92	-6,559	1,609	1,072	-0.073	0.033
94	-6,420	1,609	1,072	-0.071	0.032
96	-6,286	1,609	1,072	-0.070	0.032
98	-6,158	1,609	1,072	-0.068	0.031
100	-6,035	1,609	1,072	-0.067	0.030

Table 7C-6 – Bi-Level Electric Multiple Unit, 12-Car Trainset, (Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
0	13,489	0	0.0	1.702	0.201
2	13,489	72	5.9	1.702	0.201
4	13,489	144	11.8	1.702	0.201
6	13,489	216	17.8	1.702	0.201
8	13,489	288	23.7	1.702	0.201
10	13,489	360	29.6	1.702	0.201
12	13,489	432	35.5	1.702	0.201
14	13,489	504	41.5	1.702	0.201
16	13,489	576	47.4	1.702	0.201
18	13,489	647	53.3	1.702	0.201
20	13,489	719	59.2	1.702	0.201
22	13,489	791	65.2	1.702	0.201
24	13,489	863	71.1	1.702	0.201
26	13,489	935	77.0	1.702	0.201
28	13,489	1,007	82.9	1.702	0.201
30	13,410	1,073	88.4	1.692	0.199
32	12,572	1,073	88.4	1.586	0.187
34	11,832	1,073	88.4	1.493	0.176
36	11,175	1,073	88.4	1.410	0.166
38	10,587	1,073	88.4	1.336	0.157
40	10,058	1,073	88.4	1.269	0.150
42	9,579	1,073	88.4	1.208	0.142

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
44	9,143	1,073	88.4	1.153	0.136
46	8,746	1,073	88.4	1.103	0.130
48	8,381	1,073	88.4	1.057	0.125
50	8,046	1,073	88.4	1.015	0.120
52	7,737	1,073	88.4	0.976	0.115
54	7,450	1,073	88.4	0.940	0.111
56	7,184	1,073	88.4	0.906	0.107
58	6,936	1,073	88.4	0.875	0.103
60	6,705	1,073	88.4	0.846	0.100
62	6,489	1,073	88.4	0.819	0.096
64	6,286	1,073	88.4	0.793	0.093
66	6,095	1,073	88.4	0.769	0.091
68	5,916	1,073	88.4	0.746	0.088
70	5,747	1,073	88.4	0.725	0.085
72	5,588	1,073	88.4	0.705	0.083
74	5,436	1,073	88.4	0.686	0.081
76	5,293	1,073	88.4	0.668	0.079
78	5,158	1,073	88.4	0.651	0.077
80	5,029	1,073	88.4	0.634	0.075
82	4,906	1,073	88.4	0.619	0.073
84	4,789	1,073	88.4	0.604	0.071
86	4,678	1,073	88.4	0.590	0.070

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
88	4,572	1,073	88.4	0.577	0.068
90	4,470	1,073	88.4	0.564	0.066
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-7 – Bi-Level Electric Multiple Unit, 12-Car Trainset, (Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	0	0.000	0.000
2	0	0	0	0.000	0.000
4	0	0	0	0.000	0.000
6	-10,397	166	110	-1.312	0.155
8	-10,397	222	146	-1.312	0.155
10	-10,397	277	183	-1.312	0.155
12	-10,397	333	219	-1.312	0.155
14	-10,397	388	256	-1.312	0.155
16	-10,397	444	292	-1.312	0.155
18	-10,397	499	329	-1.312	0.155
20	-10,397	555	365	-1.312	0.155
22	-10,397	610	402	-1.312	0.155
24	-10,397	665	438	-1.312	0.155
26	-10,397	721	475	-1.312	0.155
28	-10,397	776	511	-1.312	0.155
30	-10,397	832	548	-1.312	0.155
32	-10,397	887	585	-1.312	0.155
34	-10,397	943	621	-1.312	0.155
36	-10,397	998	658	-1.312	0.155
38	-10,190	1,033	680	-1.285	0.152
40	-9,680	1,033	680	-1.221	0.144

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
42	-9,219	1,033	680	-1.163	0.137
44	-8,800	1,033	680	-1.110	0.131
46	-8,418	1,033	680	-1.062	0.125
48	-8,067	1,033	680	-1.018	0.120
50	-7,744	1,033	680	-0.977	0.115
52	-7,446	1,033	680	-0.939	0.111
54	-7,171	1,033	680	-0.905	0.107
56	-6,915	1,033	680	-0.872	0.103
58	-6,676	1,033	680	-0.842	0.099
60	-6,454	1,033	680	-0.814	0.096
62	-6,245	1,033	680	-0.788	0.093
64	-6,050	1,033	680	-0.763	0.090
66	-5,867	1,033	680	-0.740	0.087
68	-5,694	1,033	680	-0.718	0.085
70	-5,532	1,033	680	-0.698	0.082
72	-5,378	1,033	680	-0.678	0.080
74	-5,233	1,033	680	-0.660	0.078
76	-5,095	1,033	680	-0.643	0.076
78	-4,964	1,033	680	-0.626	0.074
80	-4,840	1,033	680	-0.611	0.072
82	-4,722	1,033	680	-0.596	0.070
84	-4,610	1,033	680	-0.582	0.069

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 12-Cars AW2 (mphps)	Maximum Required Adhesion
86	-4,502	1,033	680	-0.568	0.067
88	-4,400	1,033	680	-0.555	0.065
90	-4,302	1,033	680	-0.543	0.064
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-8 – Single-Level Electric Multiple Unit, 2-Car Trainset, (Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	17,750	0	0.0	2.044	0.122
2	17,750	95	5.7	2.044	0.122
4	17,750	189	11.5	2.044	0.122
6	17,750	284	17.2	2.044	0.122
8	17,750	379	22.9	2.044	0.122
10	17,750	473	28.7	2.044	0.122
12	17,750	568	34.4	2.044	0.122
14	17,750	663	40.2	2.044	0.122
16	17,750	757	45.9	2.044	0.122
18	17,750	852	51.6	2.044	0.122
20	17,750	947	57.4	2.044	0.122
22	17,750	1,041	63.1	2.044	0.122
24	17,750	1,136	68.8	2.044	0.122
26	17,750	1,231	74.6	2.044	0.122
28	17,750	1,325	80.3	2.044	0.122
30	17,750	1,420	86.1	2.044	0.122
32	17,083	1,458	88.4	1.967	0.118
34	16,078	1,458	88.4	1.851	0.111
36	15,185	1,458	88.4	1.748	0.105
38	14,386	1,458	88.4	1.656	0.099
40	13,667	1,458	88.4	1.574	0.094

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
42	13,016	1,458	88.4	1.499	0.090
44	12,424	1,458	88.4	1.431	0.086
46	11,884	1,458	88.4	1.368	0.082
48	11,389	1,458	88.4	1.311	0.079
50	10,933	1,458	88.4	1.259	0.075
52	10,513	1,458	88.4	1.210	0.073
54	10,123	1,458	88.4	1.166	0.070
56	9,762	1,458	88.4	1.124	0.067
58	9,425	1,458	88.4	1.085	0.065
60	9,111	1,458	88.4	1.049	0.063
62	8,817	1,458	88.4	1.015	0.061
64	8,542	1,458	88.4	0.984	0.059
66	8,283	1,458	88.4	0.954	0.057
68	8,039	1,458	88.4	0.926	0.055
70	7,810	1,458	88.4	0.899	0.054
72	7,593	1,458	88.4	0.874	0.052
74	7,387	1,458	88.4	0.851	0.051
76	7,193	1,458	88.4	0.828	0.050
78	7,009	1,458	88.4	0.807	0.048
80	6,833	1,458	88.4	0.787	0.047
82	6,667	1,458	88.4	0.768	0.046
84	6,508	1,458	88.4	0.749	0.045

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
86	6,357	1,458	88.4	0.732	0.044
88	6,212	1,458	88.4	0.715	0.043
90	6,074	1,458	88.4	0.699	0.042
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-9 – Single-Level Electric Multiple Unit, 2-Car Trainset, (Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	0	0.000	0.000
2	0	0	0	0.000	0.000
4	0	0	0	0.000	0.000
6	-15,000	240	158	-1.727	0.103
8	-15,000	320	211	-1.727	0.103
10	-15,000	400	264	-1.727	0.103
12	-15,000	480	316	-1.727	0.103
14	-15,000	560	369	-1.727	0.103
16	-15,000	640	422	-1.727	0.103
18	-15,000	720	474	-1.727	0.103
20	-15,000	800	527	-1.727	0.103
22	-15,000	880	580	-1.727	0.103
24	-15,000	960	632	-1.727	0.103
26	-15,000	1,040	685	-1.727	0.103
28	-15,000	1,120	738	-1.727	0.103
30	-15,000	1,200	791	-1.727	0.103
32	-14,143	1,207	795	-1.628	0.098
34	-13,311	1,207	795	-1.533	0.092
36	-12,572	1,207	795	-1.448	0.087
38	-11,910	1,207	795	-1.371	0.082
40	-11,315	1,207	795	-1.303	0.078

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
42	-10,776	1,207	795	-1.241	0.074
44	-10,286	1,207	795	-1.184	0.071
46	-9,839	1,207	795	-1.133	0.068
48	-9,429	1,207	795	-1.086	0.065
50	-9,052	1,207	795	-1.042	0.062
52	-8,704	1,207	795	-1.002	0.060
54	-8,381	1,207	795	-0.965	0.058
56	-8,082	1,207	795	-0.931	0.056
58	-7,803	1,207	795	-0.898	0.054
60	-7,543	1,207	795	-0.869	0.052
62	-7,300	1,207	795	-0.841	0.050
64	-7,072	1,207	795	-0.814	0.049
66	-6,857	1,207	795	-0.790	0.047
68	-6,656	1,207	795	-0.766	0.046
70	-6,466	1,207	795	-0.744	0.045
72	-6,286	1,207	795	-0.724	0.043
74	-6,116	1,207	795	-0.704	0.042
76	-5,955	1,207	795	-0.686	0.041
78	-5,802	1,207	795	-0.668	0.040
80	-5,657	1,207	795	-0.651	0.039
82	-5,519	1,207	795	-0.636	0.038
84	-5,388	1,207	795	-0.620	0.037

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
86	-5,263	1,207	795	-0.606	0.036
88	-5,143	1,207	795	-0.592	0.035
90	-5,029	1,207	795	-0.579	0.035
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-10 – Dual-Mode Locomotive – Electric Mode, 10-Car Trainset, (Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	71,000	0	0.0	0.750	0.247
2	71,000	379	6.4	0.750	0.247
4	71,000	757	12.8	0.750	0.247
6	71,000	1,136	19.3	0.750	0.247
8	71,000	1,515	25.7	0.750	0.247
10	71,000	1,893	32.1	0.750	0.247
12	71,000	2,272	38.5	0.750	0.247
14	71,000	2,651	44.9	0.750	0.247
16	71,000	3,029	51.3	0.750	0.247
18	71,000	3,408	57.8	0.750	0.247
20	71,000	3,787	64.2	0.750	0.247
22	71,000	4,165	70.6	0.750	0.247
24	71,000	4,544	77.0	0.750	0.247
26	71,000	4,923	83.4	0.750	0.247
28	70,563	5,269	89.3	0.746	0.245
30	65,859	5,269	89.3	0.696	0.229
32	61,743	5,269	89.3	0.652	0.214
34	58,111	5,269	89.3	0.614	0.202
36	54,882	5,269	89.3	0.580	0.191
38	51,994	5,269	89.3	0.549	0.181
40	49,394	5,269	89.3	0.522	0.172

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
42	47,042	5,269	89.3	0.497	0.163
44	44,904	5,269	89.3	0.474	0.156
46	42,951	5,269	89.3	0.454	0.149
48	41,162	5,269	89.3	0.435	0.143
50	39,515	5,269	89.3	0.418	0.137
52	37,995	5,269	89.3	0.401	0.132
54	36,588	5,269	89.3	0.387	0.127
56	35,281	5,269	89.3	0.373	0.123
58	34,065	5,269	89.3	0.360	0.118
60	32,929	5,269	89.3	0.348	0.114
62	31,867	5,269	89.3	0.337	0.111
64	30,871	5,269	89.3	0.326	0.107
66	29,936	5,269	89.3	0.316	0.104
68	29,055	5,269	89.3	0.307	0.101
70	28,225	5,269	89.3	0.298	0.098
72	27,441	5,269	89.3	0.290	0.095
74	26,699	5,269	89.3	0.282	0.093
76	25,997	5,269	89.3	0.275	0.090
78	25,330	5,269	89.3	0.268	0.088
80	24,697	5,269	89.3	0.261	0.086
82	24,095	5,269	89.3	0.255	0.084
84	23,521	5,269	89.3	0.249	0.082

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
86	22,974	5,269	89.3	0.243	0.080
88	22,452	5,269	89.3	0.237	0.078
90	21,953	5,269	89.3	0.232	0.076
92	21,476	5,269	89.3	0.227	0.075
94	21,019	5,269	89.3	0.222	0.073
96	20,581	5,269	89.3	0.217	0.071
98	20,161	5,269	89.3	0.213	0.070
100	19,758	5,269	89.3	0.209	0.069

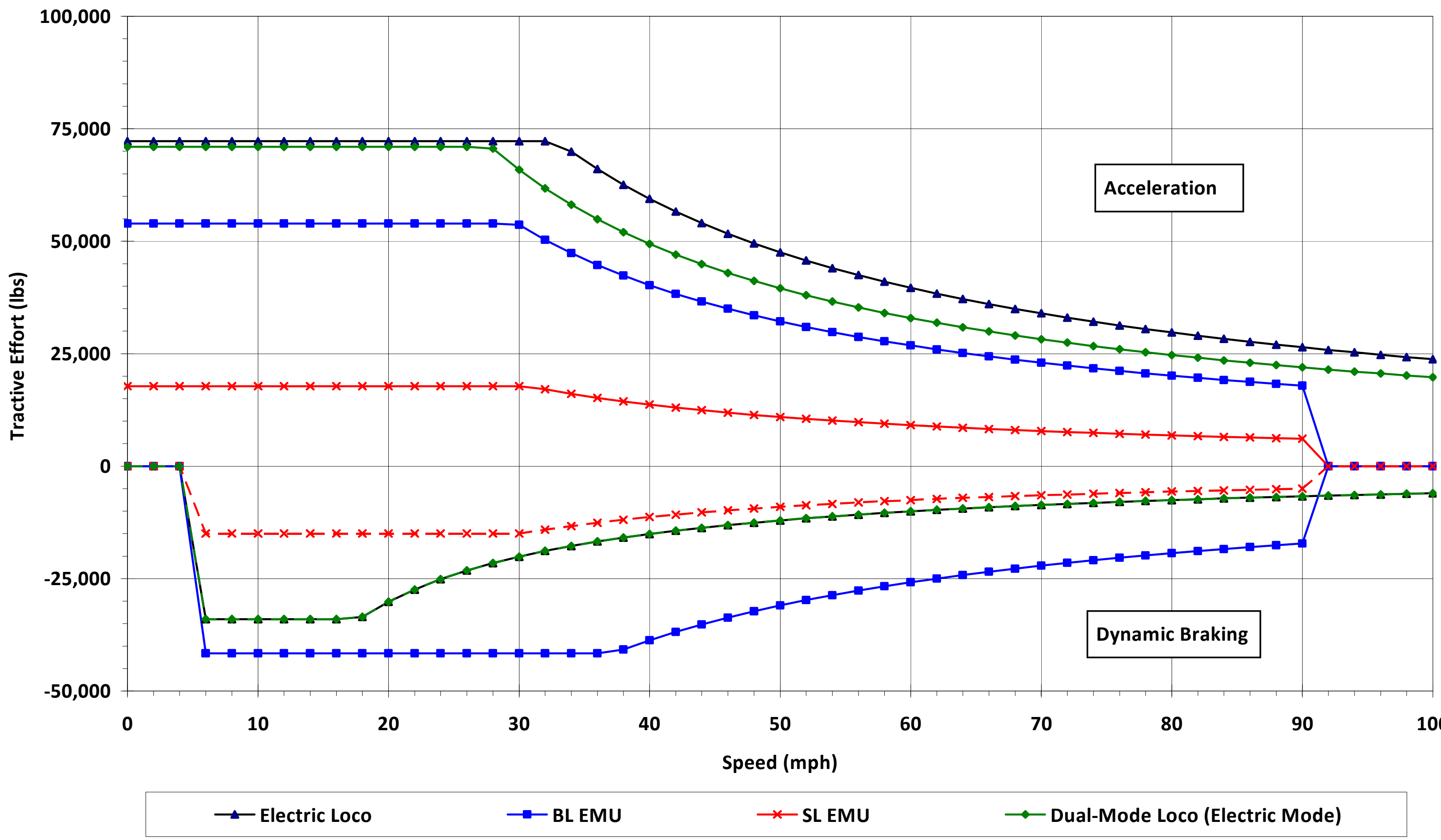
Table 7C-11 – Dual-Mode Locomotive – Electric Mode, 10-Car Trainset, (Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	0	0.000	0.000
2	0	0	0	0.000	0.000
4	0	0	0	0.000	0.000
6	-34,000	544	362	-0.359	0.118
8	-34,000	725	483	-0.359	0.118
10	-34,000	907	604	-0.359	0.118
12	-34,000	1,088	725	-0.359	0.118
14	-34,000	1,269	845	-0.359	0.118
16	-34,000	1,451	966	-0.359	0.118
18	-33,525	1,609	1,072	-0.354	0.116
20	-30,173	1,609	1,072	-0.319	0.105
22	-27,430	1,609	1,072	-0.290	0.095
24	-25,144	1,609	1,072	-0.266	0.087
26	-23,210	1,609	1,072	-0.245	0.081
28	-21,552	1,609	1,072	-0.228	0.075
30	-20,115	1,609	1,072	-0.213	0.070
32	-18,858	1,609	1,072	-0.199	0.065
34	-17,749	1,609	1,072	-0.188	0.062
36	-16,763	1,609	1,072	-0.177	0.058
38	-15,880	1,609	1,072	-0.168	0.055
40	-15,086	1,609	1,072	-0.159	0.052

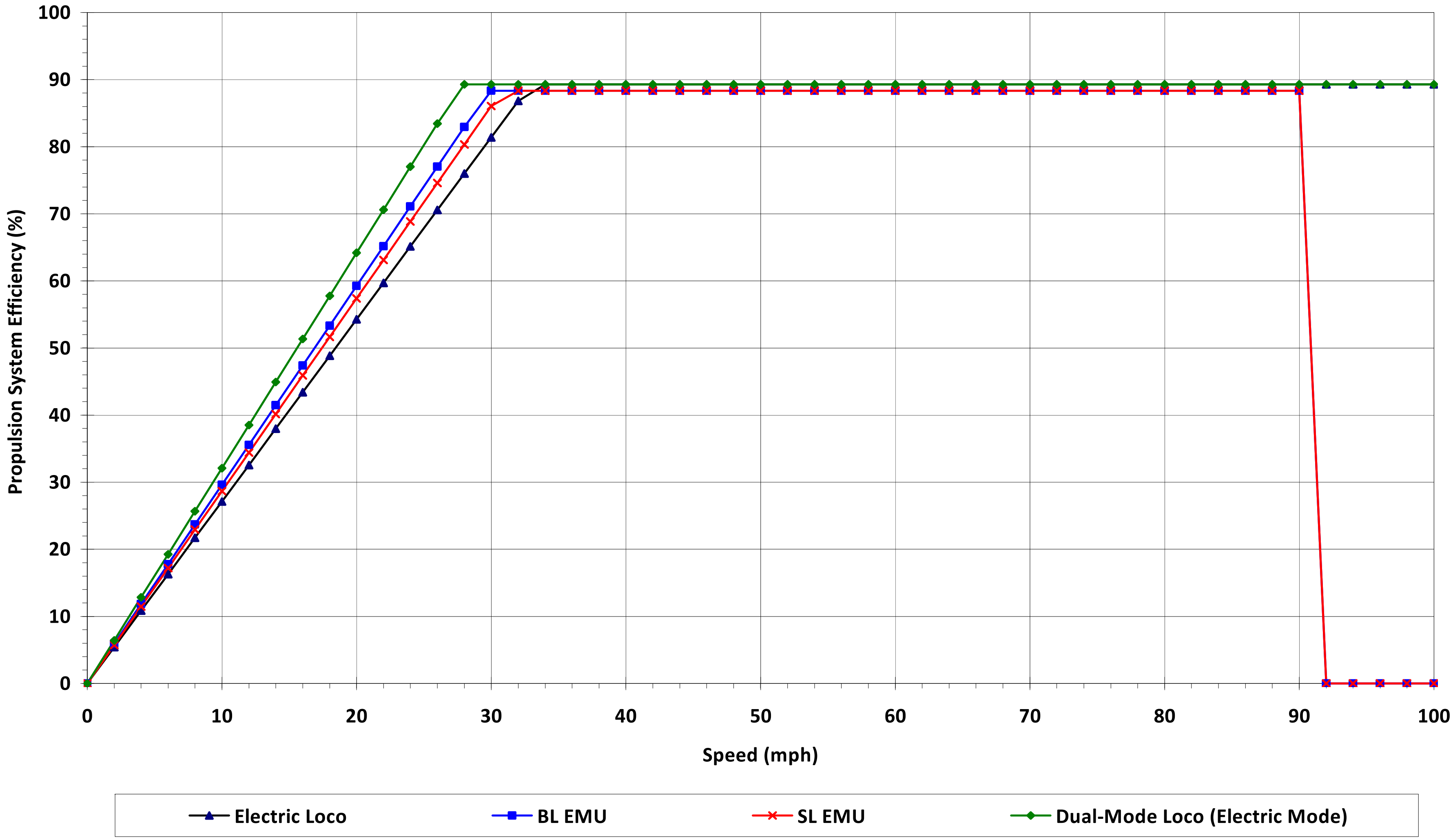
Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
42	-14,368	1,609	1,072	-0.152	0.050
44	-13,715	1,609	1,072	-0.145	0.048
46	-13,118	1,609	1,072	-0.139	0.046
48	-12,572	1,609	1,072	-0.133	0.044
50	-12,069	1,609	1,072	-0.128	0.042
52	-11,605	1,609	1,072	-0.123	0.040
54	-11,175	1,609	1,072	-0.118	0.039
56	-10,776	1,609	1,072	-0.114	0.037
58	-10,404	1,609	1,072	-0.110	0.036
60	-10,058	1,609	1,072	-0.106	0.035
62	-9,733	1,609	1,072	-0.103	0.034
64	-9,429	1,609	1,072	-0.100	0.033
66	-9,143	1,609	1,072	-0.097	0.032
68	-8,874	1,609	1,072	-0.094	0.031
70	-8,621	1,609	1,072	-0.091	0.030
72	-8,381	1,609	1,072	-0.089	0.029
74	-8,155	1,609	1,072	-0.086	0.028
76	-7,940	1,609	1,072	-0.084	0.028
78	-7,737	1,609	1,072	-0.082	0.027
80	-7,543	1,609	1,072	-0.080	0.026
82	-7,359	1,609	1,072	-0.078	0.026
84	-7,184	1,609	1,072	-0.076	0.025

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
86	-7,017	1,609	1,072	-0.074	0.024
88	-6,857	1,609	1,072	-0.072	0.024
90	-6,705	1,609	1,072	-0.071	0.023
92	-6,559	1,609	1,072	-0.069	0.023
94	-6,420	1,609	1,072	-0.068	0.022
96	-6,286	1,609	1,072	-0.066	0.022
98	-6,158	1,609	1,072	-0.065	0.021
100	-6,035	1,609	1,072	-0.064	0.021

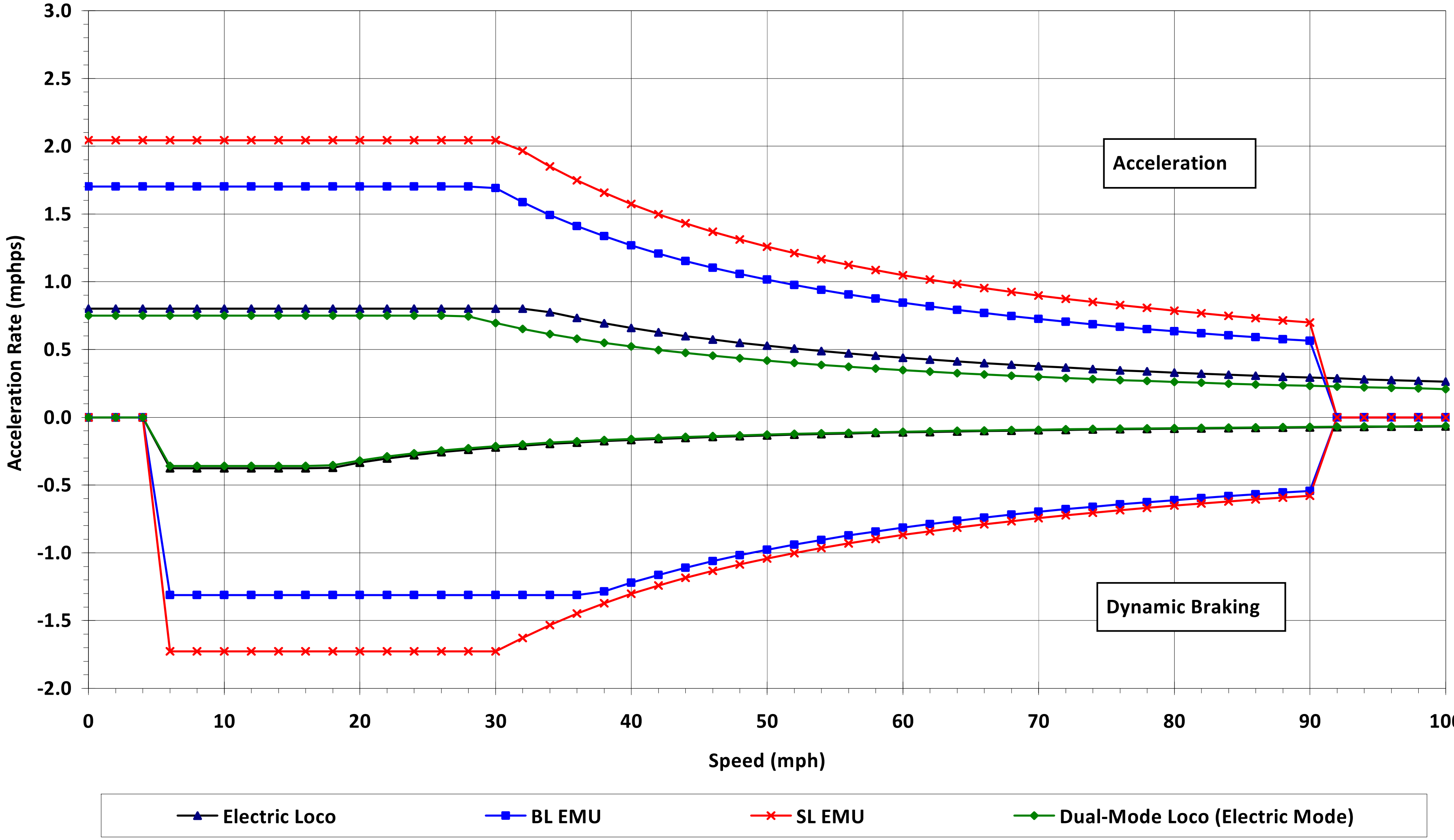
Available Tractive and Dynamic Braking Effort for Candidate Electric Propulsion

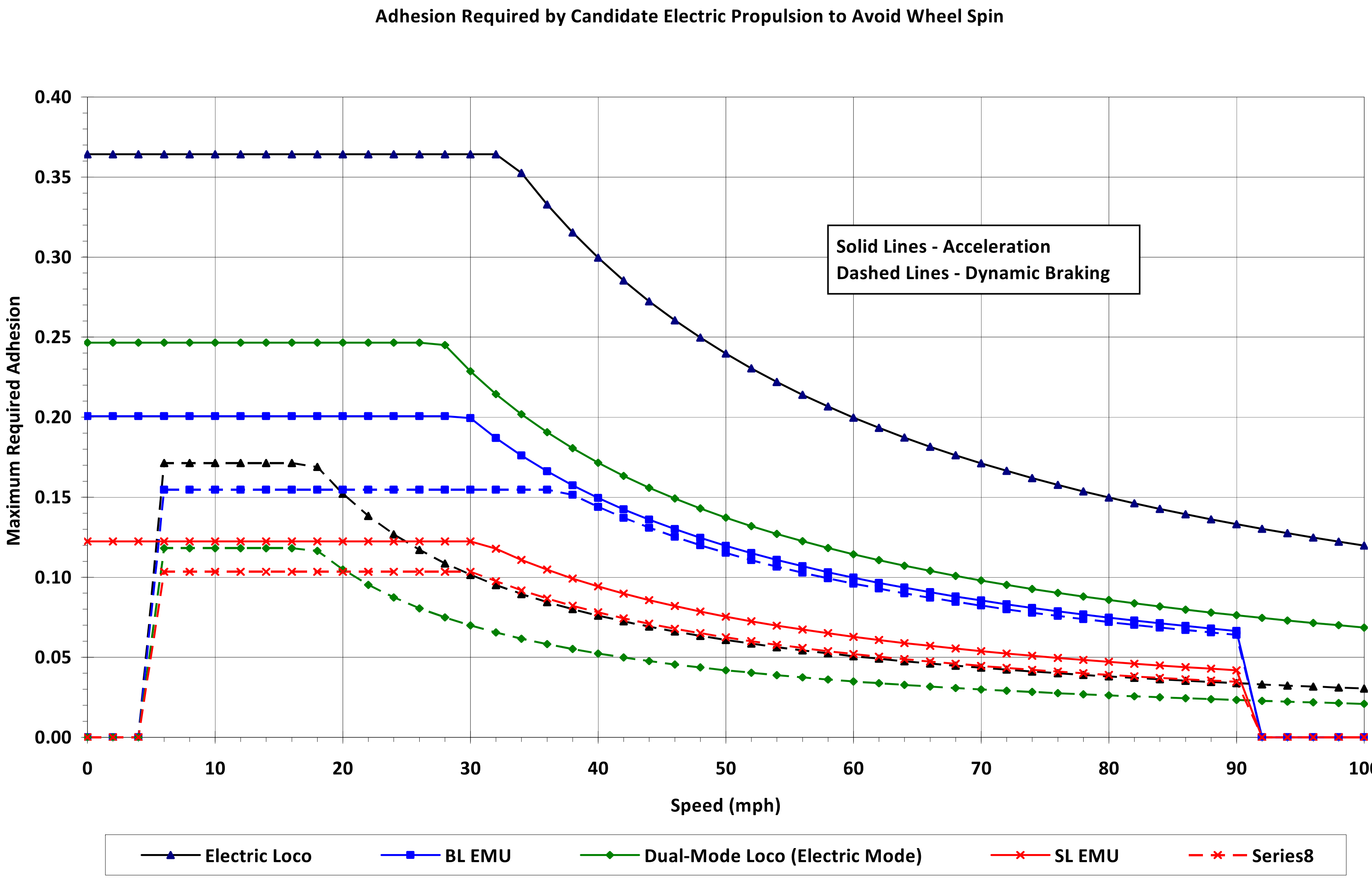


Drive Train Efficiencies for Candidate Electric Propulsion



Nominal Acceleration for 12-Car Trains, Candidate Electric Propulsion, AW2




Adhesion Required by Candidate Electric Propulsion to Avoid Wheel Spin
Maximum Required Adhesion
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
100
Speed (mph)
Solid Lines - Acceleration
Dashed Lines - Dynamic Braking
Electric Loco
BL EMU
Dual-Mode Loco (Electric Mode)
SL EMU
Series8

DIESEL ROLLING STOCK

Table 7C-12 – Power Car Definitions

Parameter	**Unit**	**Diesel Electric Locomotive**	**Single-Level DMU (Hydrodynamic)**	**Single-Level DEMU (Diesel Electric)**	**Dual-Mode Locomotive (Diesel Mode)**
Nominal Power Rating	hp	4,000	1,200	750	4,200
Maximum Initial Tractive Effort	lbs	85,000	-	15,500	71,000
Maximum Continuous Tractive Effort	lbs	78,000	-	13,500	58,867
Electrical Efficiency (Nominal)	%	92	-	91	92
Auxiliary Power, Maximum Supply	kW	800	160	100	880
Electrical Aux Power from Prop Sys	kW	0	0	50	440
Electrical Aux Power not from Prop Sys	kW	800	160	0	0
Propulsion Sys Power after Elec Aux	hp	4,000	1,200	676	3,559
Mechanical Aux Efficiency (Nominal)	%	96	96	96	96
Mech Aux Power from Prop Sys	hp	0	50	0	0
Propulsion Sys Power after Mech Aux	hp	4,000	1,148	676	3,559
Mechanical Prop Efficiency (Nominal)	%	95	92	95	95
Net Drive Train Efficiency (Nominal)	%	87.4	< 92, varies	86.5	87.4
Net Propulsion System Power	hp	3,496	1,056	585	3,110
Weight, Empty, AW0	lbs	288,000	160,000	150,000	288,000

Parameter	Unit	Diesel Electric Locomotive	Single-Level DMU (Hydrodynamic)	Single-Level DEMU (Diesel Electric)	Dual-Mode Locomotive (Diesel Mode)
Weight, Loaded, AW2	lbs	288,000	187,720	177,720	288,000
Rotating Weight	lbs	28,800	19,200	18,000	34,560
Length	ft	68’ 0”	85’ 0”	85’ 0”	71’ 6”
Width	ft	10’ 8”	10’ 6”	10’ 6”	10’ 10”
Height	ft	15’ 6”	14’ 8”	14’ 6”	14’ 4”
Frontal Area	sq-ft	155	130	130	145
Number of Axles	-	4	4	4	4
Number of Powered Axles	-	4	2	2	4
Weight on Driven Axles	lbs	72,000	40,000	37,500	72,000
Train Resistance to Motion	lbs	Davis Eq.	Davis Eq.	Davis Eq.	Davis Eq.
Acceleration, Nominal Limit	mph/s	2.5	2.5	2.1	2.5
Deceleration, Full Service Braking	mph/s	2	2.5	2.5	2
Maximum Speed	mph	90	90	90	110
Maximum Dynamic Brake Power	kW	1,200	500	450	1,200
Maximum Dynamic Brake Force	lbs	34,000	13,400	12,500	34,000
Maximum Dynamic Braking Speed	mph	90	90	90	110
Dynamic Brake Cutout Speed	mph	6	10	6	6
Regeneration Power Limit	%	0	0	Internal Loads	Internal Loads
Traction Motor Type	-	AC	n/a	AC	AC
Propulsion System Type	-	AC Inverter	Diesel Hydraulic	Diesel	AC Inverter

Parameter	Unit	Diesel Electric Locomotive	Single-Level DMU (Hydrodynamic)	Single-Level DEMU (Diesel Electric)	Dual-Mode Locomotive (Diesel Mode)
		Drive		Electric	Drive

Table 7C-13 – Consist Definitions

Parameter	Unit	Diesel Electric Locomotive, 10-Car Trainset	Single-Level DMU (Hydrodynamic), 2-Car Trainset	Single-Level DEMU (Diesel Electric), 2-Car Trainset	Dual-Mode Locomotive (Diesel Mode), 10-Car Trainset
Number of Powered Units	-	1	2	2	1
Number of Nonpowered Units	-	10	0	0	10
Weight, Empty, AW0	lbs	122,000			122,000
Weight, Loaded, AW2	lbs	162,920			162,920
Rotating Weight	lbs	13,000			13,000
Length	ft	85’ 0”			85’ 0”
Width	ft	9’ 10”			9’ 10”
Height	ft	15’ 11”			15’ 11”
Frontal Area	sq-ft	150			150
Weight of Consist, AW0	lbs	1,508,000	320,000	300,000	1,508,000
Weight of Consist, AW2	lbs	1,917,200	375,440	355,440	1,917,200
Acceleration Weight of Consist, AW0	lbs	1,666,800	358,400	336,000	1,672,560
Acceleration Weight of Consist, AW2	lbs	2,076,000	413,840	391,440	2,081,760
Acceleration at 25 mph, AW2	mphps	0.555	1.405	0.985	0.492
Acceleration at 25 mph, AW2	m/s2	0.248	0.628	0.440	0.220
Power-to-Weight, AW2	hp/ton	3.65	11.25	6.58	3.24
Power-to-Weight, Accel,	hp/ton	3.37	10.21	5.97	2.99

AW2					

Table 7C-14 - Diesel Electric Locomotive, 10-Car Trainset, (Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	85,000	0	0.0	0.898	0.295
2	84,167	449	11.2	0.889	0.292
4	83,334	889	22.2	0.881	0.289
6	82,501	1,320	33.0	0.872	0.286
8	81,668	1,742	43.6	0.863	0.284
10	80,835	2,156	53.9	0.854	0.281
12	80,002	2,560	64.0	0.845	0.278
14	79,169	2,956	73.9	0.837	0.275
16	78,336	3,342	83.6	0.828	0.272
18	72,833	3,496	87.4	0.770	0.253
20	65,550	3,496	87.4	0.693	0.228
22	59,591	3,496	87.4	0.630	0.207
24	54,625	3,496	87.4	0.577	0.190
26	50,423	3,496	87.4	0.533	0.175
28	46,821	3,496	87.4	0.495	0.163
30	43,700	3,496	87.4	0.462	0.152
32	40,969	3,496	87.4	0.433	0.142
34	38,559	3,496	87.4	0.407	0.134
36	36,417	3,496	87.4	0.385	0.126
38	34,500	3,496	87.4	0.365	0.120
40	32,775	3,496	87.4	0.346	0.114
42	31,214	3,496	87.4	0.330	0.108

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
44	29,795	3,496	87.4	0.315	0.103
46	28,500	3,496	87.4	0.301	0.099
48	27,313	3,496	87.4	0.289	0.095
50	26,220	3,496	87.4	0.277	0.091
52	25,212	3,496	87.4	0.266	0.088
54	24,278	3,496	87.4	0.257	0.084
56	23,411	3,496	87.4	0.247	0.081
58	22,603	3,496	87.4	0.239	0.078
60	21,850	3,496	87.4	0.231	0.076
62	21,145	3,496	87.4	0.223	0.073
64	20,484	3,496	87.4	0.216	0.071
66	19,864	3,496	87.4	0.210	0.069
68	19,279	3,496	87.4	0.204	0.067
70	18,729	3,496	87.4	0.198	0.065
72	18,208	3,496	87.4	0.192	0.063
74	17,716	3,496	87.4	0.187	0.062
76	17,250	3,496	87.4	0.182	0.060
78	16,808	3,496	87.4	0.178	0.058
80	16,388	3,496	87.4	0.173	0.057
82	15,988	3,496	87.4	0.169	0.056
84	15,607	3,496	87.4	0.165	0.054
86	15,244	3,496	87.4	0.161	0.053

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
88	14,898	3,496	87.4	0.157	0.052
90	14,567	3,496	87.4	0.154	0.051
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-15 – Diesel Electric Locomotive, 10-Car Trainset, (Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	Not Applicable	0.000	0.000
2	0	0	Not Applicable	0.000	0.000
4	0	0	Not Applicable	0.000	0.000
6	-34,000	544	Not Applicable	-0.359	0.118
8	-34,000	725	Not Applicable	-0.359	0.118
10	-34,000	907	Not Applicable	-0.359	0.118
12	-34,000	1,088	Not Applicable	-0.359	0.118
14	-34,000	1,269	Not Applicable	-0.359	0.118
16	-34,000	1,451	Not Applicable	-0.359	0.118
18	-33,525	1,609	Not Applicable	-0.354	0.116
20	-30,173	1,609	Not Applicable	-0.319	0.105
22	-27,430	1,609	Not Applicable	-0.290	0.095
24	-25,144	1,609	Not Applicable	-0.266	0.087
26	-23,210	1,609	Not Applicable	-0.245	0.081
28	-21,552	1,609	Not Applicable	-0.228	0.075
30	-20,115	1,609	Not Applicable	-0.213	0.070
32	-18,858	1,609	Not Applicable	-0.199	0.065
34	-17,749	1,609	Not Applicable	-0.188	0.062
36	-16,763	1,609	Not Applicable	-0.177	0.058
38	-15,880	1,609	Not Applicable	-0.168	0.055
40	-15,086	1,609	Not Applicable	-0.159	0.052

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
42	-14,368	1,609	Not Applicable	-0.152	0.050
44	-13,715	1,609	Not Applicable	-0.145	0.048
46	-13,118	1,609	Not Applicable	-0.139	0.046
48	-12,572	1,609	Not Applicable	-0.133	0.044
50	-12,069	1,609	Not Applicable	-0.128	0.042
52	-11,605	1,609	Not Applicable	-0.123	0.040
54	-11,175	1,609	Not Applicable	-0.118	0.039
56	-10,776	1,609	Not Applicable	-0.114	0.037
58	-10,404	1,609	Not Applicable	-0.110	0.036
60	-10,058	1,609	Not Applicable	-0.106	0.035
62	-9,733	1,609	Not Applicable	-0.103	0.034
64	-9,429	1,609	Not Applicable	-0.100	0.033
66	-9,143	1,609	Not Applicable	-0.097	0.032
68	-8,874	1,609	Not Applicable	-0.094	0.031
70	-8,621	1,609	Not Applicable	-0.091	0.030
72	-8,381	1,609	Not Applicable	-0.089	0.029
74	-8,155	1,609	Not Applicable	-0.086	0.028
76	-7,940	1,609	Not Applicable	-0.084	0.028
78	-7,737	1,609	Not Applicable	-0.082	0.027
80	-7,543	1,609	Not Applicable	-0.080	0.026
82	-7,359	1,609	Not Applicable	-0.078	0.026
84	-7,184	1,609	Not Applicable	-0.076	0.025

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
86	-7,017	1,609	Not Applicable	-0.074	0.024
88	-6,857	1,609	Not Applicable	-0.072	0.024
90	-6,705	1,609	Not Applicable	-0.071	0.023
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-16 – Single-Level Diesel Multiple Unit, 2-Car Trainset, (Hydrodynamic, Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	23,581	0	0.0	2.500	0.295
2	23,581	126	13.6	2.500	0.295
4	23,581	252	25.6	2.500	0.295
6	23,581	377	36.3	2.500	0.295
8	23,581	503	46.0	2.500	0.295
10	22,916	611	53.5	2.429	0.286
12	21,290	681	59.4	2.257	0.266
14	19,765	738	64.3	2.095	0.247
16	18,389	785	68.4	1.950	0.230
18	17,004	816	71.1	1.803	0.213
20	15,808	843	73.4	1.676	0.198
22	14,699	862	75.1	1.558	0.184
24	13,668	875	76.2	1.449	0.171
26	12,840	890	77.6	1.361	0.161
28	12,034	899	78.3	1.276	0.150
30	11,252	900	78.4	1.193	0.141
32	10,566	902	78.5	1.120	0.132
34	10,000	907	79.0	1.060	0.125
36	9,426	905	78.8	0.999	0.118
38	8,804	892	77.7	0.933	0.110
40	8,242	879	76.6	0.874	0.103
42	7,496	840	73.1	0.795	0.094

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
44	7,358	863	81.4	0.780	0.092
46	7,225	886	91.0	0.766	0.090
48	7,092	908	90.2	0.752	0.089
50	6,959	928	89.3	0.738	0.087
52	6,805	944	88.2	0.721	0.085
54	6,640	956	87.0	0.704	0.083
56	6,467	966	85.6	0.686	0.081
58	6,293	973	84.8	0.667	0.079
60	6,111	978	85.2	0.648	0.076
62	5,347	884	77.0	0.567	0.067
64	5,243	895	89.3	0.556	0.066
66	5,140	905	88.3	0.545	0.064
68	5,037	913	87.3	0.534	0.063
70	4,935	921	86.2	0.523	0.062
72	4,842	930	85.2	0.513	0.061
74	4,750	937	84.4	0.504	0.059
76	4,655	943	83.4	0.493	0.058
78	4,542	945	82.3	0.482	0.057
80	4,430	945	82.3	0.470	0.055
82	4,312	943	82.1	0.457	0.054
84	4,206	942	82.1	0.446	0.053
86	4,137	949	82.6	0.439	0.052

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
88	0	0	0.0	0.000	0.000
90	0	0	0.0	0.000	0.000
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-17 – Single-Level Diesel Multiple Unit, 2-Car Trainset, (Hydrodynamic, Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	Not Applicable	0.000	0.000
2	0	0	Not Applicable	0.000	0.000
4	0	0	Not Applicable	0.000	0.000
6	0	0	Not Applicable	0.000	0.000
8	0	0	Not Applicable	0.000	0.000
10	-13,400	357	Not Applicable	-1.421	0.168
12	-13,400	429	Not Applicable	-1.421	0.168
14	-13,400	500	Not Applicable	-1.421	0.168
16	-13,400	572	Not Applicable	-1.421	0.168
18	-13,400	643	Not Applicable	-1.421	0.168
20	-12,572	671	Not Applicable	-1.333	0.157
22	-11,429	671	Not Applicable	-1.212	0.143
24	-10,477	671	Not Applicable	-1.111	0.131
26	-9,671	671	Not Applicable	-1.025	0.121
28	-8,980	671	Not Applicable	-0.952	0.112
30	-8,381	671	Not Applicable	-0.889	0.105
32	-7,857	671	Not Applicable	-0.833	0.098
34	-7,395	671	Not Applicable	-0.784	0.092
36	-6,984	671	Not Applicable	-0.740	0.087
38	-6,617	671	Not Applicable	-0.701	0.083
40	-6,286	671	Not Applicable	-0.666	0.079

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
42	-5,987	671	Not Applicable	-0.635	0.075
44	-5,714	671	Not Applicable	-0.606	0.071
46	-5,466	671	Not Applicable	-0.579	0.068
48	-5,238	671	Not Applicable	-0.555	0.065
50	-5,029	671	Not Applicable	-0.533	0.063
52	-4,835	671	Not Applicable	-0.513	0.060
54	-4,656	671	Not Applicable	-0.494	0.058
56	-4,490	671	Not Applicable	-0.476	0.056
58	-4,335	671	Not Applicable	-0.460	0.054
60	-4,191	671	Not Applicable	-0.444	0.052
62	-4,055	671	Not Applicable	-0.430	0.051
64	-3,929	671	Not Applicable	-0.417	0.049
66	-3,810	671	Not Applicable	-0.404	0.048
68	-3,698	671	Not Applicable	-0.392	0.046
70	-3,592	671	Not Applicable	-0.381	0.045
72	-3,492	671	Not Applicable	-0.370	0.044
74	-3,398	671	Not Applicable	-0.360	0.042
76	-3,308	671	Not Applicable	-0.351	0.041
78	-3,224	671	Not Applicable	-0.342	0.040
80	-3,143	671	Not Applicable	-0.333	0.039
82	-3,066	671	Not Applicable	-0.325	0.038
84	-2,993	671	Not Applicable	-0.317	0.037

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
86	-2,924	671	Not Applicable	-0.310	0.037
88	-2,857	671	Not Applicable	-0.303	0.036
90	-2,794	671	Not Applicable	-0.296	0.035
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-18– Single-Level Diesel Multiple Unit, 2-Car Trainset, (Diesel Electric, Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	15,500	0	0.0	1.737	0.207
2	15,254	81	12.0	1.710	0.203
4	15,007	160	23.7	1.682	0.200
6	14,761	236	34.9	1.654	0.197
8	14,515	310	45.8	1.627	0.194
10	14,269	380	56.3	1.599	0.190
12	14,022	449	66.3	1.572	0.187
14	13,776	514	76.0	1.544	0.184
16	13,530	577	85.4	1.516	0.180
18	12,181	585	86.5	1.365	0.162
20	10,963	585	86.5	1.229	0.146
22	9,966	585	86.5	1.117	0.133
24	9,136	585	86.5	1.024	0.122
26	8,433	585	86.5	0.945	0.112
28	7,831	585	86.5	0.878	0.104
30	7,308	585	86.5	0.819	0.097
32	6,852	585	86.5	0.768	0.091
34	6,449	585	86.5	0.723	0.086
36	6,090	585	86.5	0.683	0.081
38	5,770	585	86.5	0.647	0.077
40	5,481	585	86.5	0.614	0.073
42	5,220	585	86.5	0.585	0.070

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
44	4,983	585	86.5	0.559	0.066
46	4,766	585	86.5	0.534	0.064
48	4,568	585	86.5	0.512	0.061
50	4,385	585	86.5	0.491	0.058
52	4,216	585	86.5	0.473	0.056
54	4,060	585	86.5	0.455	0.054
56	3,915	585	86.5	0.439	0.052
58	3,780	585	86.5	0.424	0.050
60	3,654	585	86.5	0.410	0.049
62	3,536	585	86.5	0.396	0.047
64	3,426	585	86.5	0.384	0.046
66	3,322	585	86.5	0.372	0.044
68	3,224	585	86.5	0.361	0.043
70	3,132	585	86.5	0.351	0.042
72	3,045	585	86.5	0.341	0.041
74	2,963	585	86.5	0.332	0.040
76	2,885	585	86.5	0.323	0.038
78	2,811	585	86.5	0.315	0.037
80	2,741	585	86.5	0.307	0.037
82	2,674	585	86.5	0.300	0.036
84	2,610	585	86.5	0.293	0.035
86	2,549	585	86.5	0.286	0.034

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
88	2,492	585	86.5	0.279	0.033
90	2,436	585	86.5	0.273	0.032
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-19 – Single-Level Diesel Multiple Unit, 10-Car Trainset, (Diesel Electric, Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	Not Applicable	0.000	0.000
2	0	0	Not Applicable	0.000	0.000
4	0	0	Not Applicable	0.000	0.000
6	-12,500	200	Not Applicable	-1.401	0.167
8	-12,500	267	Not Applicable	-1.401	0.167
10	-12,500	333	Not Applicable	-1.401	0.167
12	-12,500	400	Not Applicable	-1.401	0.167
14	-12,500	467	Not Applicable	-1.401	0.167
16	-12,500	533	Not Applicable	-1.401	0.167
18	-12,500	600	Not Applicable	-1.401	0.167
20	-11,315	603	Not Applicable	-1.268	0.151
22	-10,286	603	Not Applicable	-1.153	0.137
24	-9,429	603	Not Applicable	-1.057	0.126
26	-8,704	603	Not Applicable	-0.976	0.116
28	-8,082	603	Not Applicable	-0.906	0.108
30	-7,543	603	Not Applicable	-0.845	0.101
32	-7,072	603	Not Applicable	-0.793	0.094
34	-6,656	603	Not Applicable	-0.746	0.089
36	-6,286	603	Not Applicable	-0.705	0.084
38	-5,955	603	Not Applicable	-0.667	0.079
40	-5,657	603	Not Applicable	-0.634	0.075

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
42	-5,388	603	Not Applicable	-0.604	0.072
44	-5,143	603	Not Applicable	-0.576	0.069
46	-4,919	603	Not Applicable	-0.551	0.066
48	-4,714	603	Not Applicable	-0.528	0.063
50	-4,526	603	Not Applicable	-0.507	0.060
52	-4,352	603	Not Applicable	-0.488	0.058
54	-4,191	603	Not Applicable	-0.470	0.056
56	-4,041	603	Not Applicable	-0.453	0.054
58	-3,902	603	Not Applicable	-0.437	0.052
60	-3,772	603	Not Applicable	-0.423	0.050
62	-3,650	603	Not Applicable	-0.409	0.049
64	-3,536	603	Not Applicable	-0.396	0.047
66	-3,429	603	Not Applicable	-0.384	0.046
68	-3,328	603	Not Applicable	-0.373	0.044
70	-3,233	603	Not Applicable	-0.362	0.043
72	-3,143	603	Not Applicable	-0.352	0.042
74	-3,058	603	Not Applicable	-0.343	0.041
76	-2,978	603	Not Applicable	-0.334	0.040
78	-2,901	603	Not Applicable	-0.325	0.039
80	-2,829	603	Not Applicable	-0.317	0.038
82	-2,760	603	Not Applicable	-0.309	0.037
84	-2,694	603	Not Applicable	-0.302	0.036

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 2-Cars AW2 (mphps)	Maximum Required Adhesion
86	-2,631	603	Not Applicable	-0.295	0.035
88	-2,572	603	Not Applicable	-0.288	0.034
90	-2,514	603	Not Applicable	-0.282	0.034
92	-	-	-	-	-
94	-	-	-	-	-
96	-	-	-	-	-
98	-	-	-	-	-
100	-	-	-	-	-

Table 7C-20 – Dual-Mode Locomotive, 10-Car Trainset, (Diesel Mode, Propulsion)

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	71,000	0	0.0	0.748	0.247
2	69,775	372	10.5	0.735	0.242
4	68,551	731	20.5	0.722	0.238
6	67,326	1,077	30.3	0.709	0.234
8	66,101	1,410	39.6	0.697	0.230
10	64,876	1,730	48.6	0.684	0.225
12	63,652	2,037	57.2	0.671	0.221
14	62,427	2,331	65.5	0.658	0.217
16	61,202	2,611	73.4	0.645	0.213
18	59,977	2,879	80.9	0.632	0.208
20	58,317	3,110	87.4	0.615	0.202
22	53,016	3,110	87.4	0.559	0.184
24	48,598	3,110	87.4	0.512	0.169
26	44,860	3,110	87.4	0.473	0.156
28	41,655	3,110	87.4	0.439	0.145
30	38,878	3,110	87.4	0.410	0.135
32	36,448	3,110	87.4	0.384	0.127
34	34,304	3,110	87.4	0.361	0.119
36	32,399	3,110	87.4	0.341	0.112
38	30,693	3,110	87.4	0.323	0.107
40	29,159	3,110	87.4	0.307	0.101
42	27,770	3,110	87.4	0.293	0.096

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
44	26,508	3,110	87.4	0.279	0.092
46	25,355	3,110	87.4	0.267	0.088
48	24,299	3,110	87.4	0.256	0.084
50	23,327	3,110	87.4	0.246	0.081
52	22,430	3,110	87.4	0.236	0.078
54	21,599	3,110	87.4	0.228	0.075
56	20,828	3,110	87.4	0.219	0.072
58	20,109	3,110	87.4	0.212	0.070
60	19,439	3,110	87.4	0.205	0.067
62	18,812	3,110	87.4	0.198	0.065
64	18,224	3,110	87.4	0.192	0.063
66	17,672	3,110	87.4	0.186	0.061
68	17,152	3,110	87.4	0.181	0.060
70	16,662	3,110	87.4	0.176	0.058
72	16,199	3,110	87.4	0.171	0.056
74	15,761	3,110	87.4	0.166	0.055
76	15,347	3,110	87.4	0.162	0.053
78	14,953	3,110	87.4	0.158	0.052
80	14,579	3,110	87.4	0.154	0.051
82	14,224	3,110	87.4	0.150	0.049
84	13,885	3,110	87.4	0.146	0.048
86	13,562	3,110	87.4	0.143	0.047

Speed (mph)	Tractive Effort (lbs)	Power at Wheel/Rail (Hp)	Eff (%) Calculated	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
88	13,254	3,110	87.4	0.140	0.046
90	12,959	3,110	87.4	0.137	0.045
92	12,678	3,110	87.4	0.134	0.044
94	12,408	3,110	87.4	0.131	0.043
96	12,149	3,110	87.4	0.128	0.042
98	11,902	3,110	87.4	0.125	0.041
100	11,663	3,110	87.4	0.123	0.040

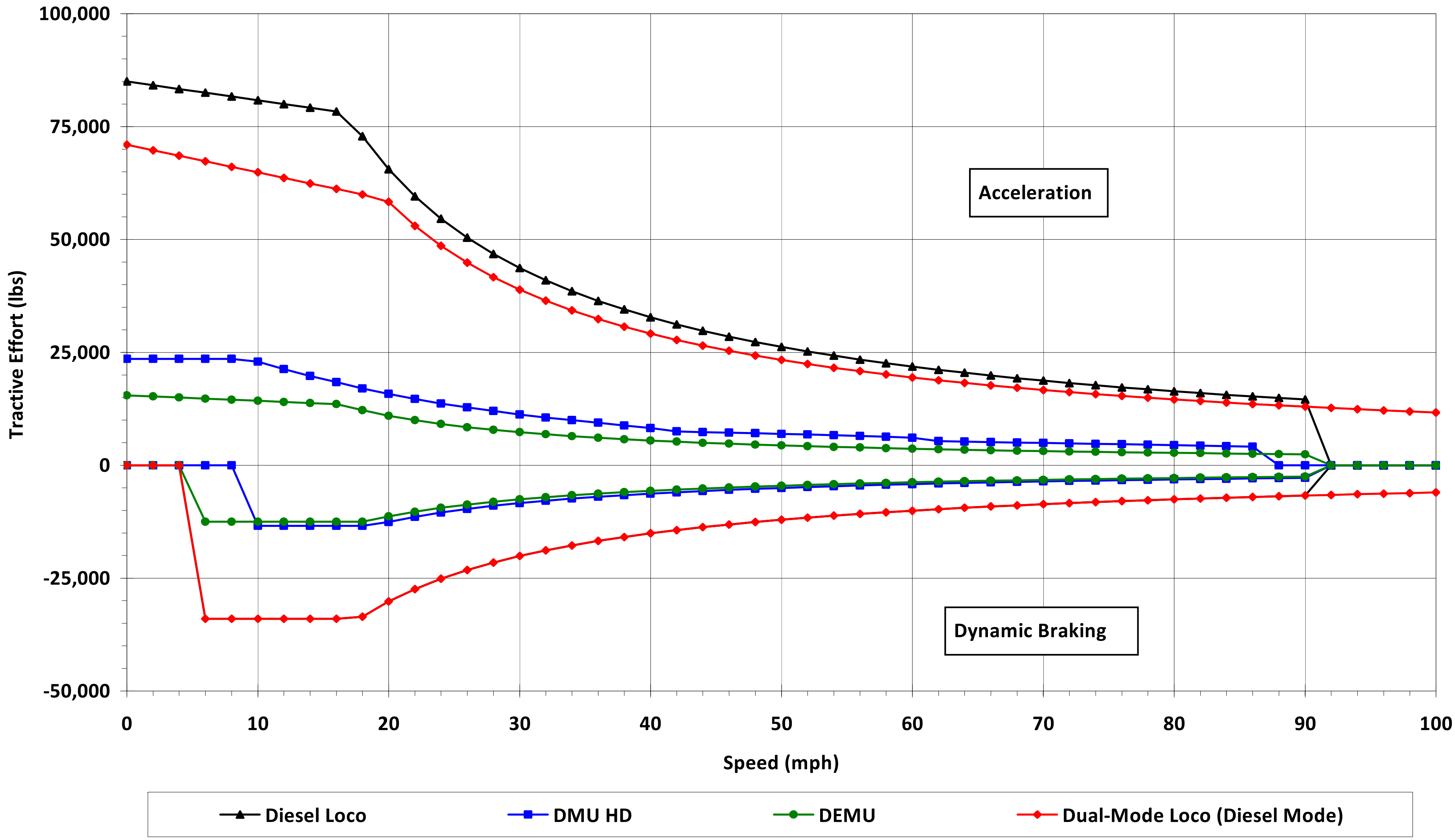
Table 7C-21 – Dual-Mode Locomotive, 10-Car Trainset, (Diesel Mode, Braking)

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
0	0	0	Not Applicable	0.000	0.000
2	0	0	Not Applicable	0.000	0.000
4	0	0	Not Applicable	0.000	0.000
6	-34,000	544	Not Applicable	-0.358	0.118
8	-34,000	725	Not Applicable	-0.358	0.118
10	-34,000	907	Not Applicable	-0.358	0.118
12	-34,000	1,088	Not Applicable	-0.358	0.118
14	-34,000	1,269	Not Applicable	-0.358	0.118
16	-34,000	1,451	Not Applicable	-0.358	0.118
18	-33,525	1,609	Not Applicable	-0.353	0.116
20	-30,173	1,609	Not Applicable	-0.318	0.105
22	-27,430	1,609	Not Applicable	-0.289	0.095
24	-25,144	1,609	Not Applicable	-0.265	0.087
26	-23,210	1,609	Not Applicable	-0.245	0.081
28	-21,552	1,609	Not Applicable	-0.227	0.075
30	-20,115	1,609	Not Applicable	-0.212	0.070
32	-18,858	1,609	Not Applicable	-0.199	0.065
34	-17,749	1,609	Not Applicable	-0.187	0.062
36	-16,763	1,609	Not Applicable	-0.177	0.058
38	-15,880	1,609	Not Applicable	-0.167	0.055
40	-15,086	1,609	Not Applicable	-0.159	0.052

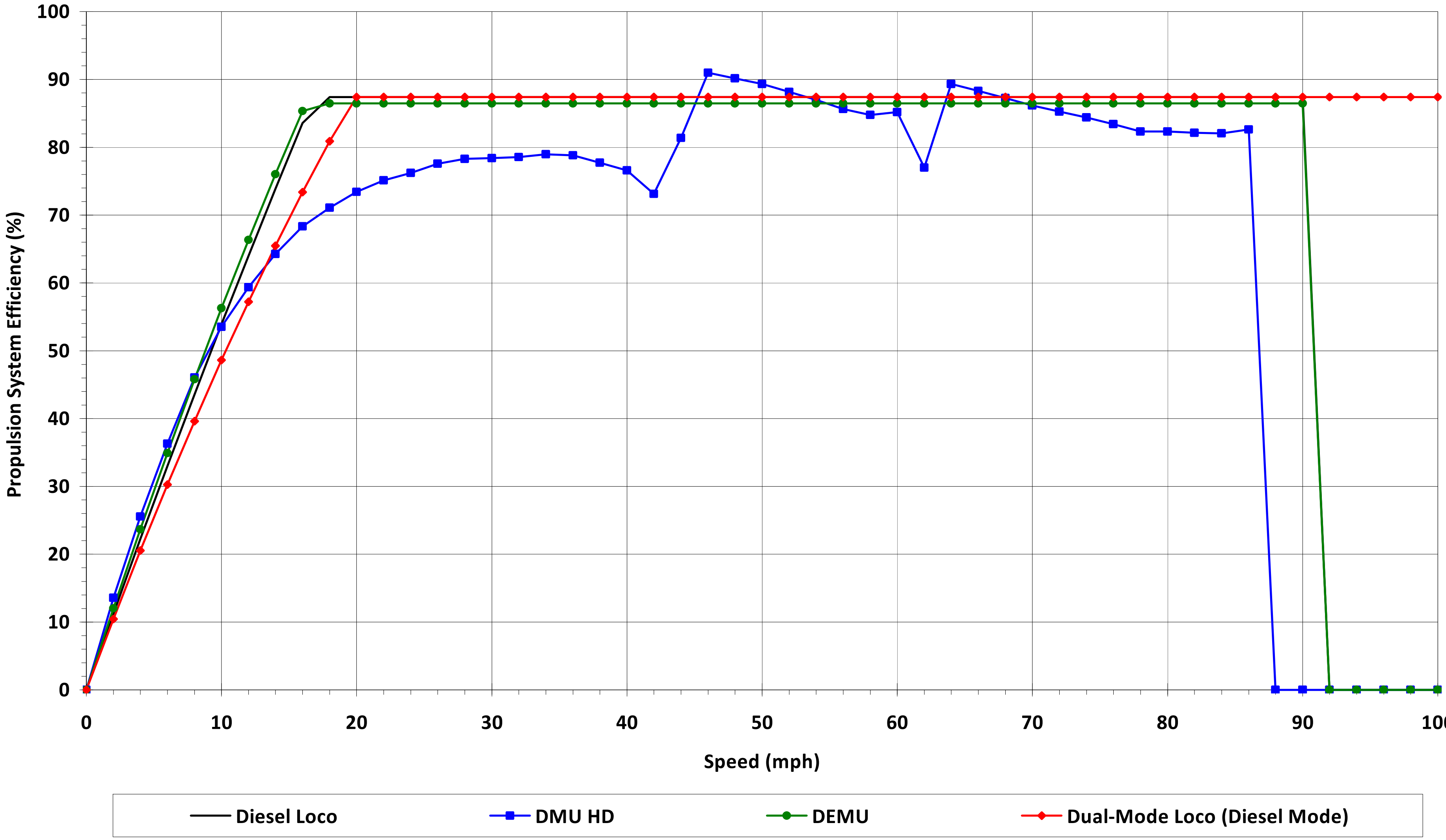
Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
42	-14,368	1,609	Not Applicable	-0.151	0.050
44	-13,715	1,609	Not Applicable	-0.145	0.048
46	-13,118	1,609	Not Applicable	-0.138	0.046
48	-12,572	1,609	Not Applicable	-0.132	0.044
50	-12,069	1,609	Not Applicable	-0.127	0.042
52	-11,605	1,609	Not Applicable	-0.122	0.040
54	-11,175	1,609	Not Applicable	-0.118	0.039
56	-10,776	1,609	Not Applicable	-0.114	0.037
58	-10,404	1,609	Not Applicable	-0.110	0.036
60	-10,058	1,609	Not Applicable	-0.106	0.035
62	-9,733	1,609	Not Applicable	-0.103	0.034
64	-9,429	1,609	Not Applicable	-0.099	0.033
66	-9,143	1,609	Not Applicable	-0.096	0.032
68	-8,874	1,609	Not Applicable	-0.094	0.031
70	-8,621	1,609	Not Applicable	-0.091	0.030
72	-8,381	1,609	Not Applicable	-0.088	0.029
74	-8,155	1,609	Not Applicable	-0.086	0.028
76	-7,940	1,609	Not Applicable	-0.084	0.028
78	-7,737	1,609	Not Applicable	-0.082	0.027
80	-7,543	1,609	Not Applicable	-0.079	0.026
82	-7,359	1,609	Not Applicable	-0.078	0.026
84	-7,184	1,609	Not Applicable	-0.076	0.025

Speed (mph)	Braking Effort (lbs)	Power at Wheel/Rail (Hp)	Power at Pantograph (kW)	Nominal Max Accel, 10-Cars AW2 (mphps)	Maximum Required Adhesion
86	-7,017	1,609	Not Applicable	-0.074	0.024
88	-6,857	1,609	Not Applicable	-0.072	0.024
90	-6,705	1,609	Not Applicable	-0.071	0.023
92	-6,559	1,609	Not Applicable	-0.069	0.023
94	-6,420	1,609	Not Applicable	-0.068	0.022
96	-6,286	1,609	Not Applicable	-0.066	0.022
98	-6,158	1,609	Not Applicable	-0.065	0.021
100	-6,035	1,609	Not Applicable	-0.064	0.021

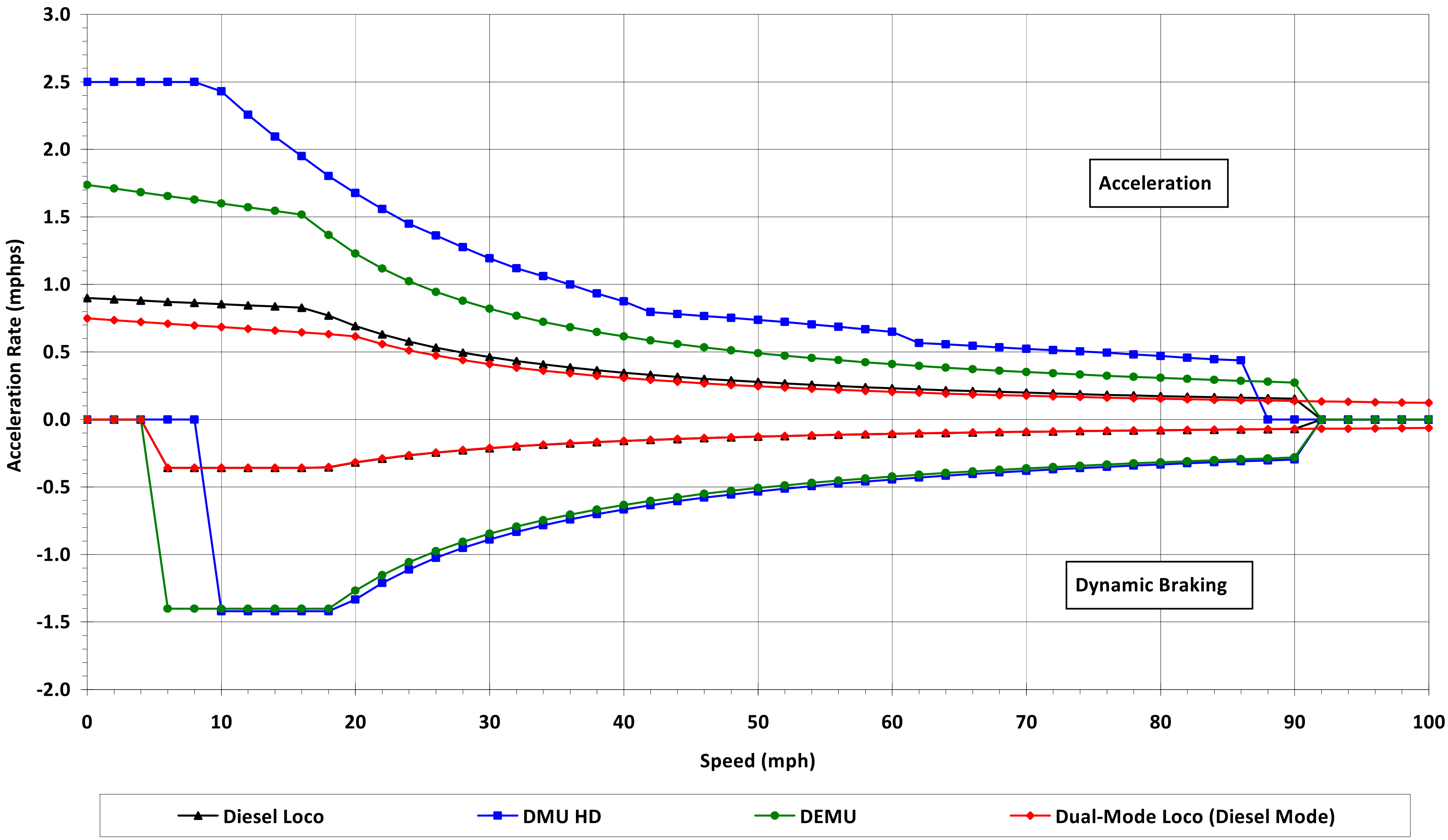
Available Tractive and Dynamic Braking Effort for Candidate Diesel Propulsion



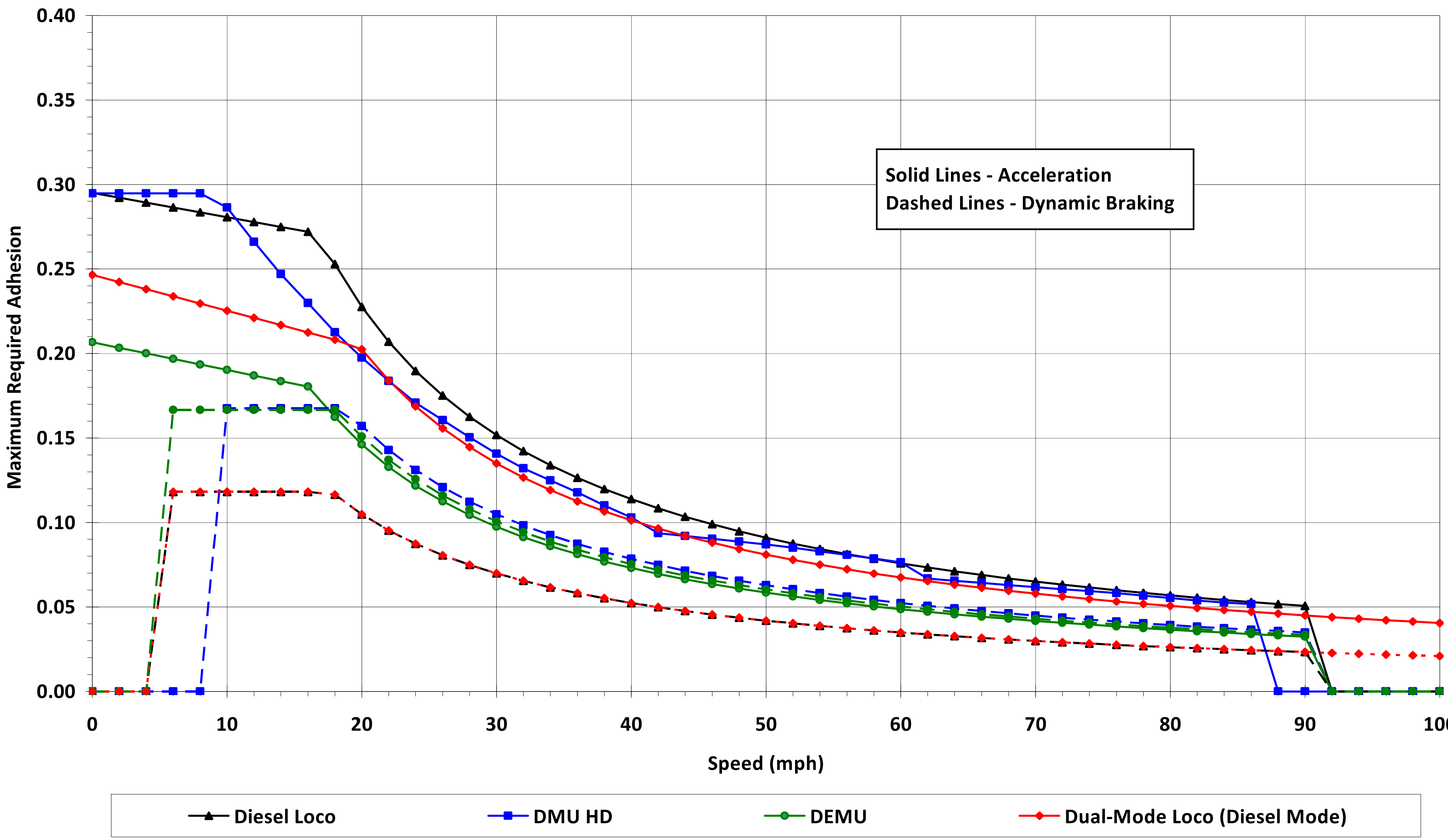
Drive Train Efficiencies for Candidate Diesel Propulsion



Nominal Acceleration for 12-Car Trains, Candidate Diesel Propulsion, AW2



Adhesion Required by Candidate Diesel Propulsion to Avoid Wheel Spin



APPENDIX 7D - ELECTRIFICATION SYSTEM DATA

GENERAL

The Appendix presents electrical parameters required for the system simulation. The system base is 100 MVA.

UTILITY SYSTEM DATA

The traction power substations will be supplied from utility supply points at 230 kV transmission voltage. In the model, the utility system is represented by its equivalent reactance. The equivalent system reactances are derived in Table D-1 from short-circuit fault levels furnished by Hydro One.

Table 7D-1 – Utility System Equivalent Impedances

Substation Name	Transformer	System Short-Circuit Fault Level			Equivalent Impedance (p.u.)
		Three-Phase (A)	Three-Phase (MVA)	Phase-to-Phase (MVA)	
Mimico	Transformer 1	33.1	13,186	11,419	0.009
	Transformer 2	33.5	13,345	11,557	0.009
Burlington West	Transformer 1	27.7	11,035	9,556	0.010
	Transformer 2	27.7	11,035	9,556	0.010
Scarborough	Transformer 1	14.5	5,776	5,002	0.020
	Transformer 2	14.1	5,617	4,864	0.021
Oshawa	Transformer 1	10.7	4,262	3,691	0.027
	Transformer 2	10.7	4,262	3,691	0.027
Dixie Road	Transformer 1	35.3	14,062	12,178	0.008
	Transformer 2	35.0	13,943	12,075	0.008
Guelph	Transformer 1	8.2	3,267	2,829	0.035
	Transformer 2	8.2	3,267	2,829	0.035
New Market	Transformer 1	8.7	3,466	3,002	0.033
	Transformer 2	8.7	3,466	3,002	0.033

TRANSFORMER REACTANCES

The reactance of each traction power substation traction power transformer was assumed 7% on own rating, as shown in Table D-2. The transformer resistance is neglected.

Table 7D-2 – Traction Power Transformer Ratings and Impedances

Rating (MVA)	Impedance (%)
20	7
30	7

AUTOTRANSFORMER REACTANCES

The reactance of each autotransformer was assumed 1.5% on own rating of 5 MVA. In the model, the autotransformers are represented as two-winding transformers. Therefore, it is necessary to convert the autotransformer rating and reactance into equivalent two-winding transformer rating and reactance, as shown in Table D-3. The autotransformer resistance is neglected.

Table 7D-3 – Autotransformer Rating and Impedance Conversion

Autotransformer		Equivalent Two-Winding Transformer	
Rating (MVA)	**Impedance (%)**	**Rating (MVA)**	**Impedance (%)**
5	1.5	2.5	3

TRACTION POWER DISTRIBUTION AND RETURN SYSTEM RESISTANCES AND REACTANCES

The distribution and return system impedances were calculated for one mile length of one-track to four-track electrified railroad segments, using the Alternative Transient Program (ATP) and MathCAD 2000 Professional software[26].

The calculation resulted in the resistance and reactance values presented in Tables D-4 and D-5.

[26] T. Kneschke, P. Mbika, Determination of Traction Power Distribution System Impedances and Susceptances for AC Railroad Electrification Systems, Proceedings of the 2004 ASME/IEEE Joint Railroad Conference, April 6-8, Baltimore, MD. Paper No. RTD2004-66011.

Table 7D-4 - Distribution System Impedances – Direct-Fed System

Number of Tracks	Catenary System Impedance (Ω/mile)			
	Track 1	Track 2	Track 3	Track 4
1	0.188+j 0.707			
2	0.202+j 0.813	0.202+j 0.813		
3	0.213+j 0.873	0.185+j 1.103	0.213+j 0.873	
4	0.220+j 0.905	0.186+j 1.123	0.186+j 1.123	0.220+j 0.905

Table 7D-5 – Distribution System Impedances - Autotransformer-Fed System

Number of Tracks	Feeder System Impedance (Ω/mile)		Catenary System Impedance (Ω/mile)			
	Feeder 1	Feeder 2	Track 1	Track 2	Track 3	Track 4
1	0.270+j 1.229		0.224+j 0.860			
2	0.311+j 1.356	0.311+j 1.356	0.248+j 1.024	0.248+j 1.024		
3	0.317+j 1.400	0.317+j 1.400	0.250+j 1.068	0.213+j 1.202	0.250+j 1.068	
4	0.322+j 1.428	0.322+j 1.428	0.253+j 1.091	0.207+j 1.263	0.207+j 1.263	0.253+j 1.091

For six- and eight-track electrification, two feeder and four-track impedances were used.

APPENDIX 7E - SYSTEM MODELING AND SIMULATION RESULTS

The modeling and simulation of the Metrolinx rolling stock and proposed electrification system has been performed for the Reference Case using electric locomotive hauled trains, each with 10 bi-level coaches. The only exception is the Airport Rail Link service which has been modeled with 2-car EMUs.

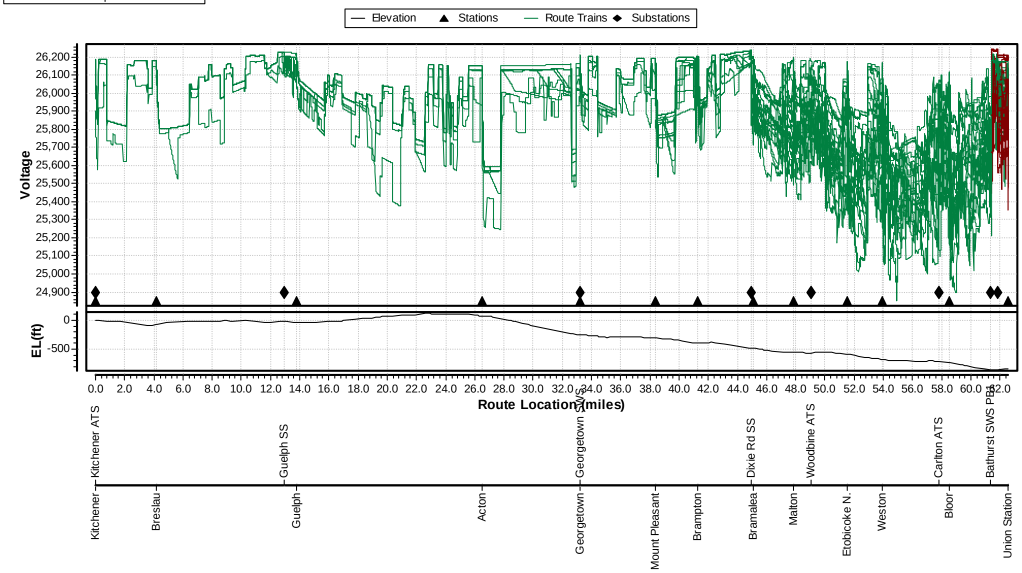
The following results of the modeling and simulation are included:

- Voltage profiles along each corridor
- Maximum autotransformer power demands
- Traction power substation power demands
- Maximum traction power substation transformer power demands averaged over several time intervals
- System-wide energy consumption
- 24-hour power demand with 1-hour running average

VOLTAGE PROFILES ALONG EACH CORRIDOR

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: KIT-Kitchener to Union Station
Run Duration: 21:15:03

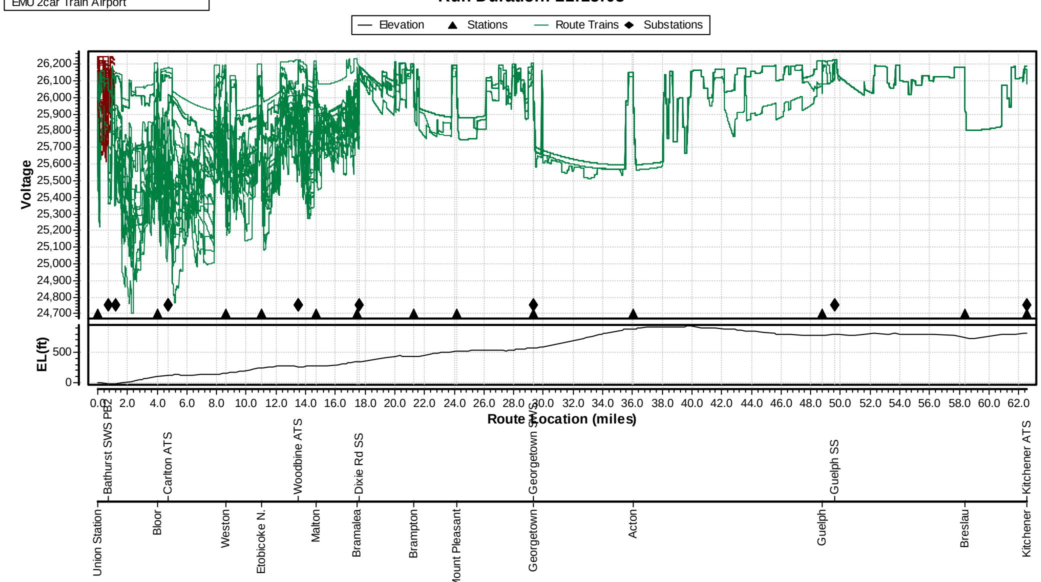


C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: KIT-Union Station to Kitchener
Run Duration: 21:15:03



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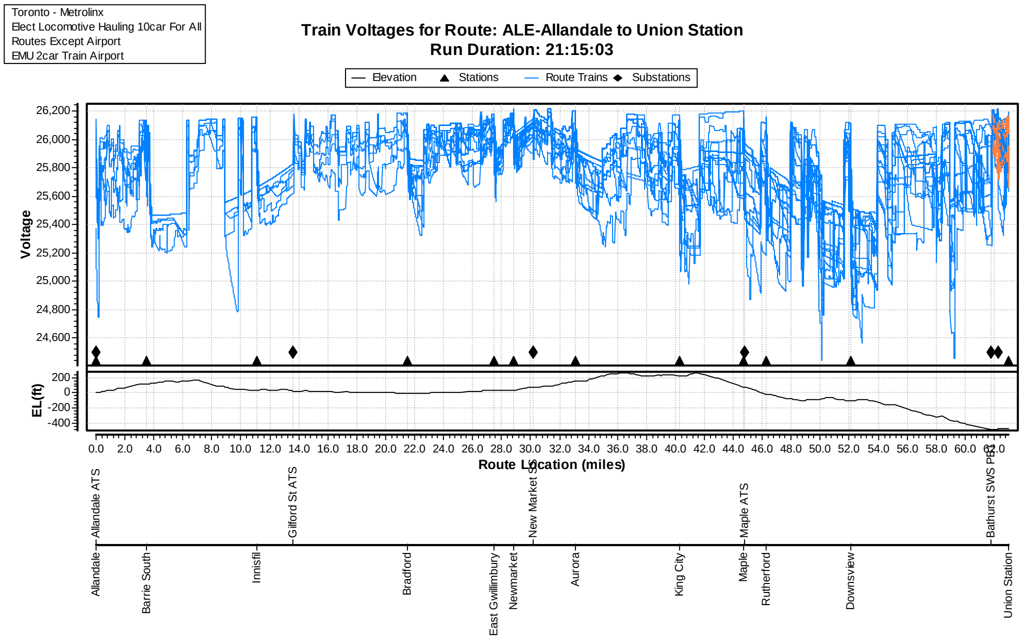
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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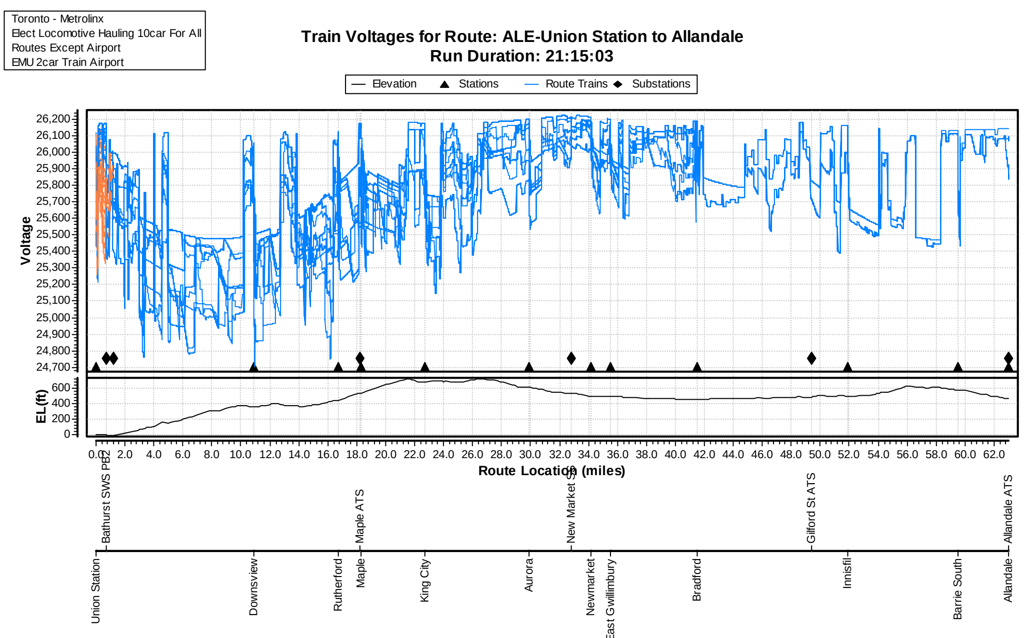
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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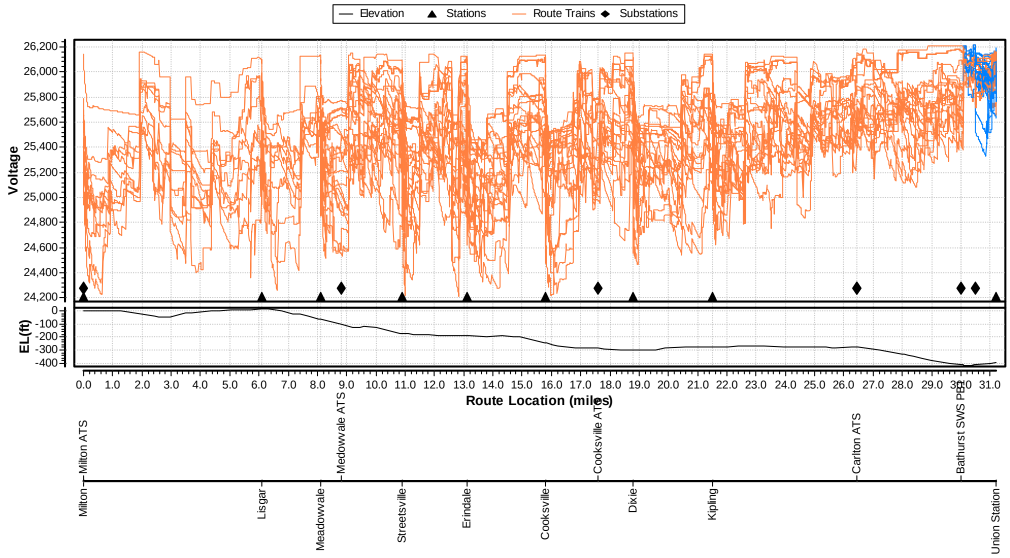
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: MIL-Milton to Union Station
Run Duration: 21:15:03



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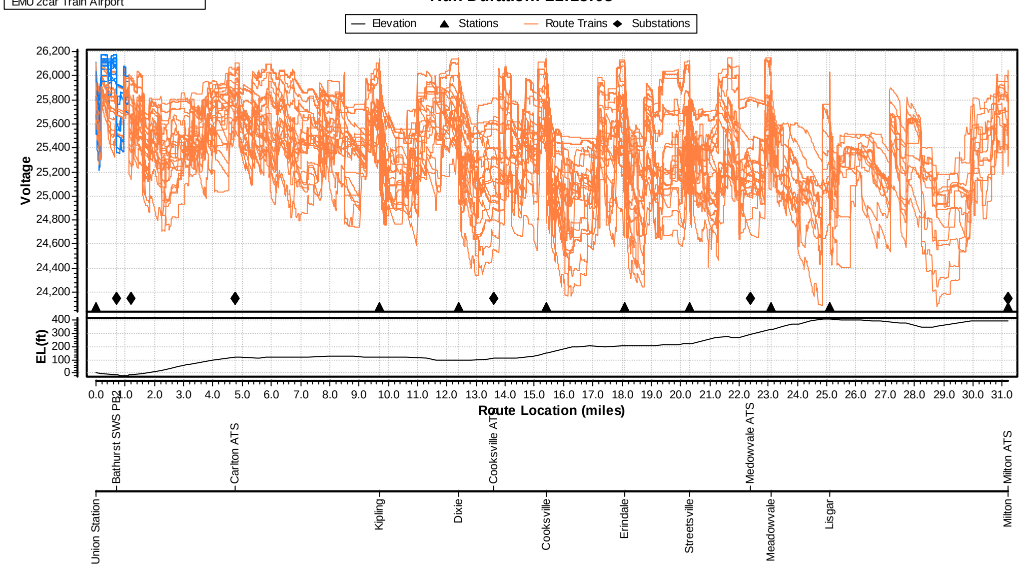
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: MIL-Union Station to Milton
Run Duration: 21:15:03



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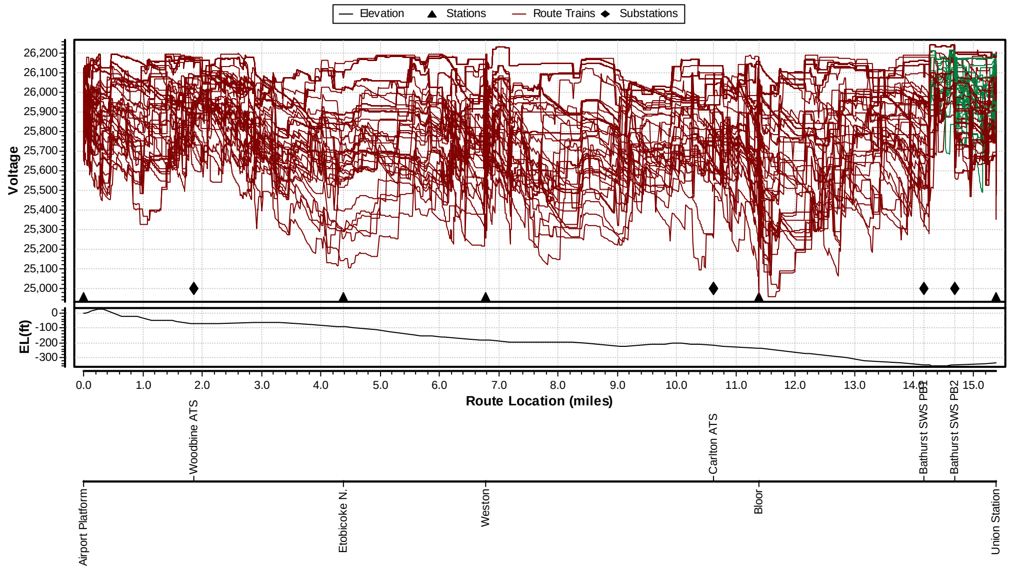
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: AIR-Airport to Union Station
Run Duration: 21:15:03



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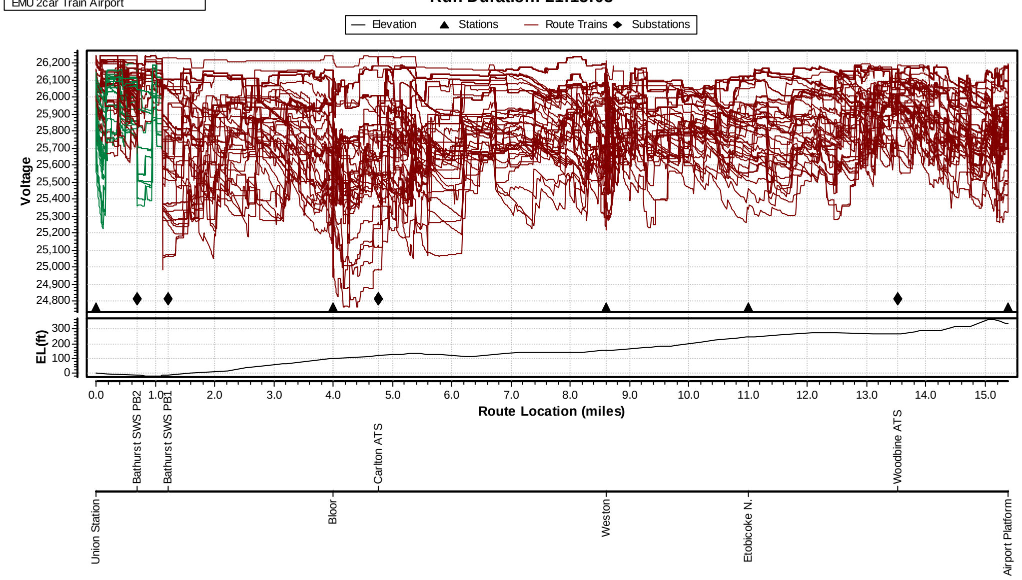
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: AIR-Union Station to Airport
Run Duration: 21:15:03



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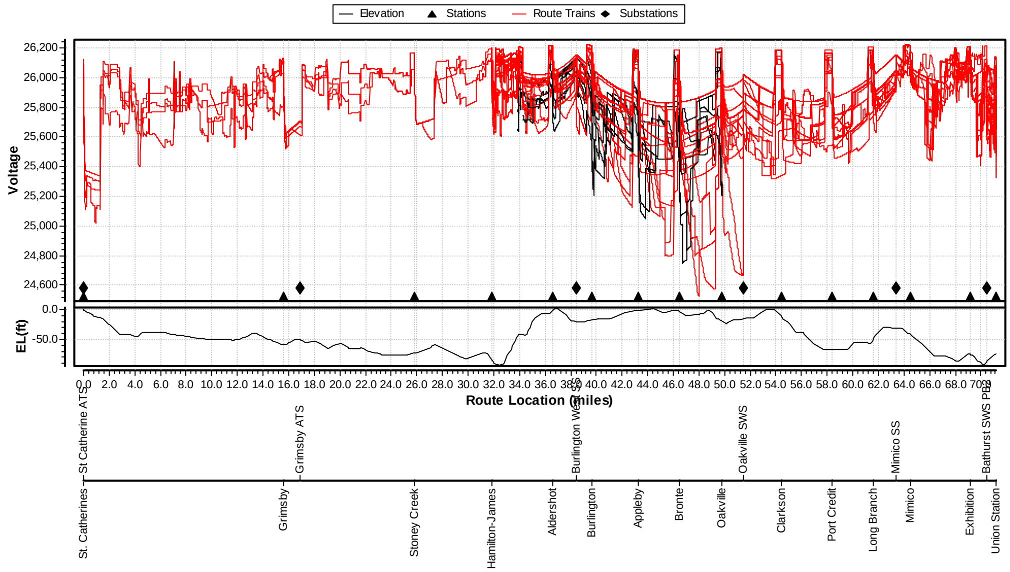
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: LW-St Catherines to Union Station
Run Duration: 21:15:03



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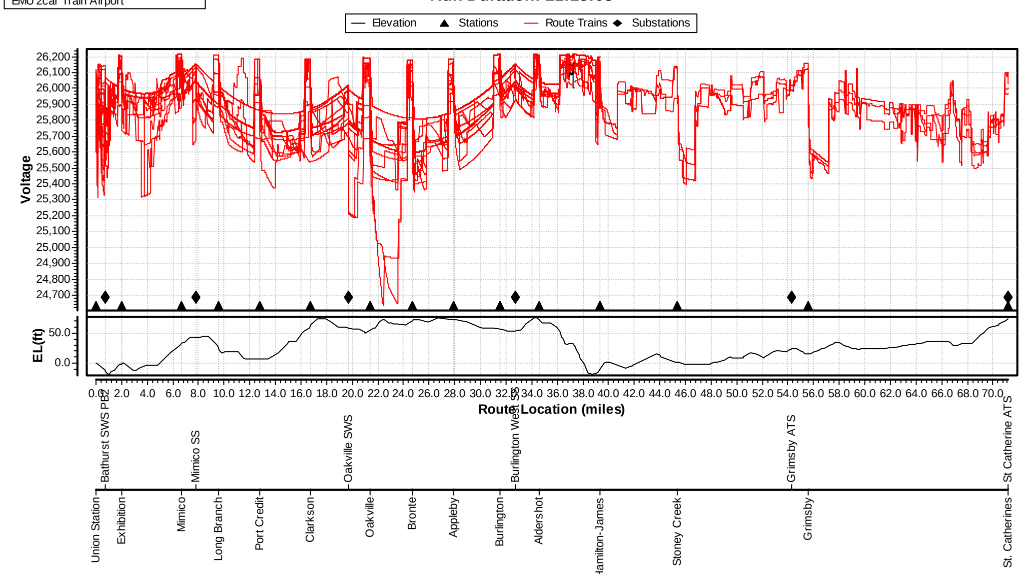
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: LW-Union Station to St Catherines
Run Duration: 21:15:03



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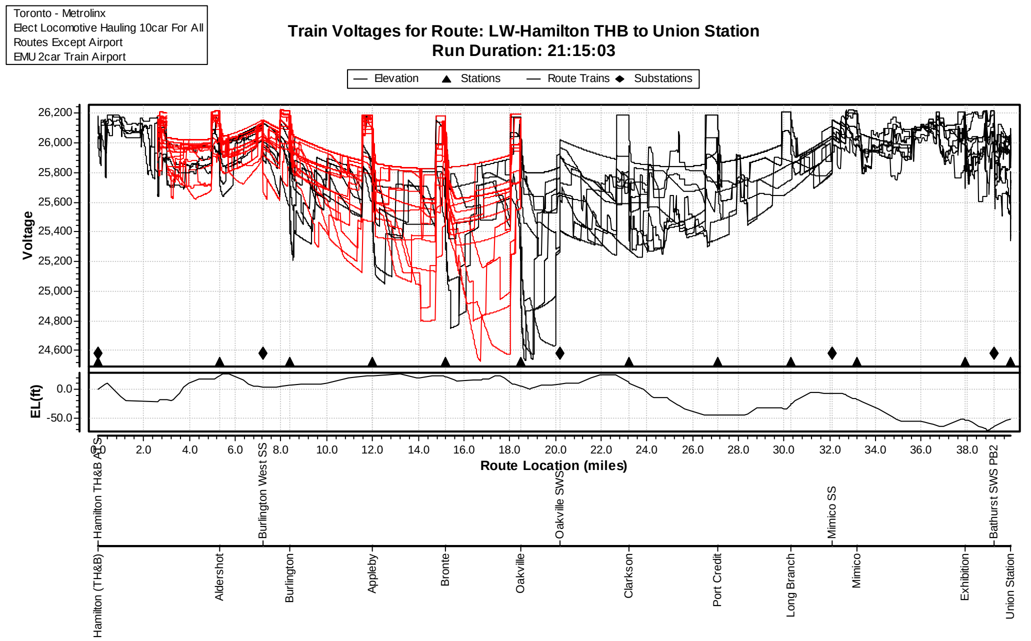
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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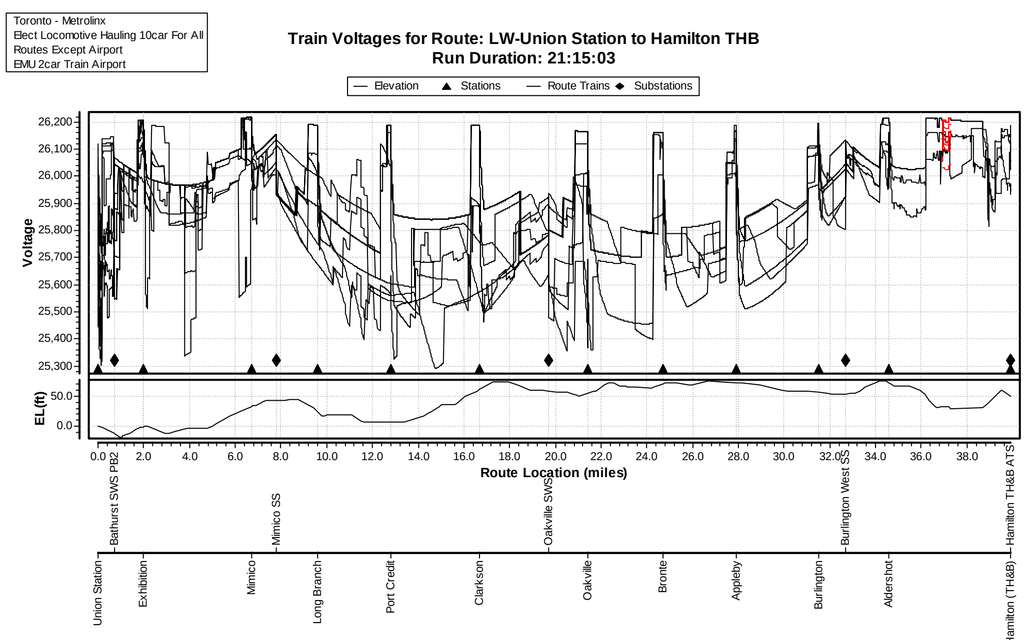
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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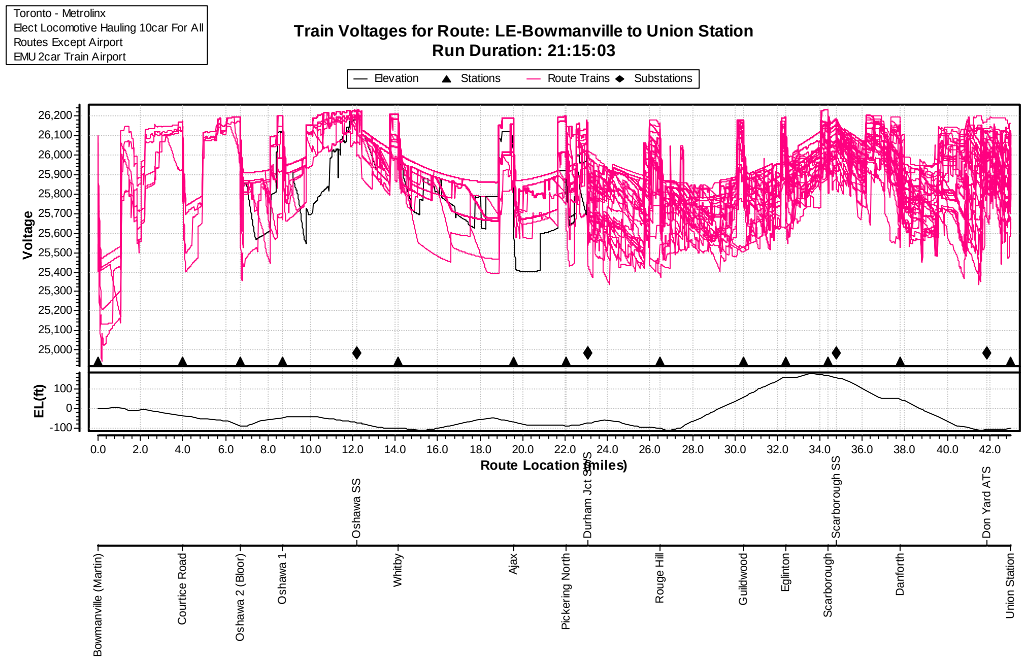
LTK RR v14.7.3.0



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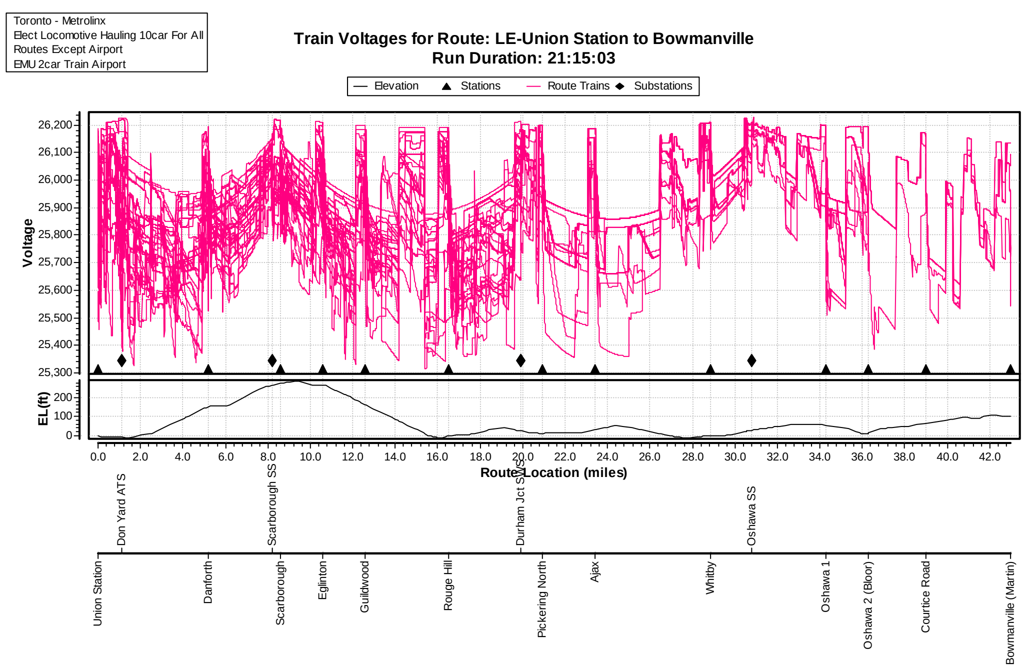
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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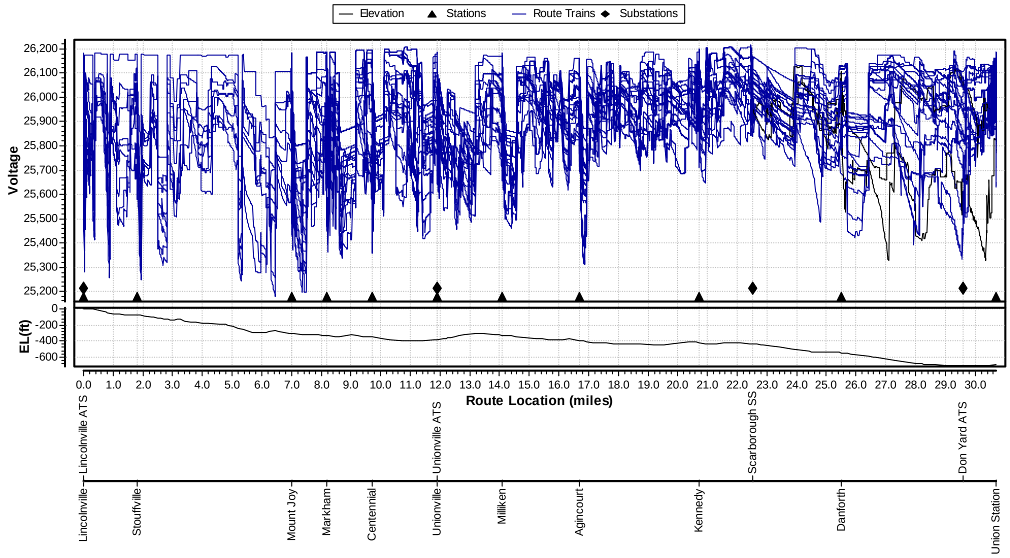
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: LIN-Lincolnville to Union Station
Run Duration: 21:15:03



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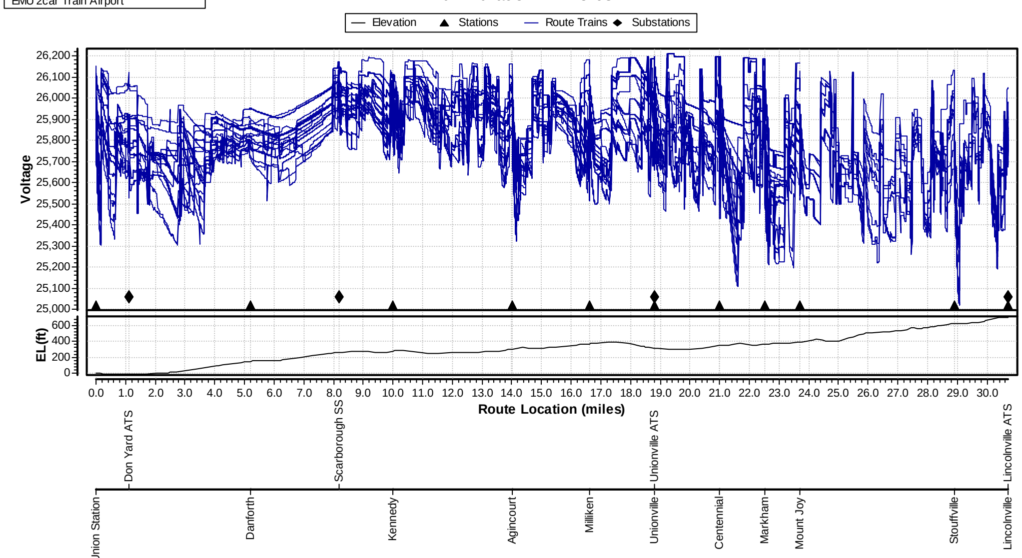
Network Type: AC; Network is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport

Train Voltages for Route: LIN-Union Station to Lincolnville
Run Duration: 21:15:03



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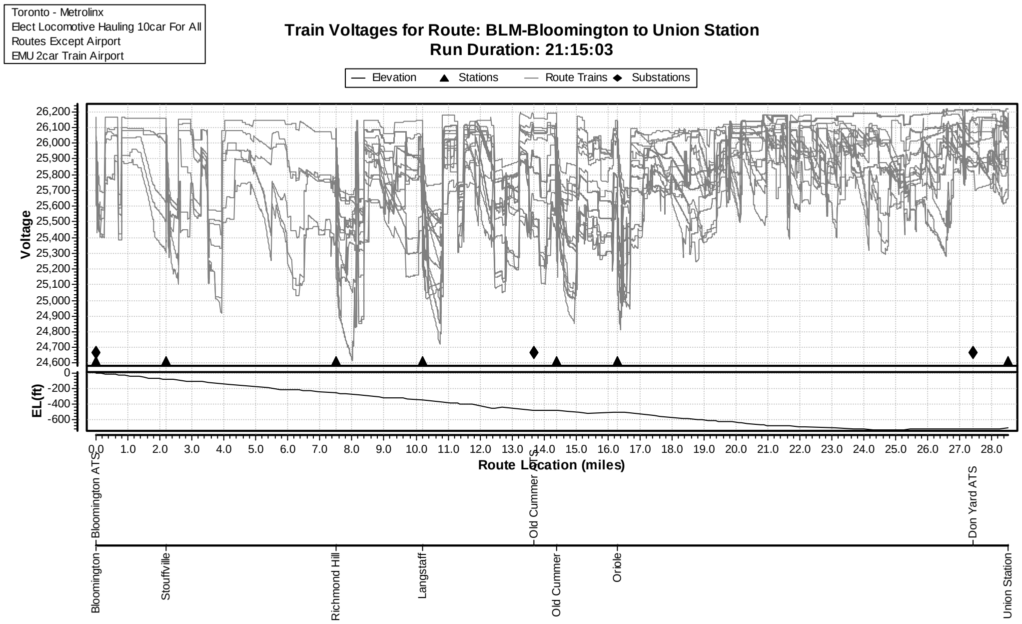
Network Type: AC; Network is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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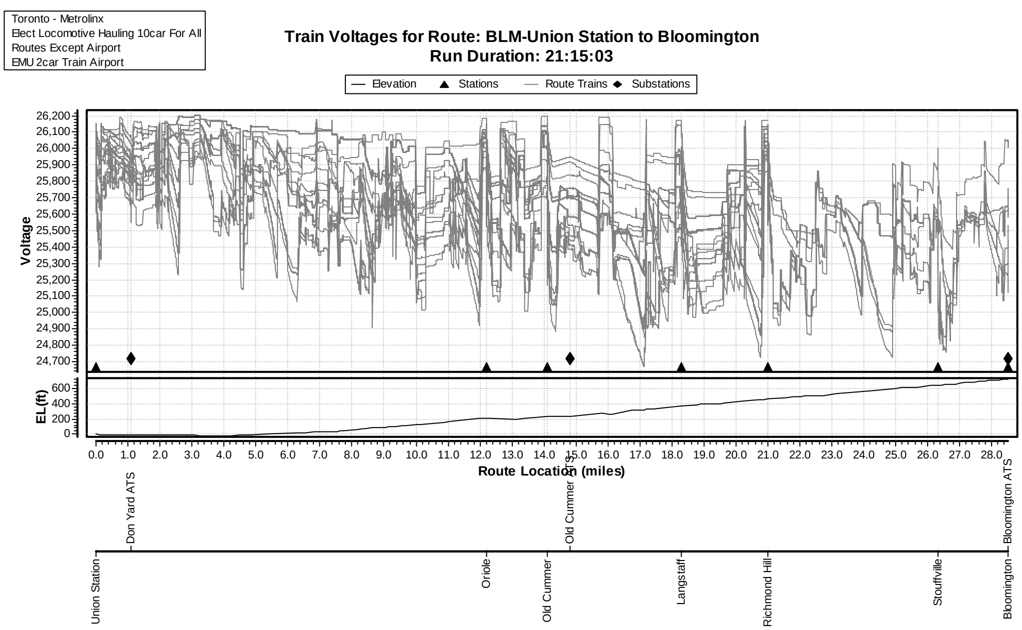
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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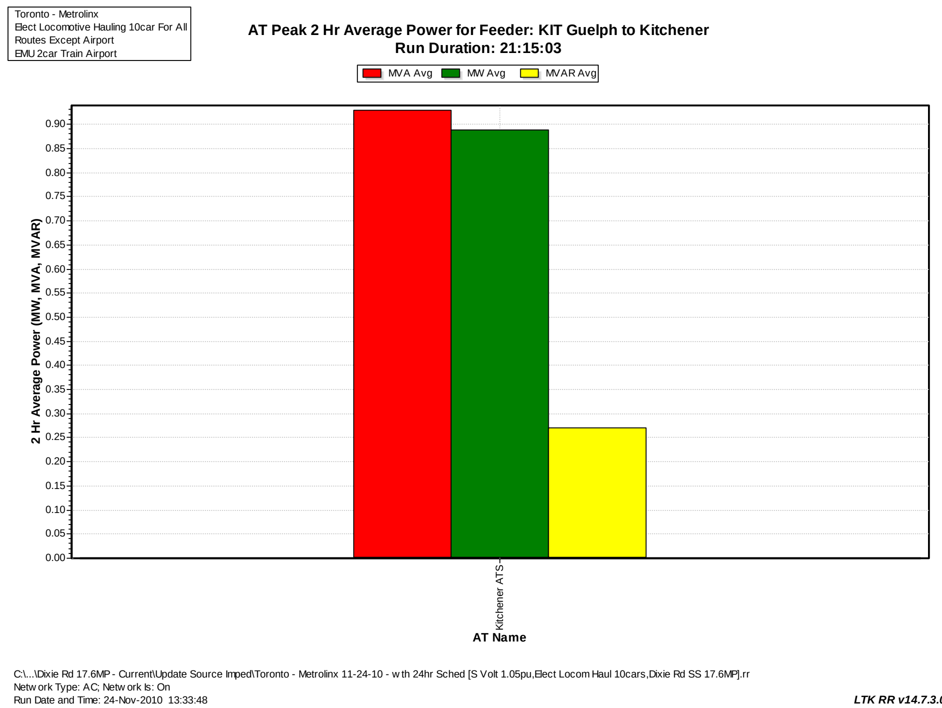
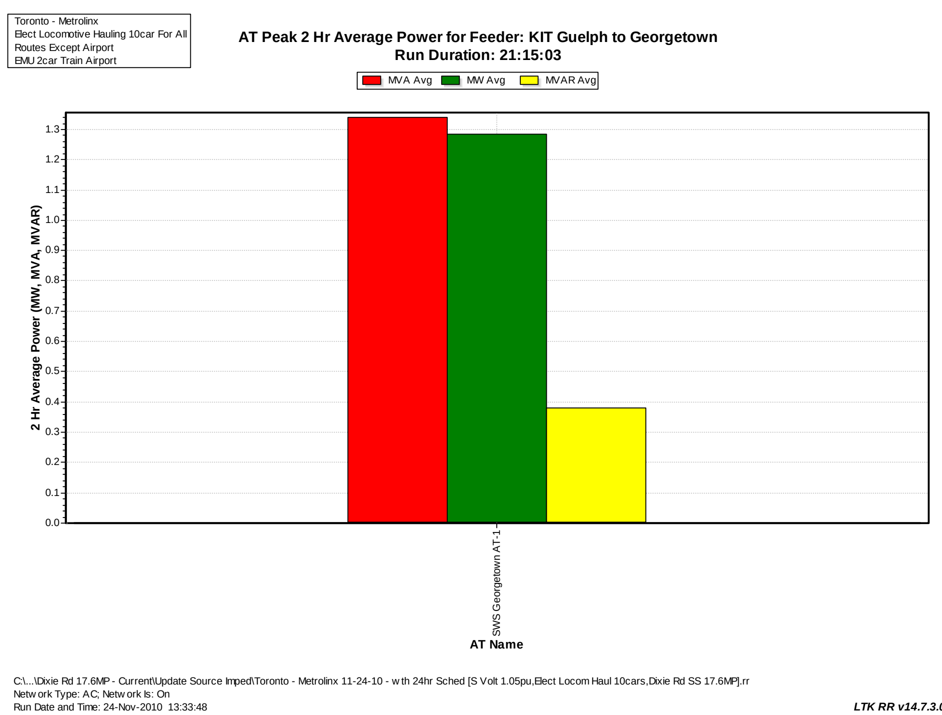
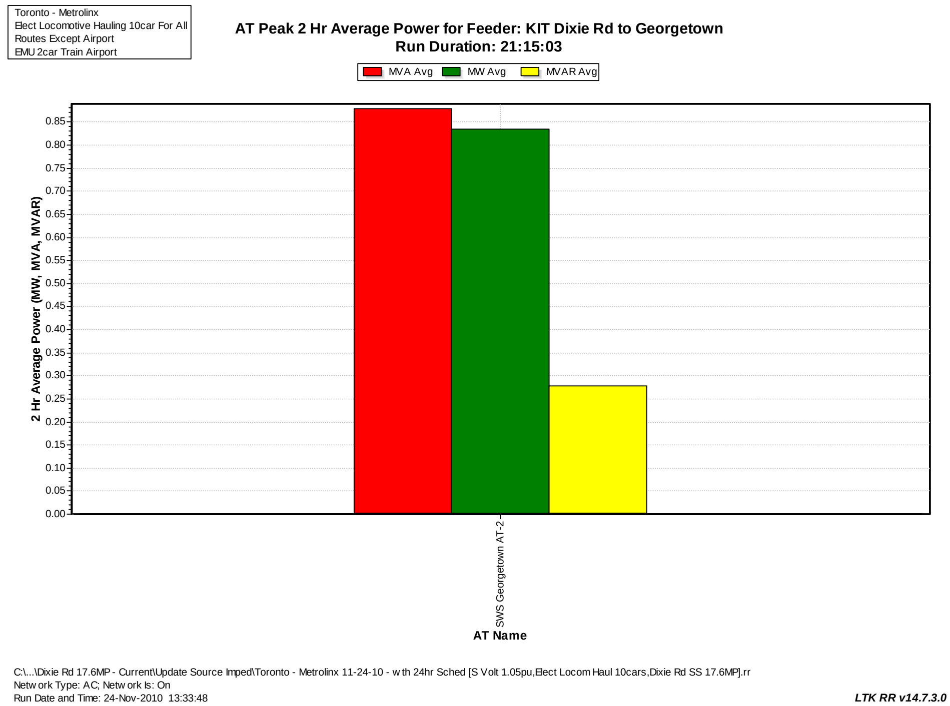
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

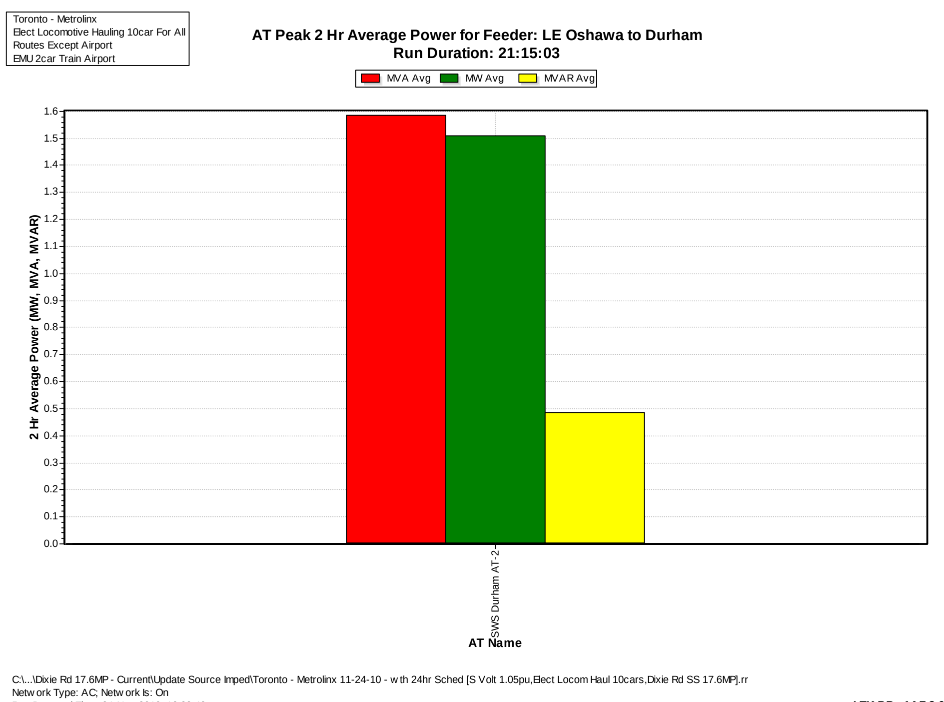
LTK RR v14.7.3.0

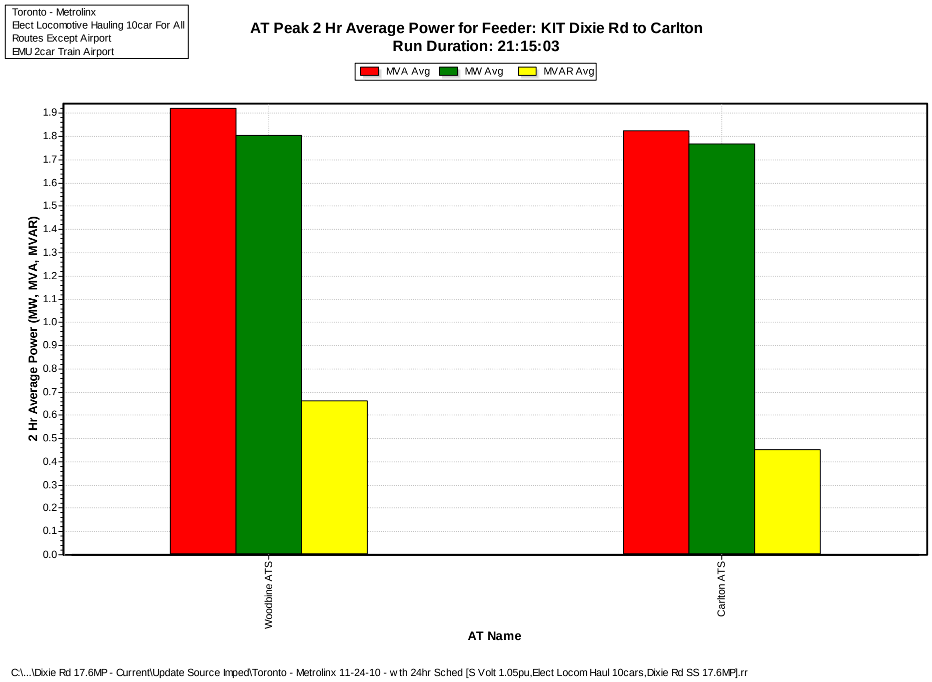
AUTOTRANSFORMER POWER DEMANDS

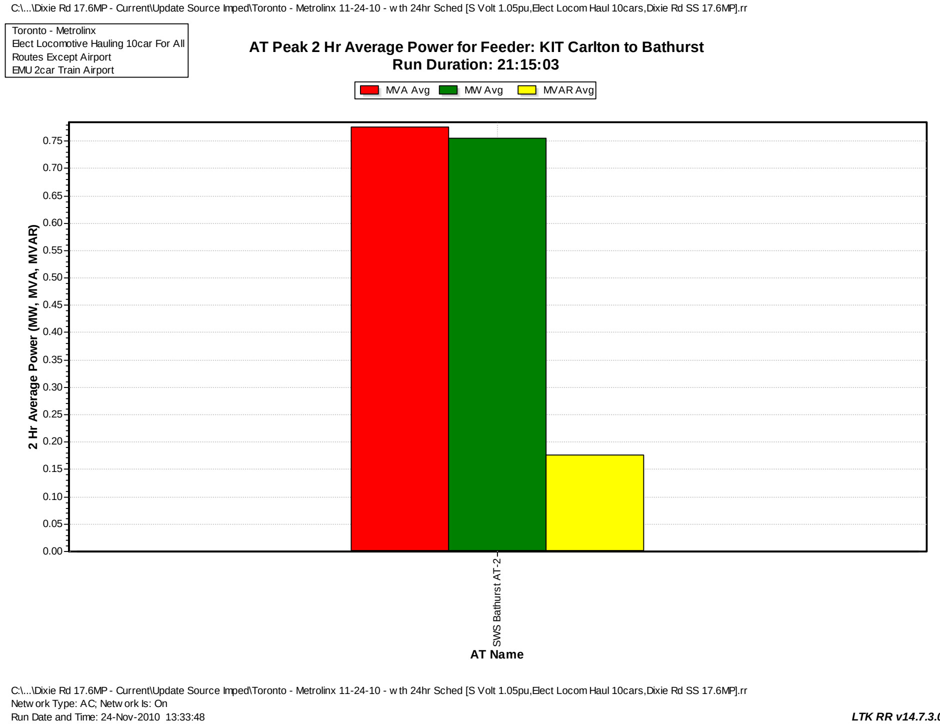


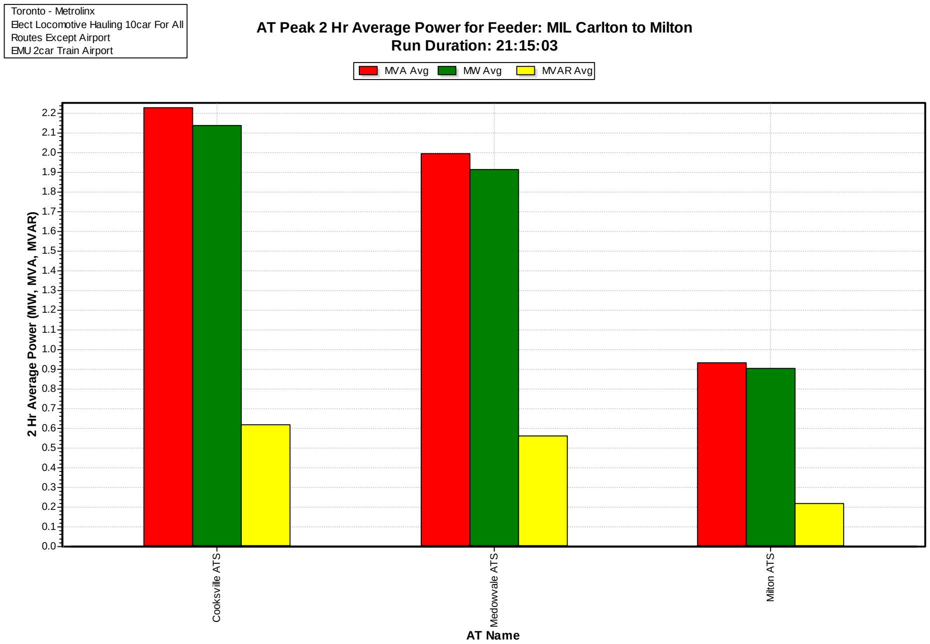



Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: KIT Dixie Rd to Georgetown
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Georgetown AT-2
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All
Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LE Oshawa to Durham
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Durham AT-2
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: KIT Dixie Rd to Carlton
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Woodbine ATS
Carlton ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: KIT Carlton to Bathurst
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Bathurst AT-2
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0



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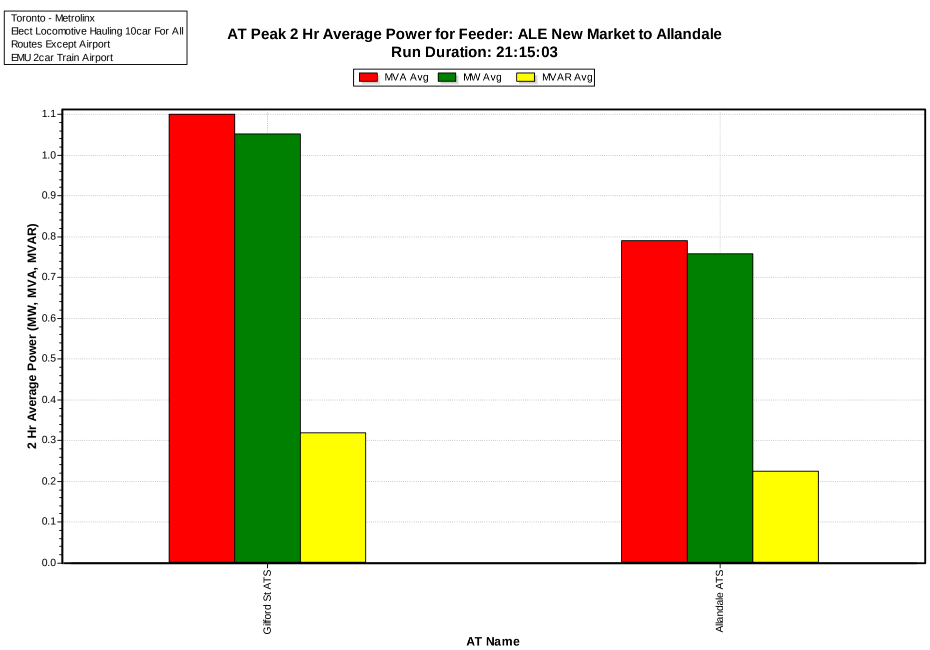
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

LTK RR v14.7.3.0



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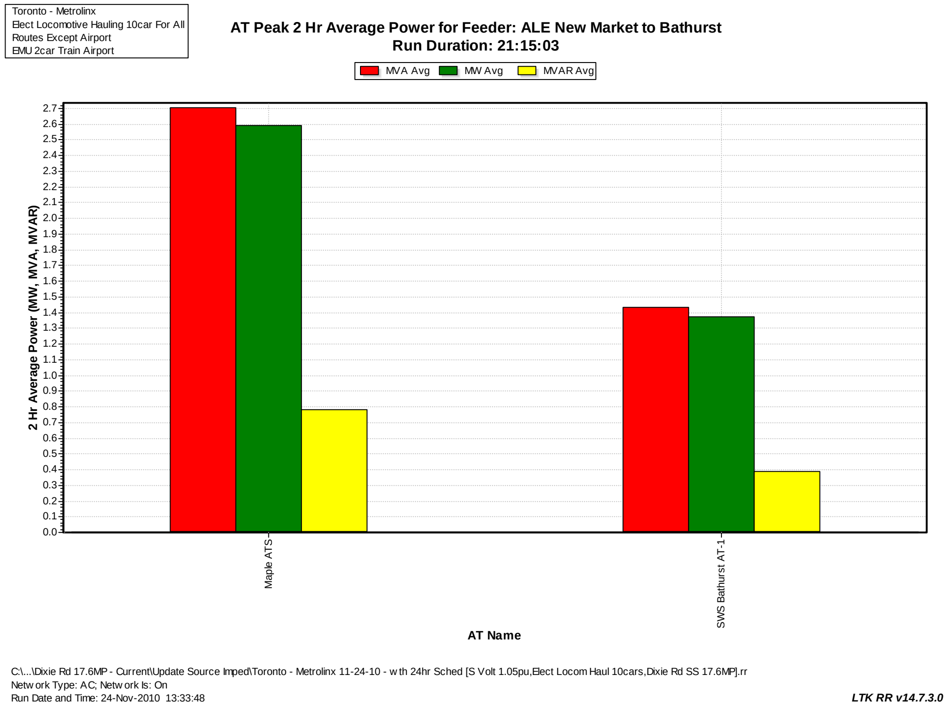
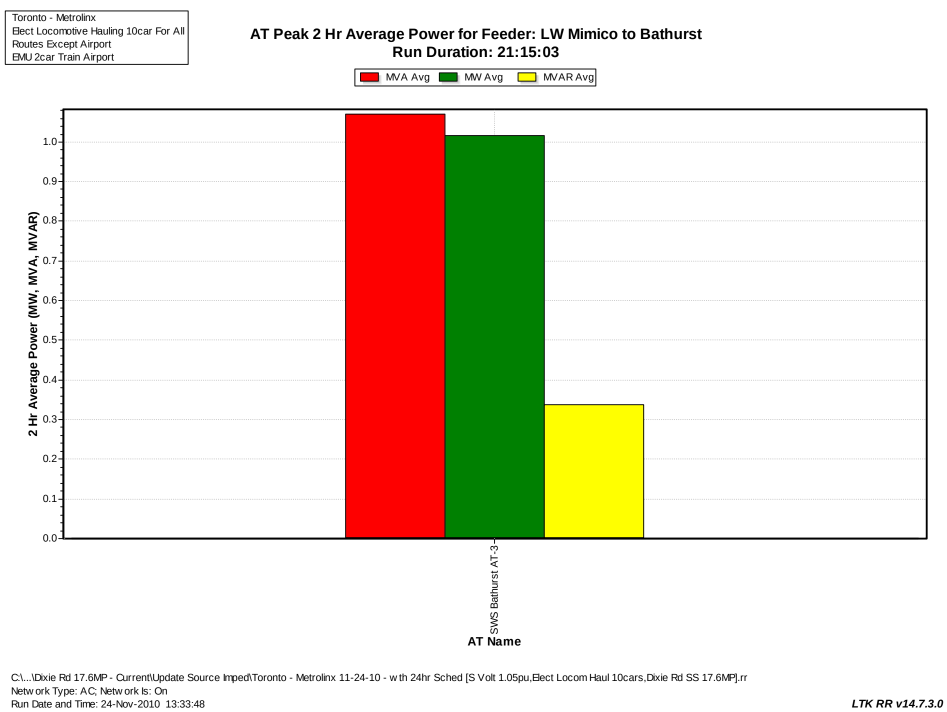
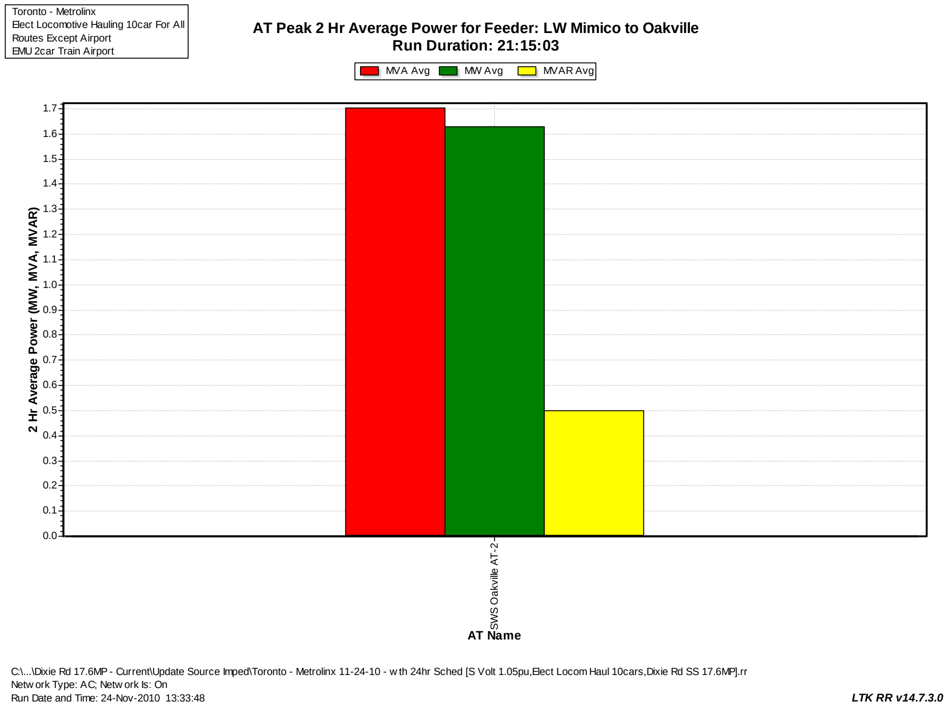
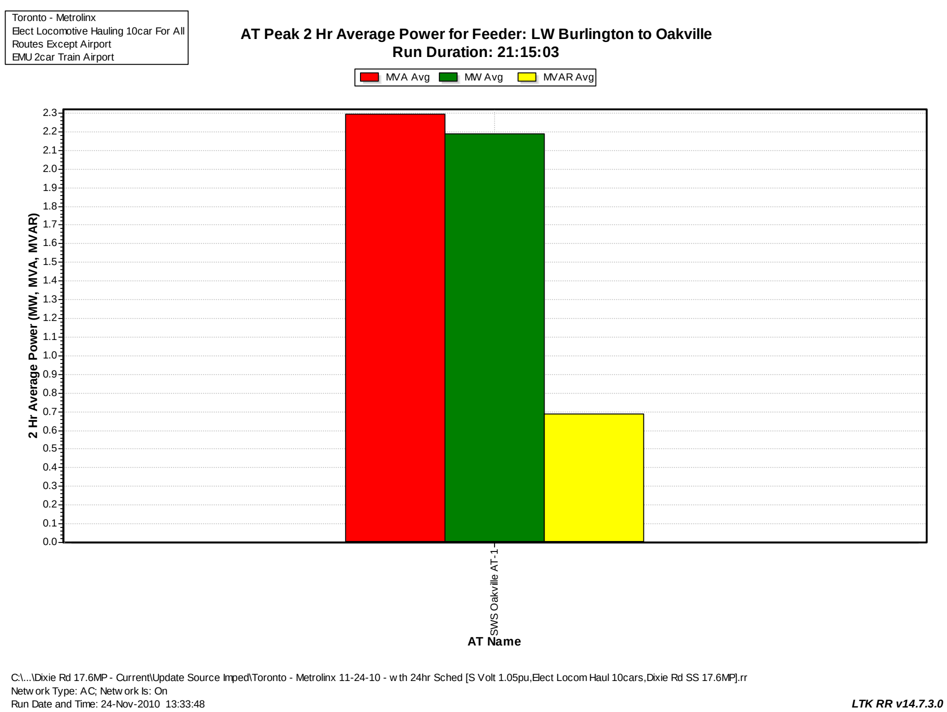
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48

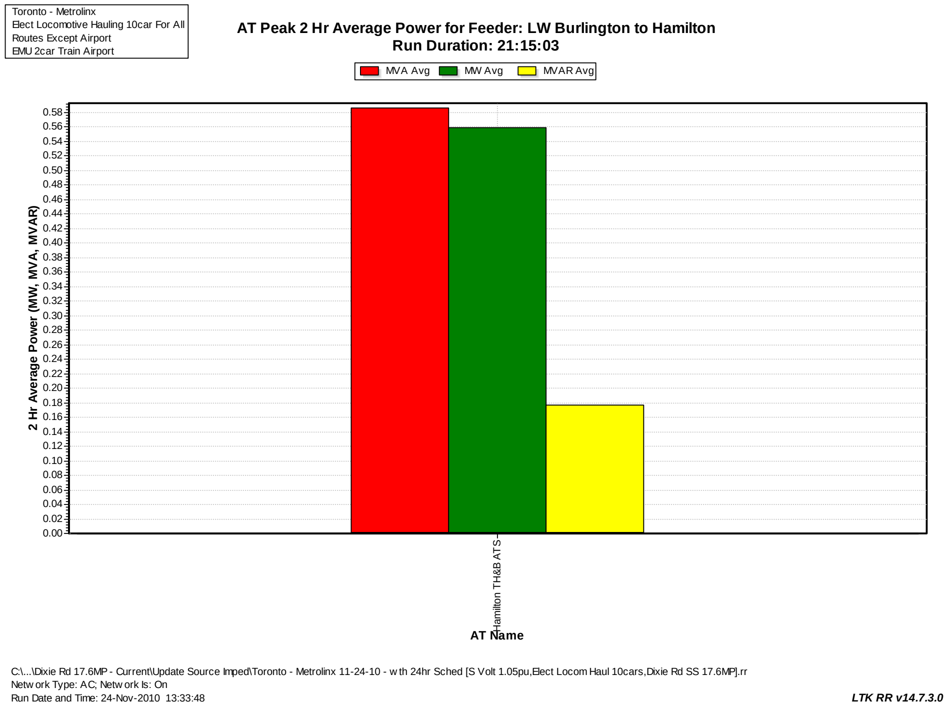
LTK RR v14.7.3.0

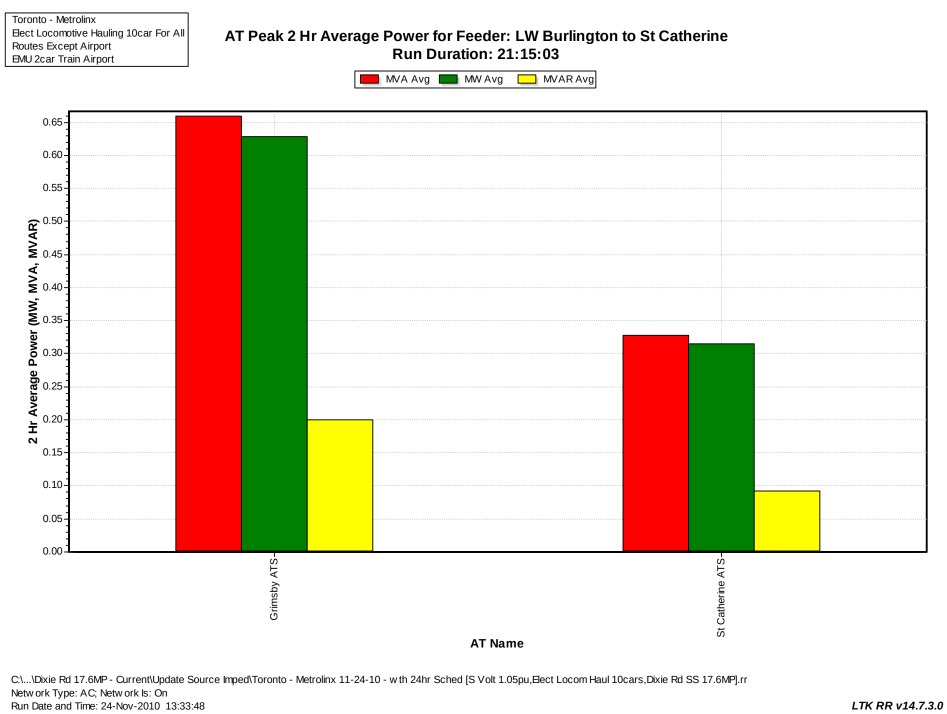

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: ALE New Market to Bathurst
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Maple ATS
SWS Bathurst AT-1
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

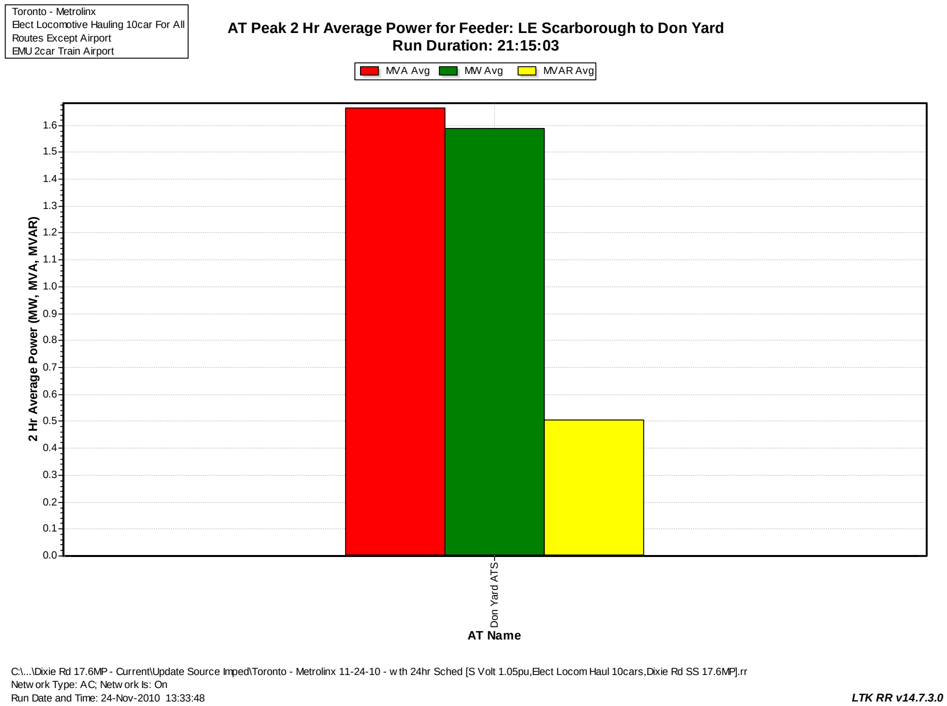

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LW Mimico to Bathurst
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Bathurst AT-3
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

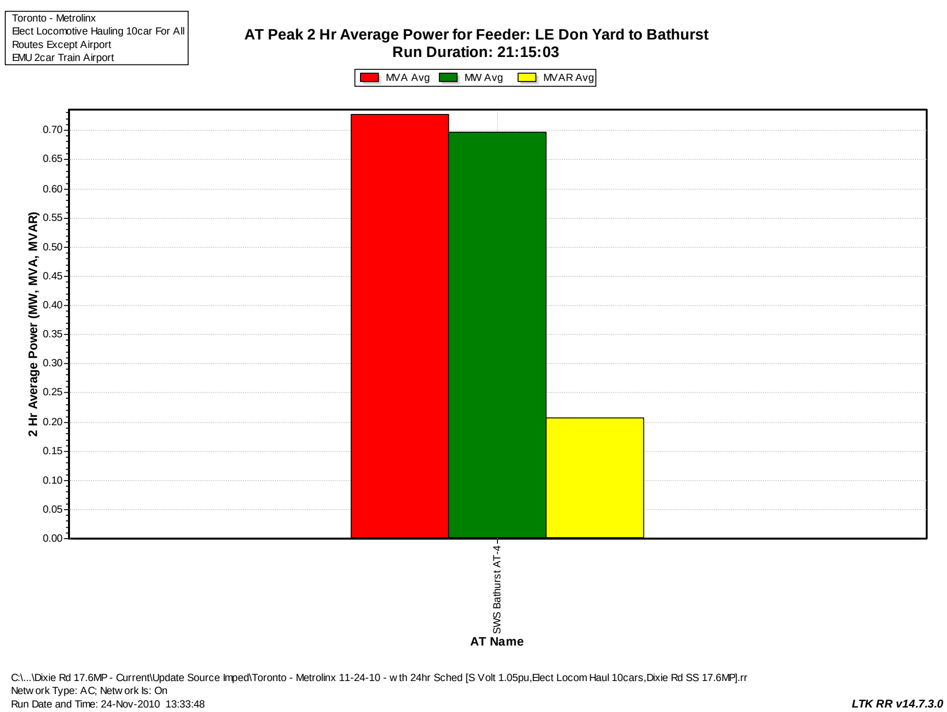

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LW Mimico to Oakville
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Oakville AT-2
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

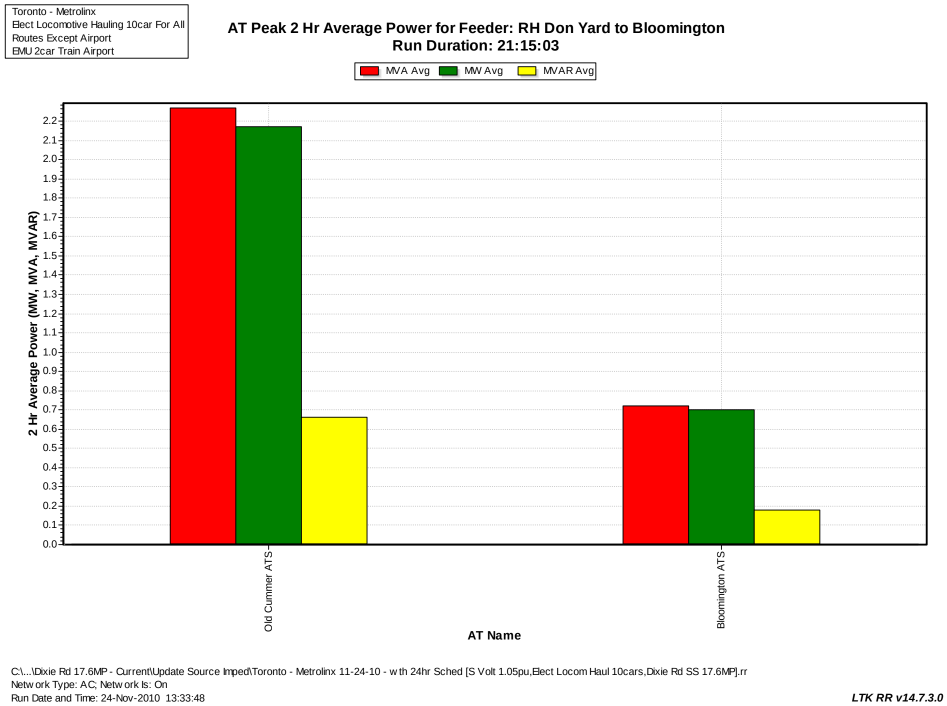

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LW Burlington to Oakville
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
SWS Oakville AT-1
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

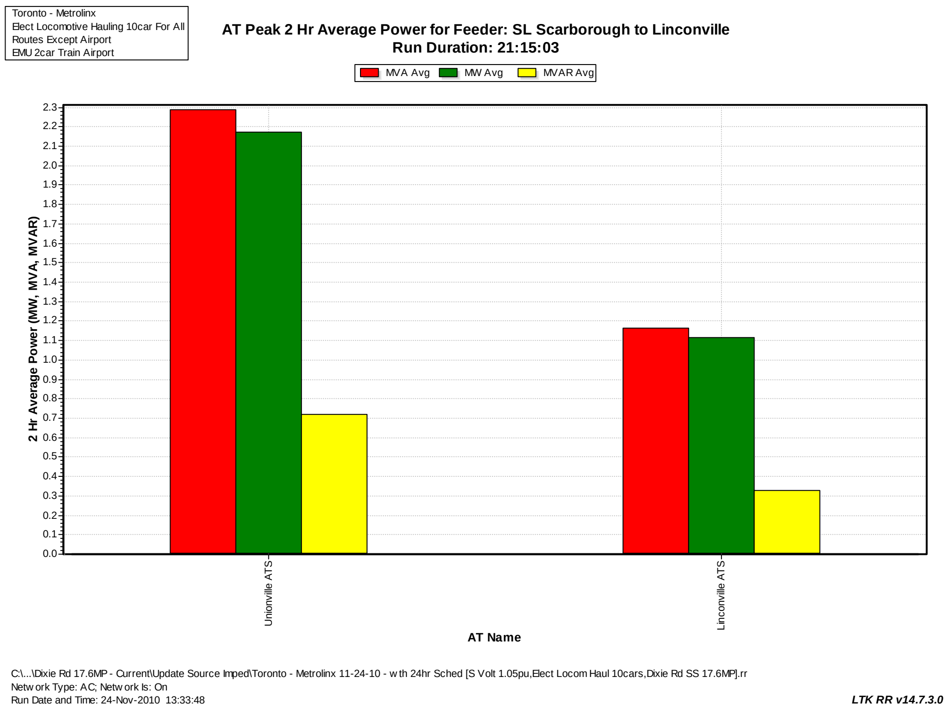

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LW Burlington to Hamilton
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Hamilton TH&B ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

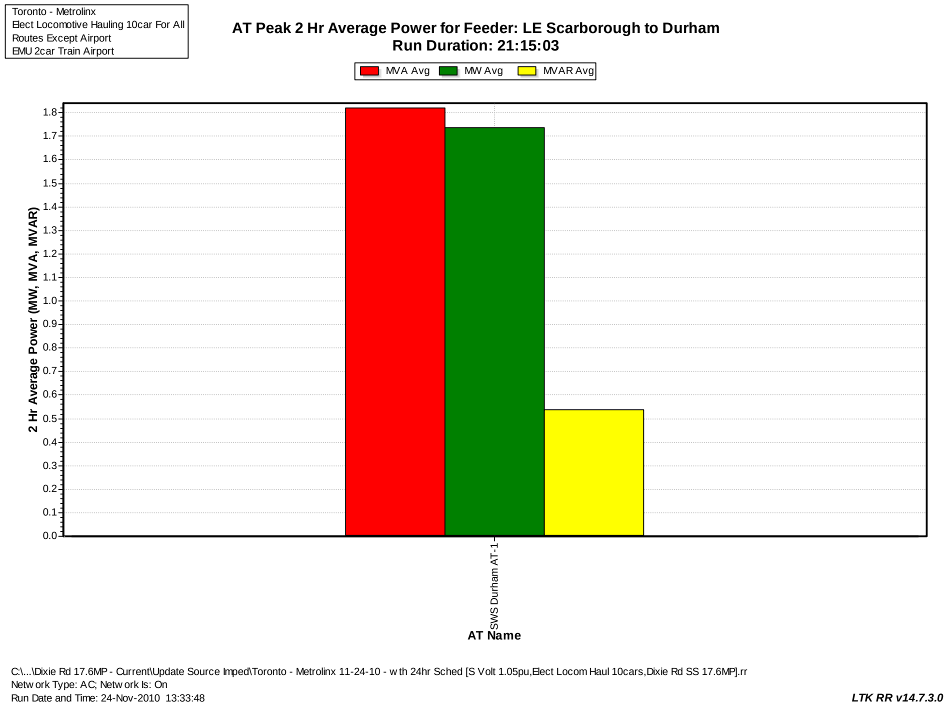

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LW Burlington to St Catherine
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Grimsby ATS
St Catherine ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LE Scarborough to Don Yard
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Don Yard ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

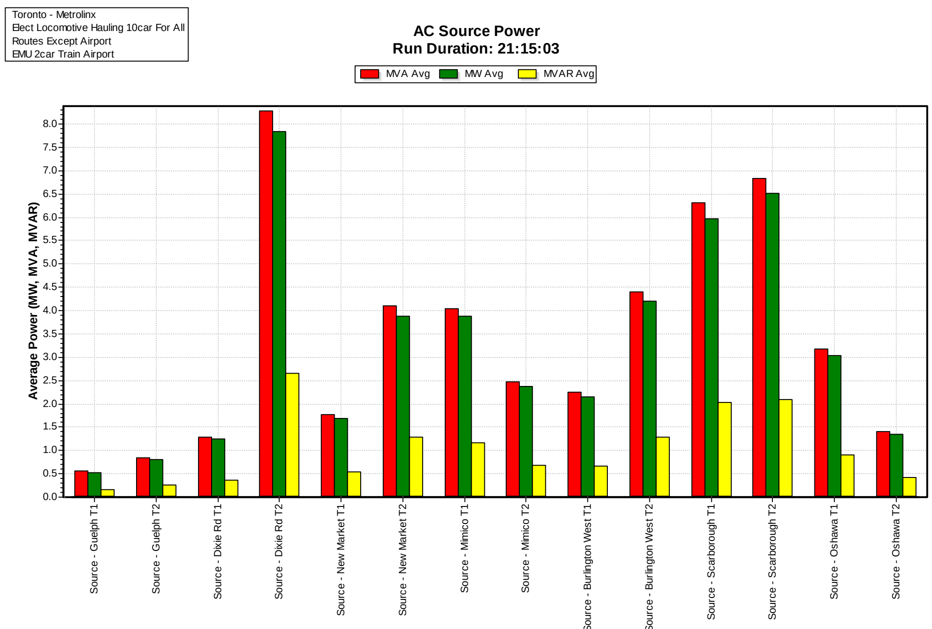

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LE Don Yard to Bathurst
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
SWS Bathurst AT-4
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: RH Don Yard to Bloomington
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Old Cummer ATS
Bloomington ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

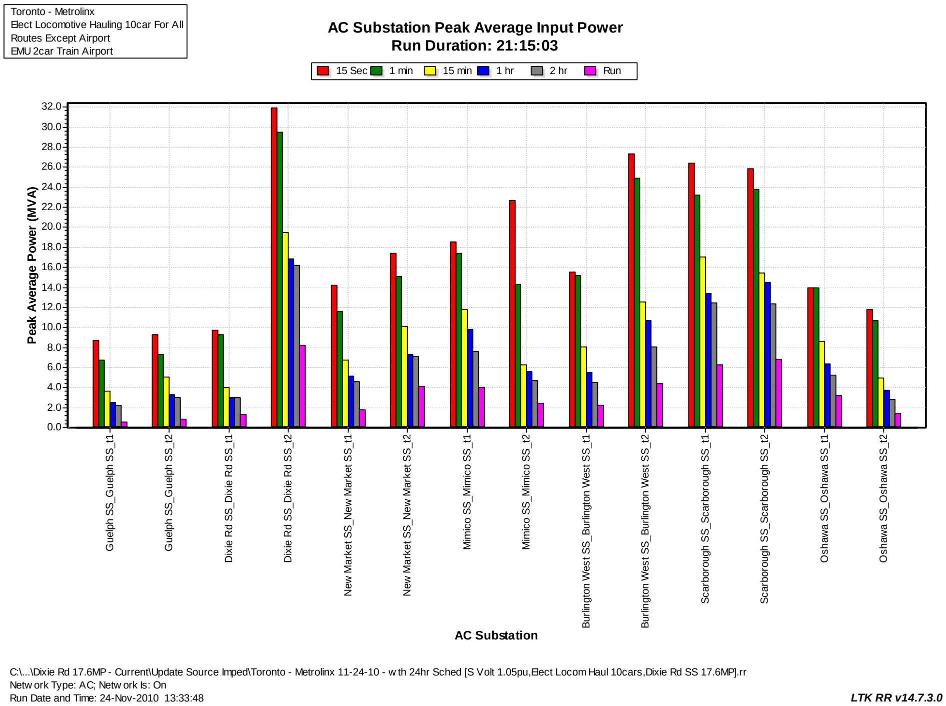

Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: SL Scarborough to Linconville
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
Unionville ATS
Linconville ATS
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0


Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
AT Peak 2 Hr Average Power for Feeder: LE Scarborough to Durham
Run Duration: 21:15:03
MVA Avg
MW Avg
MVAR Avg
2 Hr Average Power (MW, MVA, MVAR)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
SWS Durham AT-1
AT Name
C:\...\Dixie Rd 17.6MP - Current\Update Source Imped\Toronto - Metrolinx 11-24-10 - with 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Network Type: AC; Network Is: On
Run Date and Time: 24-Nov-2010 13:33:48
LTK RR v14.7.3.0

TRACTION POWER SUBSTATION TRANSFORMER POWER DEMANDS



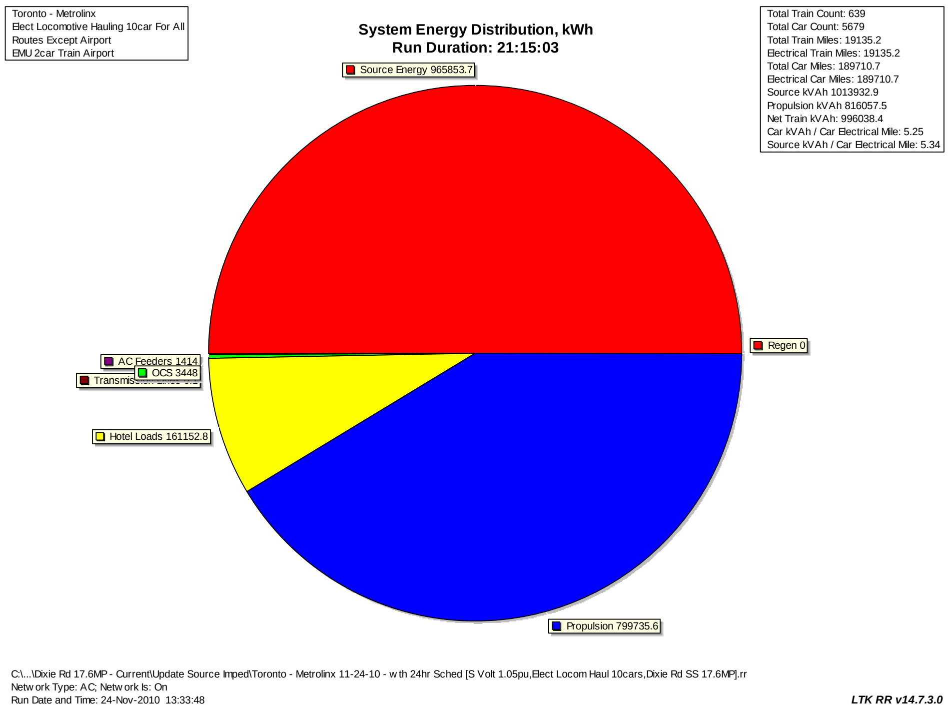
MAXIMUM SUBSTATION TRANSFORMER POWER DEMANDS AVERAGED OVER SEVERAL TIME INTERVALS

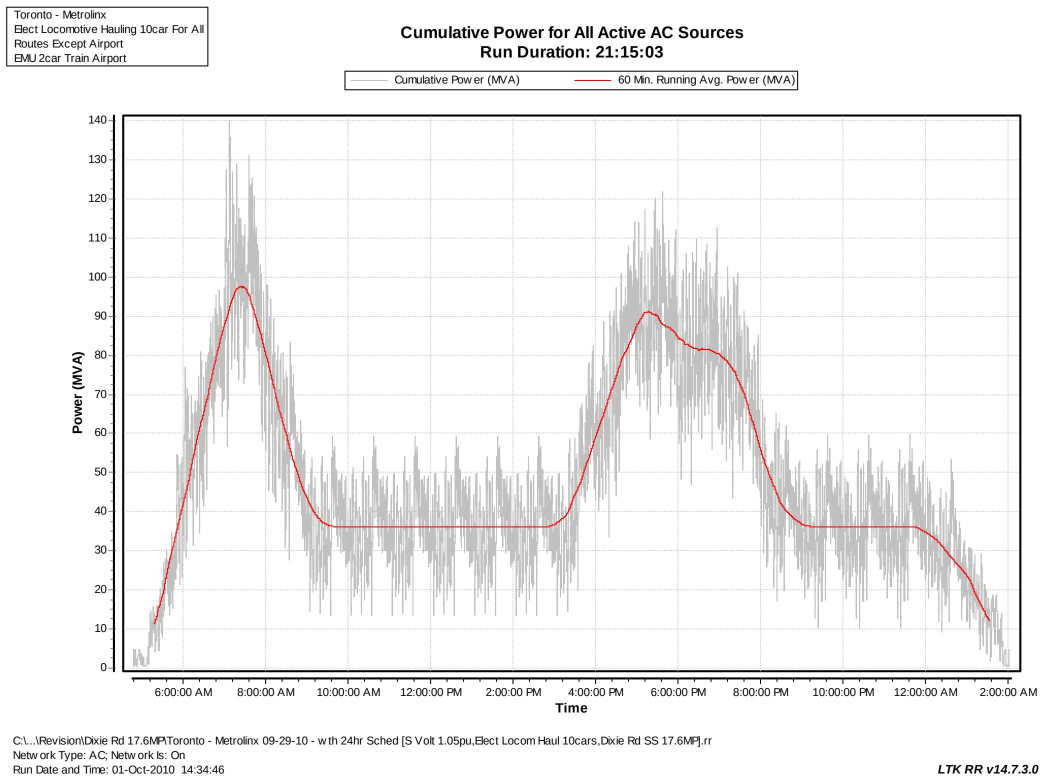


SYSTEM-

WIDE ENERGY CONSUMPTION

24-HOUR POWER DEMAND WITH 1-HOUR RUNNING AVERAGE




Toronto - Metrolinx
Elect Locomotive Hauling 10car For All Routes Except Airport
EMU 2car Train Airport
Cumulative Power for All Active AC Sources
Run Duration: 21:15:03
Cumulative Pow er (MVA)
60 Min. Running Avg. Pow er (MVA)
Power (MVA)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
6:00:00 AM
8:00:00 AM
10:00:00 AM
12:00:00 PM
2:00:00 PM
4:00:00 PM
6:00:00 PM
8:00:00 PM
10:00:00 PM
12:00:00 AM
2:00:00 AM
Time
C:\...\Revision\Dixie Rd 17.6MP\Toronto - Metrolinx 09-29-10 - w th 24hr Sched [S Volt 1.05pu,Elect Locom Haul 10cars,Dixie Rd SS 17.6MP].rr
Netw ork Type: AC; Netw ork Is: On
Run Date and Time: 01-Oct-2010 14:34:46
LTK RR v14.7.3.0