REGIONAL CONNECTOR TRANSIT CORRIDOR PROJECT
Contract No. E0119

Traction Power Load Flow Report (PE)
Task No. 7.3.3 (Deliverable No. 7.3.3.b21)

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December 1, 2011
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Ampere; Amp</td>
</tr>
<tr>
<td>ac</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CB</td>
<td>Cross bond</td>
</tr>
<tr>
<td>ºC</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>CW</td>
<td>Contact Wire</td>
</tr>
<tr>
<td>dc</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DTO</td>
<td>Directional Timing Offset</td>
</tr>
<tr>
<td>DWP</td>
<td>Department of Water and Power</td>
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<tr>
<td>E</td>
<td>East</td>
</tr>
<tr>
<td>EB</td>
<td>Eastbound</td>
</tr>
<tr>
<td>EJ</td>
<td>Equalizing Jumper (of the OCS)</td>
</tr>
<tr>
<td>EOL</td>
<td>End of Line</td>
</tr>
<tr>
<td>F</td>
<td>Fahrenheit</td>
</tr>
<tr>
<td>ft</td>
<td>Foot or Feet</td>
</tr>
<tr>
<td>FRP</td>
<td>Forced Reduced Performance</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>kcmil</td>
<td>Thousand Circular Mils</td>
</tr>
<tr>
<td>kV</td>
<td>Kilovolt</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hours</td>
</tr>
<tr>
<td>LA</td>
<td>Los Angeles</td>
</tr>
<tr>
<td>LACMTA</td>
<td>Los Angeles County Metropolitan Transportation Authority</td>
</tr>
<tr>
<td>lb</td>
<td>Pound</td>
</tr>
<tr>
<td>Max</td>
<td>Maximum</td>
</tr>
<tr>
<td>Metro</td>
<td>Same as LACMTA</td>
</tr>
<tr>
<td>mm:ss</td>
<td>Minutes and seconds</td>
</tr>
<tr>
<td>mph</td>
<td>Miles per hour</td>
</tr>
<tr>
<td>MVA</td>
<td>Mega volt amperes</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt; or, Messenger Wire</td>
</tr>
<tr>
<td>N/A</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>NB</td>
<td>Northbound</td>
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<tr>
<td>NEMA</td>
<td>National Electrical Manufacturer’s Association</td>
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<td>NEC</td>
<td>National Electric Code</td>
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<tr>
<td>NR</td>
<td>Negative Return</td>
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<tr>
<td>OCS</td>
<td>Overhead Contact System</td>
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<td>PE</td>
<td>Preliminary Engineering</td>
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<tr>
<th>Acronym</th>
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<tr>
<td>PL</td>
<td>Performance Level</td>
</tr>
<tr>
<td>RC</td>
<td>Regional Connector</td>
</tr>
<tr>
<td>RMS or rms</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SB</td>
<td>Southbound</td>
</tr>
<tr>
<td>SCW</td>
<td>Single Contact Wire</td>
</tr>
<tr>
<td>SE</td>
<td>Southeast</td>
</tr>
<tr>
<td>sec</td>
<td>Second(s)</td>
</tr>
<tr>
<td>SG</td>
<td>Sectionalizing Gap</td>
</tr>
<tr>
<td>SI</td>
<td>Section Insulator</td>
</tr>
<tr>
<td>sq</td>
<td>Square</td>
</tr>
<tr>
<td>TE</td>
<td>Tractive Effort</td>
</tr>
<tr>
<td>TELS</td>
<td>Traction Electrification Load Simulator</td>
</tr>
<tr>
<td>TES</td>
<td>Traction Electrification System</td>
</tr>
<tr>
<td>TP</td>
<td>Traction Power</td>
</tr>
<tr>
<td>TPSS</td>
<td>Traction Power Substation</td>
</tr>
<tr>
<td>TRU</td>
<td>Transformer-Rectifier Unit</td>
</tr>
<tr>
<td>V</td>
<td>Volt</td>
</tr>
<tr>
<td>vs</td>
<td>Versus</td>
</tr>
<tr>
<td>W</td>
<td>West</td>
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<tr>
<td>WB</td>
<td>Westbound</td>
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EXECUTIVE SUMMARY

Parsons Brinckerhoff has conducted a traction power load flow study for the Regional Connector Transit Corridor of the Los Angeles light rail transit (LRT) system, as part of the preliminary engineering services for the project. The Regional Connector (RC) will link the end of the Blue Line, presently at the 7th St/Metro Center Station in downtown Los Angeles (LA) with the Gold Line, which passes nearby. The study evaluates also the traction power systems of the existing LRT lines adjoining RC, with the RC line assumed as built and in service.

The main objectives of the study are to

a. determine the number, locations and ratings of the traction power (TP) substations needed to support train operations on RC

b. determine the configuration and conductor sizes of the along-track dc distribution system of RC

c. size the major new traction power equipment, such as substations’ dc circuit breakers and dc feeders, and

d. assess the adequacy of the traction power systems of the adjacent existing LRT lines in view of the change in configuration and operating pattern of the overall LRT system in downtown LA.

Initial estimates were that RC would require one or two traction power substations, given its 1.7-mile length. The load flow analysis showed that two substations are needed. The reason is that the system must be designed to support normal train operations with one traction power substation (TPSS) out-of-service. If there was just one TPSS, in a scenario where that substation is out-of-service the load flow simulations showed unacceptably low train voltages on RC, as well as thermal overload on some of the existing positive dc circuits on the Blue Line and Gold Line. Therefore, even though the adjacent existing substations proved to have adequate capacity for such a contingency scenario, the “single TPSS” alternative was discarded in favor of two substations.

For the “two TPSS” alternative the substations were located at passenger stations for convenience and practicality, given that RC is underground. Also, to minimize the need for a supplemental feeder to the overhead contact system (OCS) from train voltage and RMS loading point of view in contingency operations, the substations were located at the two central passenger stations, which are close to each other.

The traction power substations have been labeled RC1 and RC2 for the study, and their locations are provided in Table ES-1. The equipment of each TPSS will be housed in an underground room, as part of the overall passenger station complex.
Table ES-1: Recommended TP Substations for Regional Connector

<table>
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<tr>
<th>TPSS</th>
<th>Location</th>
<th>Description</th>
<th>Primary Voltage</th>
<th>El. Utility</th>
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<td>RC1</td>
<td>31+08</td>
<td>At 2nd/Hope Station. TPSS room near center of platform.</td>
<td>34.5 kV</td>
<td>DWP</td>
</tr>
<tr>
<td>RC2</td>
<td>50+16</td>
<td>At 2nd/Broadway Station. TPSS room at West end of platform.</td>
<td>34.5 kV</td>
<td>DWP</td>
</tr>
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Both substations will feature a single transformer-rectifier unit (TRU) and based on the simulation results will be rated at 2000 kW nominal. The substations should be designed with extra heavy-duty traction overload capability, as defined in the NEMA RI-9 standard.

Concerning utility power, it is recommended that the primary 34.5 kV feeders for RC1 and RC2 be as independent as possible, preferably supplied from different high-voltage transformers. This is desirable to minimize the possibility of a utility power outage taking out of service both substations.

The study includes also dynamic temperature analysis of the overhead contact system (OCS), with climatic conditions as detailed in Section 4.5. It was established that a 500 kcmil copper supplemental conductor to the standard OCS is needed between the two RC substations to avoid overheating the OCS in contingency operations. The extra conductor is in the form of a second messenger wire, and as proposed it extends from the RC/Blue Line interface to the tracks divergence point at the Alameda junction at the other end.

This greater length of the double messenger wire is conservative from OCS temperature viewpoint but is recommended as it provides an extra margin between the minimum train voltages in contingency operations and the 525-volt criteria (minimum voltage of 536 dc with standard OCS vs. 563 V dc with the proposed length of double messenger). The larger voltage margin is desirable as another vehicle in the Metro fleet, the P865 car by Nippon Sharyo, draws higher propulsion current than the P2550 car used in the study. Another reason is the possibility of irregular headway pattern on RC rather than the ideal 2.5/2.5 minute split of the 5-minute headway cycle used in the study, which could result in somewhat lower voltages than those of the present simulation analysis.

The study was performed with 3-car trains, with all trains made up of the P2550 car. On the branch lines linked to RC peak period headway of 5 minutes was used, resulting in 2.5-minute average headway on the trunk line, which includes RC and part of the existing Blue Line.

The study evaluated also the traction electrification system (TES) of the existing LRT lines in the vicinity of Regional Connector. To avoid artificial end-of-line effects, segments of these lines including three substations from the RC interface were included in the model. A schematic diagram of the overall LRT system covered by the simulation model is shown on Figure 1-1 in the Introduction.

The evaluation of the TES of the existing lines showed several problems in contingency operations: minimum train voltages below the 525 V dc criteria level if a TPSS on the Gold Line adjacent to RC is out-of-service; overload on some of the positive feeders of PICO TPSS on the Blue Line, if RC1 is out of service; and a hot spot in the contact wire near the PICO Station.
On the Gold Line, with Red Line Yard TPSS out-of-service the load flow simulations resulted in 499 V dc worst-case minimum train voltage, while if Union TPSS is out-of-service, the worst-case minimum train voltage was 474 V dc. The below-criteria voltages in these scenarios may be due in part to a weakness of the Gold Line, even though for this to be proven the Gold Line would have to be simulated on its own without RC. Another factor is the addition of RC, which not only changes the TES configuration but due to the 2.5-min headways on RC results in higher concentration of trains on the Gold Line near the Alameda junction than would be otherwise at a regular 5-minute headway. As shown later in the report, there are four trains inside the outage zone between the adjacent healthy substations in both of these scenarios.

On the Blue Line, in contingency operations with RC1 out-of-service, the two positive feeders of the PICO TPSS facing RC are at risk of overload in the segment between the TPSS building and the first feeder connection to the contact wire (the feeders continue underground with subsequent tap connections to the contact wire through riser poles). Each of these feeders consists of 2-750 kcmil copper cables, and in such operations the estimated feeder ampacity of 1230 A may be exceeded by up to 19 % (depending on the timing offset between the trains on the NB and SB tracks).

The other problem found in the area is a hot spot in the contact wire of the SB track, just south of the PICO Station. Based on dynamic temperature analysis of the OCS, the mean contact wire temperature over the headway cycle at that location was determined as 88.2 ºC (191 F), which exceeds the 75 ºC limit.

The dc feeder currents, as well as the contact wire temperature are affected by the OCS sectionalizing scheme and feeder connection details in the vicinity of the PICO TPSS. The scheme used in the study, based on available record drawings of the Blue Line, is shown on Figure 3-2. It is desirable that LACMTA confirm the validity of this scheme before remedial measures are considered.

As the identified problems with the existing lines occur outside the Regional Connector boundaries (even though caused by its addition to the downtown LRT network), simulations for corrective measures were deferred till possible solutions have been discussed with Metro.

The study’s approach, system data and criteria, as well as analysis of results are provided in the body of the report. Additional coverage of the main findings is provided in Section 6, Conclusions and Recommendations. The original printouts from the load flow simulation runs can be furnished in a separate volume, if required by Metro.
1.0 INTRODUCTION

Regional Connector (RC) Transit Corridor will be a 1.7-mile long underground LRT line with three passenger stations, linking the end of the Blue Line in downtown Los Angeles with the Gold Line (GL). The GL/RC interface will be at the Alameda St/First St intersection via new track junction, which will allow EB trains on RC to proceed in either direction on the Gold Line. The existing Little Tokyo Station on the Gold Line will be removed as part of the track realignment related to the new junction, and replaced with the nearby 1st/Central Ave Station on the Regional Connector.

Presently the Blue Line (BL) ends at the underground 7th/Metro Center Station on Flower Street, which is also a station for the heavy rail system. The station thus links the light-rail and heavy-rail (subway) systems in downtown LA. The Regional Connector will begin from the end of track behind the 7th/Metro Center Station.

The RC route and track alignment per present preliminary engineering (PE) design are according to the Locally Preferred Alternative (LPA), defined in the Draft Environmental Impact Statement/Environmental Impact Report (Draft EIS/EIR). The PE design of RC is the source of data for the study, in addition to available documentation, such as record drawings, for the existing LRT lines in the vicinity.

The Regional Connector Transit Corridor will connect the Blue Line and future Expo Line (presently in construction) with the Gold Line, enabling passengers to travel

a) from Long Beach (BL) to Pasadena (GL), and

b) from Culver City/Santa Monica (EL) to East Los Angeles (other end of GL)

using a "one seat ride". By providing continuous through service between these lines, plus transfer capability, the Regional Connector is intended to improve the connectivity of the transportation network for the region.

As described, RC will form part of a new LRT trunk line through downtown Los Angeles. This trunk line will extend from the track junction at Flower St/Washington Blvd crossing (Flower Junction), which marks the beginning of the Exposition Line off the Blue Line, to the new junction at Alameda St/First St intersection (Alameda Junction), which interfaces Regional Connector with the Gold Line.

A schematic diagram of the Regional Connector and segments of the adjacent LRT lines included in the traction power simulation model for the study is shown on Figure 1-1.
Presently, there is a gap-breaker station at the 7th/Metro Center Station on the Blue Line, interconnecting electrically the OCS of the two tracks. However, as Metro has indicated that this gap-breaker station will be removed once RC is in service, it has been omitted from the model. Also, even though at the time of the study the Exposition Line is still under construction, for the purposes of the study the modeled segment was assumed as existing.
2.0 APPROACH

2.1 General

Given the complexity of the traction electrification system (TES) comprising multiple trains, traction power substations and a wayside distribution system, and that the trains are both moving and varying their power demand depending on multiple factors, hand calculations or even static utility-type network solutions are not appropriate for the study. Hence, the load flow analysis was performed with software that carries out dynamic simulations of the transit system’s operations, encompassing moving trains and concurrent solutions of the electrical supply network.

The main focus of the TP load flow analysis is to obtain the line voltages at the trains, and the RMS and momentary peak currents in key components of the electrical network, such as transformer-rectifier units, circuit breakers, feeders and other parts of the along-track distribution system.

For evaluation of the capability of the TES to support a given train operations plan the minimum voltages at the trains and the maximum RMS currents in substations and feeders are of main practical interest. They are determined for normal and contingency operations, the latter representing usually equipment out-of-service. Even though in some cases operational disturbances, such as train bunching scenarios and subsequent recovery operations may also be important and be simulated.

If power to the trains is delivered via an overhead contact system (OCS), calculations of the RMS currents in the OCS sections and the temperature of the OCS wires for the simulated operations are also essential, to ensure there is no overheating, especially to the point of annealing of the OCS conductors. For systems with contact (3-rd) rail dc distribution, however, thermal evaluation of the contact rail is usually not needed, as contact rail temperature has not been a problem on mass transit systems.

The potential-to-ground of the running rails due to train operations may also be of interest, usually in relation to dc corrosion issues or system safety. The latter because the rail potentials are transferred to the body of trains to which the public could be exposed at passenger stations. They are also transferred to equipment directly connected to the running rails, such as train control equipment and the substations’ negative buses.

As Metro apparently treats rail potentials as only informational and not a factor in determining the number and locations of the substations, simulations for the running rails to ground potentials were not performed.

2.2 Description of Computer Simulation Program

The following is a brief description of the Traction Electrification Load Simulator (TELS) computer program, which was used to carry out the simulations for the study. The TELS software has been used for design and analysis of many rail transit systems (mostly in the US) for over 25 years, and has been successfully validated by the Bay Area Rapid Transit (BART) District of San Francisco, California, on the BART C-Line through field tests in 1991.
TELs is a time-driven, multi-line simulation model that runs on a personal computer. The program was developed as an engineering tool for design and analysis of dc-electrified transit systems, such as light rail, heavy rail, and commuter train type. It performs dynamic simulation of the train operations while simultaneously solving the electrical network supplying power to the trains. The software allows modeling of all key elements of the transit system and aspects of its operations that have a bearing on the TES performance, incorporating them into one integrated model. These system elements and operational aspects include:

- Horizontal alignment
- Vertical profile
- Signaling system (fixed block, comm. based, or operation on civil speed limits)
- DC distribution system
- Traction power substations
- Primary ac distribution system
- Track configuration
- Transit vehicle
- Train movement dynamics and resistance-to-motion
- Train operations plan

The program models the trains as operating simultaneously and solves the electrical network concurrently with the train movements. Train performance is also voltage sensitive and integrated with the network solution, resulting in a single-stage simulation. This provides for realistic replication of the transit system’s operations, including accounting for the impact of low voltages on the trains’ power demand and performance.

A variety of features and options have been built into the software, for simulation analysis of transit systems with different characteristics and requirements. For example, the program can model also the primary ac distribution system supplying power to the rectifier substations, which is convenient for transit properties employing their own medium-voltage ac distribution. With regards to traction power substations, they can be with diode-based or thyristor-controlled rectifiers, and may also include dc/ac inverter to backfeed excess regenerative braking energy to the utility system. On the transit vehicle side, a number of options are available for modeling the effects of the line voltage on the tractive effort and propulsion current, including automatic forced reduced performance (FRP) if the voltage falls below certain level. This option includes the frequently used in modern vehicles sliding propulsion current limit as a function of the line voltage.

The program can calculate also the temperature of the OCS conductors, such as contact wire and messenger wire, in the course of the simulation. Wire ampacity, thermal time constant and other parameters are determined in accordance with IEEE Standard 738-1993. Detailed ladder-type model of the OCS with separate conductors and multi-point train representation are used in this case, to obtain more accurate results for the currents and wire temperatures.

The voltage to ground of the running rails can be determined as well, if the tracks’ grounding resistances are specified. This is achieved by solving the additional network between running rails and ground (remote earth) characterized by distributed resistances, by replacing them with...
a series of discrete resistances. The rail potentials at passenger platforms, substations and along the track, and stray current levels of the system, can be evaluated with this option.

TELS can also perform statistical runs comprising automated multiple simulations, each with different timing offset between the trains moving in opposite directions. This is a highly desirable feature for establishing the worst-case minimum train voltages and maximum RMS loads on substations and feeders. More details on the statistical runs are provided later in this section.

The program has been validated via field-testing conducted by BART on the BART C-Line in 1991, prior to its use for design of the traction power systems for several BART Extensions built in the early and late 1990s. The field tests included running a test train wired with instrumentation on the C-Line midday during off-peak hours, as well as peak period operations when data was recorded only in substations equipped with monitoring equipment. Comparison of test data with simulations performed subsequently for the same conditions showed that the minimum train voltages from the simulations were within +/- 1 % of those recorded during the field tests; and that the substations’ RMS currents from the simulations were within +/- 3 % of the values from the field tests.

A more detailed description of the simulation software can be provided upon request.

2.3 Statistical Runs

It is important to note that train voltages, as well as currents in the TES, are sensitive to the directional timing offset (DTO) between trains moving in opposite directions on the same line. For instance, at one DTO two trains may meet and start simultaneously from a given station, which imposes a heavy load on the nearby substations and feeders; while at another DTO one train may be departing when the train in the opposite direction is just arriving. The latter condition is the best-case scenario with regards to train voltage and substation loading, as some of the power for the accelerating train will be supplied from regenerative braking energy fed into the dc network by the braking train. Also of note is that the DTO inherent in the train schedule on a given line is often subject to significant changes and frequent random variations.

To ensure that the worst possible minimum voltages and maximum RMS currents in the TES components due to DTO variations are properly accounted for, the load flow study used statistical runs, which are a built-in feature of the simulation program. A statistical run in essence comprises multiple dynamic simulations with the same headway and consist size but with different DTO, so that the set of “simple” simulations covers all possible timing offsets and associated loads between trains moving in opposite directions. This allows a statistical run to discover the worst possible minimum train voltage for operations with a given headway, as well as the maximum RMS and peak currents in the substations. In contrast to the statistical run, a simple run is a dynamic simulation with one DTO, as inherent in a fixed train dispatch schedule from the terminal stations of a line.

The statistical run results include also the probability of the train voltage falling below a certain level depending on the DTO. The probability is calculated as the ratio of the number of simple runs in which the minimum voltage is below the specified level, to the total number of simple runs comprising the statistical run.

The minimum voltages typically result from two or more trains drawing maximum, or near maximum power while generally at the same locale. This may involve simultaneous train
accelerations from the same or adjacent stations, trains drawing high power due to movement on uphill gradients, or trains re-accelerating following change in the speed limit. A statistical run with properly selected parameters ensures that the most adverse of such combinations are taken into account. The same applies for the maximum RMS currents, where the circumstances and DTO leading to the highest RMS load in a particular system element, like TPSS, dc feeder or line section, are difficult or even impossible to determine in advance by inspection or simple rationale.

With respect to the train voltage, the output from a statistical run provides the so-called absolute minimum voltage, which is the lowest recorded voltage from operations with all directional timing offsets specified. If the range of DTO variation matches the headway, and the DTO increment between successive simple simulations is sufficiently small, then the absolute minimum voltage is the lowest possible for the headway and TES configuration. In addition, the probability of the minimum train voltage (as function of the DTO) to fall below several user-defined voltage levels is also calculated. The probability calculations assume uniform DTO distribution, meaning that all timing offsets within the specified range are considered equally likely. This probability is essentially the ratio of the number of simple runs for which the minimum voltage is below the given threshold, to the total number of simple simulations for the statistical run.

With respect to the RMS currents through transformer-rectifier units and in feeder circuits, the output of the statistical run provides the maximum and minimum values, which define the possible range of variation of the RMS current for the given headway pattern and system configuration. The variations of RMS currents with the DTO are due to changes in the current form factor in the circuit, and of the receptivity of the line to regenerative braking.

A key difference between computerized simulations and actual train operations should also be highlighted. In the real system, if the line voltage falls below the minimum operational voltage of the vehicle, the car's propulsion is cut off by the under-voltage protection and the car loses power. In a simulation model, however, all trains are always connected to the TES and the magnitude of an excursion of the train voltage below the minimum operational is a gauge for the severity of the under-voltage condition. Therefore, results showing train voltages below the minimum acceptable are only hypothetical.

For the Regional Connector the statistical runs were made with the following parameters:

- Number of simple simulations per statistical run = 100
- DTO increment between simple simulations = 3 sec
- Duration of a simple simulation = 5:00 minutes
- Time interval between successive network solutions & train status updates = 1 sec

As the peak period headway on the lines connected to RC is 5 minutes and the system's loading pattern repeats itself during each headway cycle (assuming no operational disturbances), there is no need for the simple simulations to last more than 5 minutes.
3.0 SYSTEM DATA AND ASSUMPTIONS

3.1 Transit Vehicle

There are several types of light-rail vehicles in operation on the Metro LRT lines: P865 and P2020 by Nippon Sharyo, P2000 by Siemens, and P2550 by AnsaldoBreda. There is also a new/future vehicle in the process of procurement, known as the P3010. As agreed with Metro, the load flow study was performed with the P2550 car. It is a 6-axle, articulated LRV with main parameters, as used in the study, summarized in Table 3-1.

Table 3-1: P2550 Car, Key Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>90 ft</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>100 sq. ft.</td>
</tr>
<tr>
<td>AW0 weight (empty car)</td>
<td>103,265 lbs</td>
</tr>
<tr>
<td>AW2 weight (fully seated + 4 standees per sq. meter)</td>
<td>128,765 lbs</td>
</tr>
<tr>
<td></td>
<td>(AW0 + 170 people x 150 lb/person)</td>
</tr>
<tr>
<td>Rotational mass</td>
<td>10% of AW0 (assumed)</td>
</tr>
<tr>
<td>Initial acceleration rate</td>
<td>3.0 mph/sec</td>
</tr>
<tr>
<td>Maximum propulsion current</td>
<td>1185 A dc</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>40 kW (assumed)</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>750 V dc</td>
</tr>
<tr>
<td>Weak Power Limitation</td>
<td>At voltage in the 650–750 V dc range</td>
</tr>
<tr>
<td>Strong Power Limitation</td>
<td>At Voltage below 650 V dc</td>
</tr>
<tr>
<td>Minimum operating voltage</td>
<td>525 V dc</td>
</tr>
<tr>
<td>Note: This is a value per Metro Rail Design Criteria. Not clear from the available tech documentation what the car’s actual minimum voltage is.</td>
<td></td>
</tr>
<tr>
<td>Service braking rate (average)</td>
<td>2.2 mph/sec</td>
</tr>
<tr>
<td>Regenerative braking</td>
<td>Yes</td>
</tr>
<tr>
<td>Voltage Ceiling in Regenerative Braking Mode</td>
<td>870 V dc</td>
</tr>
<tr>
<td>Electrical Braking Effort (in the 0 – 55 mph range)</td>
<td>0 lb at 0–3 mph</td>
</tr>
<tr>
<td></td>
<td>15300 lb at 5 mph</td>
</tr>
<tr>
<td></td>
<td>15300 lb at 55 mph</td>
</tr>
<tr>
<td>Resistance to Motion</td>
<td>Per Davis formula with standard coefficients (assumed).</td>
</tr>
</tbody>
</table>
Based on AnsaldoBreda’s design submittals, these are voltages at the input of the traction inverter. Therefore, correction is required to obtain the corresponding voltage at the pantograph, by accounting for the voltage drop in the line reactor (the latter volt drop referred to also as dc link voltage).

As noted in Table 3-1, the P2550 car has two zones of reduced performance. In the 650-750 V dc range there is a weak power limitation, where the maximum propulsion current is maintained constant at the same level as at the nominal 750 V dc. This results in linear reduction of the car’s output power with the falling OCS voltage.

The zone below 650 V dc features strong power limitation, where the propulsion current is reduced with the falling voltage. This is also referred to as forced reduced performance (FRP). Per AnsaldoBreda documents, the power reduction here is calculated by the following formula:

\[
\text{PowerLimit} = \left(\frac{\text{MaxPower}}{750}\right) \times [650/\left(650-250\right)] \times (U_f - 250)
\]

where \( U_f \) is the voltage at the filter capacitor (inverter input).

It can be shown that for voltage levels of interest to the study, which is voltages above 525 V dc, Formula 1 above can be well approximated with linear reduction of the propulsion current limit by 1.41 Amp/volt/car. This is the way the strong power reduction mode was simulated.

The tractive effort (TE) vs. Speed curve of the car at nominal voltage and AW2 weight is shown on Figure 3-1 below.

Figure 3-1: P2550 Car, Ttractive Effort vs. Speed
The TP simulation model requires also data on the car’s efficiency, to account for power losses in the propulsion system and gears. For the P2550, the efficiency except for the losses in the line reactors was calculated from propulsion current and tractive effort data at nominal filter voltage. Adding estimated losses in the line reactors resulted in overall car efficiency of 84% for the 20-50 mph speed range. This compares favorably with known efficiency data for other vehicles.

Auxiliary power was assumed as continuous 40 kW/car. Its voltage regulation, considering that the aux power inverter tries to maintain steady secondary ac voltage, is of the constant power type.

The maximum propulsion current for the P2550 occurs when the car is accelerating from 20 to 50 mph, and it remains constant in this speed range due to the TE following a constant power curve. As the maximum propulsion current is maintained down to 650 V dc while the auxiliary current increases at lower voltage, the maximum total current will be drawn at 650 V dc, and will be about 1245 A (1185 A for propulsion and 60 A auxiliary). For a 3-car train as used in the study, the maximum train current then is 1245*3 = 3735 A dc.

The P2550 car has regenerative braking capability, which was accounted for in the simulation model. If the dc line is not receptive, depending on the locations and status of other trains in the area, the braking energy will be dissipated in the braking resistors. The maximum regenerative braking voltage, per available technical data, is limited to 870 V dc.

3.2 Alignment and Speed Limits

The alignment data for the model includes passenger stations, speed limits, horizontal curves and vertical profile. The RC alignment data used is per Preliminary Engineering Track Alignment Plan and Profile drawings of September 2011. As shown on Figure 1-1, the TP model includes also parts of several existing LRT lines, the alignment data for which was obtained from as-built Plan and Profile drawings.

The studied LRT lines have six different civil stationing systems (two on the Blue Line, one on the Expo Line, one on RC, and two on the Gold Line). For the model, the Blue Line, Regional Connector and Eastside portion of the Gold Line were defined as a main line, while the Expo Line and Pasadena side of the Gold Line were treated as branch lines. For the main line uniform stationing was used derived from the RC stationing by adding 1000+00. The original civil stationing was retained for the Expo Line. For the Pasadena branch of the Gold Line, a new stationing system was used for convenience, starting from zero at the Alameda junction.

As the model uses numerical track designations, the Eastbound (EB) or R track of the Regional Connector was selected as Track 1, extending as such through the entire main line. The Westbound (WB) track, or the L track of Regional Connector, is Track 2. For the branch lines, the track with normal direction away from the main line it Track 1.

RC will feature automatic train control with cab signaling, based on a fixed block system. Preliminary train control block design for RC was available at the time of building of the model, so it was used for the study. As no operational disturbances were simulated, and train from the outer lines were assumed to arrive on schedule to result in nearly uniform 2.5-minute headway on RC, only the normal block speeds were needed and used. With regards to the maximum achievable speed it was assumed that it matches the nominal speed of the block without offset.
For example, if the speed code is 45 mph the train’s maximum speed, if achieved, is also 45 mph.

Outside RC, the trains were run on civil speed limits, or legal speed restrictions in case of street running, as appropriate.

Concerning station dwell, 30 seconds measured wheel-stop to wheel-move was used on the Regional Connector Stations, and 7th St/ Metro Center Station. For the remaining stations 20-sec dwell time was assumed.

Horizontal curves with radius ≤ 1000 feet were included in the model to account for the increased train resistance-to-motion due to track curvature.

As noted, RC is mostly in an underground tunnel, as a continuation of the Blue Line tunnel in downtown. The overall tunnel length, existing segment and new, is about 2.2 miles. The RC tunnel diameter will be 18’-10”, with corresponding cross-sectional area of the clear space estimated at approximately 245 sq. ft. Given that the frontal area of the car is about 100 sq. ft. this results in 100/245 = 0.41 blockage ratio. Experience on other projects has shown that if the tunnel’s blockage ratio is less than 0.5, at typical station spacing (or vent zone length) the air drag on the train is close to the one in open air. Therefore, the air drag of open air per Davis formula was used in the TP simulations for trains inside the tunnel.

The vertical profile of each line, comprising segments with constant grades and vertical curves was included in the model.

### 3.3 Traction Power Substations

The traction power substations for RC will be equipped with one transformer-rectifier unit (TRU), utilizing a diode-based rectifier. They will feature extra heavy-duty traction overload capability per NEMA RI-9, which means that a TPSS can support 160% RMS loading for up to 2 hours, and 450% peak current for up to 15 seconds. All existing substations have been designed with the same overload capability.

Primary utility voltage on RC will be 34.5 kV nominal, supplied by the Department of Water and Power (DWP). At the time of the study no utility data was available on the strength of the medium-voltage grid at the TPSS interface points, and on typical voltage levels maintained in the area. As an equivalent Thevenin circuit was used to represent the utility system at each TPSS, the following utility data was assumed for the purposes of the study:

- 3-phase fault level: 225 MVA
- X/R ratio: 3 for both voltage levels
- No voltage bias on the primary TPSS side. This means 0% deviation from the nominal 34.5 kV with the TPSS at no-load.

Per Metro Rail Design Criteria the nominal voltage (at 100% load) on the substation’s dc bus is 750 V dc, assuming nominal 34.5 kV from the utility system on the primary side.

Concerning voltage regulation of the TRU, linear 4.5 % regulation was used for all substations, existing and new. With 750 V dc nominal, the corresponding light (1%) load dc voltage of the TPSS is 784 V dc (at nominal primary ac voltage).
3.4 Positive Distribution System

For Metro’s LRT lines the positive distribution system consists of overhead contact system (OCS) and positive feeders. Most of the OCS is a simple catenary with 1-350 kcmil contact wire (CW) and 1-500 kcmil messenger wire (MW), referred to as standard OCS. Both CW and MW are made of copper. There are also areas of single contact wire (SCW) reinforced with parallel underground feeder, which for the system included in the model is the at-grade portion of the Blue Line. The positive feeders connect the OCS to the dc switchgear in the traction power substations. In case of a SCW, there is also parallel underground feeder connected to the contact wire through cable risers. For the Blue Line, the parallel feeder has been sized at 2-750 kcmil copper cables per track.

On the Regional Connector the OCS will be low-profile simple catenary with standard wire sizes: 350 kcmil copper CW and 500 kcmil copper MW. One of the tasks of the study was to determine if the standard OCS would be adequate from thermal capacity point of view, given the operations of 3-car trains at relatively short 2.5-minute headway. The issue of supplemental conductor to the standard OCS is addressed in Section 5 of the report.

For the purpose of the study, the contact wire on all lines was assumed as worn by 25%, which reduces its cross-sectional area from 350 kcmil to 262 kcmil.

As the electrical resistance, apart from the material and size of the conductor depends also on its temperature, the circuit resistances of the positive distribution system were calculated at the following assumed average conductor temperatures:

- 60 ºC for OCS in open air
- 45 ºC for OCS in tunnels (downtown and on part of Eastside)
- 75 ºC for feeders in underground raceways

The positive distribution circuits of the two tracks of the Metro’s LRT lines are electrically separate, except at the traction power substations where they are tied through the positive feeders and TPSS positive bus. The positive circuits are also sectionalized in the vicinity of each TPSS, which results in four positive dc feeders per TPSS (assuming the substation is connected to only one line). For the model, there are two locations where the OCS sectionalizing requires special attention, given the purpose of the study. One is the area of the PICO substation on the Blue Line, the other the Alameda junction, which interfaces Regional Connector with the Gold Line.

Figure 3-2 shows how the positive distribution system was modeled in the vicinity of the PICO substation and PICO passenger station. The schematic diagram and related details, such as the locations of the section insulators and cable risers, were obtained from available Blue Line record drawings.
As seen from Figure 3-2, the OCS (single contact wire in this case) is sectionalized via section insulators located about 600 ft to the south of PICO Station. The contact wire (CW) of each track is reinforced by parallel underground feeder connected to contact wire via riser cables at locations as indicated. Pull box PB-1 through which all positive feeders from the TPSS apparently pass, is located on the SE corner of the Flower St/Pico Blvd intersection. All locations are shown in the civil stationing system of the Blue Line.

The OCS sectionalizing of the Alameda junction in normal operations, and positive feeder connections of the adjacent traction power substations are shown on Figure 3-3. This is a simplified schematic showing the system in this area as modeled functionally, without unnecessary for the study details, such as the means of isolation of the lines at the junction (additional section insulators with normally closed bypass switches), and without crossovers.
The software assigns automatic labels of the substations’ positive dc feeders in accordance with the following convention, which for convenience is used also in the report:

<table>
<thead>
<tr>
<th>Positive Feeder</th>
<th>To Track</th>
<th>Side of Sectionalizing Gap (SG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Trains moving towards SG</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Trains moving away from SG</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Trains moving away from SG</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>Trains moving towards SG</td>
</tr>
</tbody>
</table>

The dc feeders supplying the Alameda junction have been labeled per above convention (numbers at the connections to the OCS). As seen, each OCS segment is fed from two of the three substations in the area. For instance, feeders RC2-3 and TPS01-1 supply the OCS of Track 1 on RC and Gold Line segment from the junction towards East LA.

Metro uses insulated 750 kcmil copper cables for the dc feeders on the LRT lines, and the same type of cable will be used on RC. The positive feeders of the existing substations on the Blue Line, Exposition Line and Pasadena segment of the Gold Line have been all sized 2-750 kcmil, while on the Eastside segment of the Gold Line they are 3-750 kcmil. For the substations on Regional Connector, the positive feeders are sized in Section 5 of the report based on the maximum RMS currents in the respective circuits from the study and estimated cable ampacity.
The locations of TPSS sectionalizing gaps and feeder connection points to the OCS for the existing system were obtained from record drawings, and feeder lengths estimated from the locations of the feeder poles relative to the TPSS site.

For Regional Connector the OCS sectionalizing at the proposed two substations RC1 and RC2 is shown schematically on Figure 3-4. The feeder lengths were estimated considering the location of the TPSS room in the respective passenger station complex and likely feeder connection points.

As indicated, the sectionalizing for TPSS RC1 at the 2nd/Hope Station is on the outgoing sides of the platform, which is per Metro criteria. For TPSS RC2 at the 2nd/Broadway Station the sectionalizing is at the double crossover east of the station, as it is desirable for greater operational flexibility and reliability in case of single tracking. With the TPSS room near the West end of the platform, this results in feeders RC2-3 and RC2-4 being about 600 ft long.

The section insulators used to create TPSS sectionalizing gaps have normally open bypass disconnect switches, which are not shown on Figure 3-4 for clarity.

3.5 Negative Distribution System

The negative side of the dc distribution system serves to return the currents from the trains to the substations. It consists of the running rails, cross bonds and the negative feeders. The latter connect the running rails to the negative buses of the traction power substations.

The running rails on the existing LRT lines are RE 115 type, weighing 115 lb/yard, and the same rail will be used on RC. According to data in the technical literature, the electrical dc resistance of this rail is 0.0092 ohms/1000ft at 20 °C. For the study, the resistance was corrected for temperature, assuming running rail temperature of 42 °C in the open, and 28 °C inside tunnel segments. As already noted, the model includes two such tunnel segments: in downtown LA and on a portion of the Gold Line’s Eastside Extension.
The two tracks will be cross-bonded on RC for current equalization purposes, which tends to reduce the voltage drop along the negative return path, as well as the related track to ground potentials and stray current levels.

Both running rails of each track will be (are) utilized for traction power negative return, excepting possibly short stretches at track interlockings where single-rail return may be used, which has been ignored as negligible.

Also of note is that the overall negative return system - existing lines and RC – will be floating relative to earth, with no intentional connections to ground. Therefore, all currents from the trains return to the supplying traction power substations through the running rails, negligible (from TP return point of view) stray currents excepted.

### 3.6 Train Operations Plan

The simulated operations were based on Metro’s plan for the peak period service once the Regional Connector has been added to the system. The study used the following operating plan elements:

- **Vehicle:** P2550
- **Train Consist:** 3 cars
- **Headways:** 2.5 minutes average on the trunk line from the Flower Junction to the Alameda Junction. The trunk line is about 2.7 miles long and includes the Regional Connector and a small part of the Blue Line (see Figure 1-1). At the two junctions 50/50 split is assumed, resulting in 5-minute headway on the Exposition Line and Blue Line in the south, and similar 5-minute headway beyond Alameda junction on the Eastside and Pasadena parts of the Gold Line.
- **Train Passenger Loading:** AW2 uniform for all trains
- **Train Performance Level:** PL1 (maximum performance)
- **Station Dwell:** 30 seconds at the 7th/Flower, 2nd/Hope, 2nd/Broadway and 1st/Central Stations, and 20 seconds at all others.
- **Peak Period Duration:** not exceeding 2 hours, preceded and followed by a transition period to off-peak operations

Given the long branch-lines (including street running) converging into the two junctions of the trunk line, trains probably won’t arrive exactly on time to split the 5-minute headway on the branches into uniform 2.5-minute headway on the trunk line. Most likely the headway on the trunk line, including Regional Connector, will be irregular to some degree, the 2.5 minutes being just an average value (derived from 24 trains per direction per hour). Occasional train bunching, where two trains follow very close one behind the other, as permitted by the signaling system, also can’t be ruled out.

For the purposes of the study, however, is was assumed that the trains from the outlying branch lines arrive at the junctions exactly on time to result in uniform (or almost uniform) 2.5 minute
headway on the trunk line, and the train dispatch schedules from the end-of-line stations in the model were set up accordingly.
4.0 TRACTION POWER CRITERIA

This section of the report covers the TES performance criteria as used in the load flow study.

4.1 Contingency Operation Scenarios

The contingency operations considered by the study consist of one TPSS being out-of-service. The contingency represents loss of primary utility power, or fault in the substation’s TRU or ac switchgear. The substation’s dc bus, however, is assumed as remaining energized with all dc feeder circuit breakers closed. This provides for electrical continuity at the TPSS sectionalizing gap.

An outage zone is defined as the zone around the afflicted TPSS and extending to the adjacent healthy substations on either side. When a train is inside an outage zone the study assumed that the operator would not attempt running the train at reduced performance (at lower acceleration or lower speed) but will request full train performance as usual. This policy has been confirmed by Metro on other projects.

The P2550 cars, however, are equipped with controls for automatic reduction of performance via propulsion current limitation at line voltage below 650 V dc. This is a self-regulating feature of the car, which was taken into account in the load flow simulations. To note, the propulsion current reduction of the P2550 car is fairly modest and not as strong or effective as specified for the future P3010 car.

4.2 Acceptable Train Voltage

Per Metro Rail Design Criteria the minimum acceptable voltage at LRT trains is 525 V dc, and this is the value used in the study. The train voltage is measured between OCS and running rails at the center of the train, and is the average over the 60 Hz rectification cycle.

The Metro Rail Design Criteria also includes limits for the running rails to ground potentials. Article 9.18.5.A.5 of Metro Rail Design Criteria (Revision 1 of 11/04/10) states, “The negative to ground voltages shall be maintained below 50 V – at any point of the line and at any time – during normal operation with all substations on service, and below 70 V dc with any one substation out-of-service”. However, Metro has clarified in the past that this requirement is informational and that the negative-to-ground voltages are not to be used as governing or limiting factor in the determination of the spacing and locations of the traction power substations. Therefore, simulations for the rails-to-ground potentials were not performed, as the study’s focus is the design of the TES for Regional Connector, and evaluation of the existing lines in the vicinity.

4.3 Substation Overload Limits

As the traction power substations will (do) feature extra heavy-duty traction overload capability as defined in NEMA RI-9, they are be able to support 160% RMS load for 2 hours. This overload capability can be utilized as the duration of the peak period operations will be less than 2 hours. To allow for “out of range” variability of the load and tolerances of the protective relays, however, some safety margin is desirable. Therefore, the maximum RMS current of the TRU from the statistical runs will be compared to 1.5 times the nominal current, or the 150% load level, which will be treated as the practical limit.
With respect to short-term loading, with the extra heavy-duty traction overload capability the TPSS will be able to support currents of up to 450% of the nominal for durations of up to 15 seconds. However, to provide a small safety margin for reasons similar to those for the RMS loading, 440% peak current will be considered as the maximum acceptable. Hence, the maximum instantaneous load current of the TPSS from the statistical runs will be compared to 4.4 times the nominal current of the TRU.

### 4.4 DC Feeder Ampacity

The cable type for the dc feeders on RC will be 750 kcmil copper, non-shielded, with 2-kV insulation, similar to the cables used on the existing LRT lines. On the existing system the dc feeders have two or three cables, installed in one underground conduit, which leads to a difference in the cable ampacity. For RC the initial plan was for three cables in a 5-inch conduit, assuming 3-750 kcmil positive feeder size and 3-750 kcmil cables per track for the negative return, subject to confirmation from the load flow runs.

Apart from the number of cable per conduit, the cable ampacity depends also on the number of filled conduits in the ductbank. For Regional Connector, given the TPSS locations, OCS sectionalizing and feeder routing (see Fig. 3-4) two positive feeders maximum will be installed in close proximity or in a common ductbank. The negative “per track” feeders will be routed separately from the positive ones, so in this case we also have two three-conductor circuits per ductbank.

Accurate determination of the cables’ current-carrying capability in a traction power circuit is complicated, and even for a steady load (not the case anyway) would require the use of specialty software. There are also unknowns in the early stage of a system design, which affect the cable ampacity, such as lack of data on thermal resistivity of the soil, depth of burial, and ductbank configuration and routing details. Further complications arise from the uneven current loading between circuits in a common raceway, and relatively short duration of the peak period compared to the time it would take for underground cables to reach stable temperature corresponding to the RMS current.

Hence, a simplified approach is used to determine the ampacity of the 750 kcmil cable, which would then permit to size the positive and negative feeders of the new substations on the basis of the maximum RMS currents from the simulations. As well as check the adequacy of the dc feeders of the existing substations.

NEC uses standard conditions for ampacity of cables installed in underground duct-banks as follows: ambient earth temperature of 20 °C, 7.5” conduit spacing in concrete duct-bank, thermal resistance of 90, 100 percent load factor, conductor temperature of 90 °C, and three cables per duct/conduit. Per NEC ampacity table, at the standard conditions the ampacity of the 750 kcmil cable is 585 A in case of one circuit (3-750 kcmil cables), and 460 A in case of three circuits per ductbank (total of nine cables). Using interpolation, for two circuits with 3-750 kcmil cables each, the cable ampacity will be 523 A.

To account for load factor less than 100 percent due to the relatively short duration of the peak period, will assume a 7 percent higher cable ampacity, which results 523*1.07 = 560 A.

For circuits with 2-750 kcmil cables, first an interpolation can be made for a single circuit per ductbank at the standard conditions. For a three-cable circuit, as stated already the cable
ampacity per NEC is 585 A. Cable ampacity tables from Okonite Company (cable manufacturer) provide also ampacity for one cable per conduit. For the 750 kcmil copper cable, it is 706 A. For the two-cable circuit, then by linear interpolation we have \( \frac{585+706}{2} = 645 \) A. As the ampacity increase relative to the standard three-cable per conduit installation is 645/585 = 1.1, for the two circuits per ductbank the cable ampacity could be likewise approximated as 523*1.1 = 575 A. Finally, applying the 7 percent load factor correction results in 575*1.07 = 615 A.

The estimated cable and feeder ampacities for the two circuit per ductbank installation the can be summarized as follows:

<table>
<thead>
<tr>
<th>DC Feeder Size</th>
<th>Cable Ampacity</th>
<th>Feeder Ampacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-750 kcmil</td>
<td>615 A</td>
<td>1230 A</td>
</tr>
<tr>
<td>3-750 kcmil</td>
<td>560 A</td>
<td>1680 A</td>
</tr>
</tbody>
</table>

It should be noted that the above ampacities are for the Regional Connector, where per PE design no more than two dc feeder circuits share a common route or duct-bank. For the three existing traction power substations subject for evaluation by the study, however, raceway routing data was not available and it is possible that more than two dc feeder circuits have been combined in a common ductbank. If the latter turns out to be the case, it would require further de-rating of the cable ampacity. These substations are the PICO TPSS on the Blue Line, and Red Line Yard TPSS and Union TPSS on the Gold Line.

Cross bonding of the two tracks will be via 500 kcmil copper cables, installed in embedded conduit between the two tracks. Per NEC, the ampacity of the 500 kcmil cable at the standard conditions, single circuit of 3-500 kcmil cables in a 4-inch conduit, is 470 A/cable.

The 470 A per cable ampacity will be used to size the cross bonding links on the Regional Connector, based on the results for the maximum RMS currents through the cross bonds.

4.5 OCS Ampacity and Temperature Limit

The current carrying capability (ampacity) of the OCS wires was calculated in accordance with the Institute of Electrical and Electronics Engineers (IEEE) Standard 738-1993, using the following climate conditions and other essential parameters:

- Maximum ambient air temperature: 100 F (37.8 °C) outdoors in open air, and 80 F (26.7 °C) inside the Regional Connector tunnel. These are assumed maximum air temperatures summertime during the afternoon peak period, mostly on judgment.
- Atmosphere (air clarity): clear
- Elevation: 100 ft
- Solar altitude: 45 degrees
- Wind velocity for convection cooling: 3 ft/sec.
- Contact wire wear: 25 percent (grooved CW cross section was used, with corresponding perimeter reduction of 9 percent)
• Maximum acceptable OCS wire temperature: 75 °C (167 F) per AREMA guidelines, and as recommended by OCS design engineers for RC.

It may be noted that NEC and most engineering textbooks use 2 ft/sec wind velocity in the calculation of the ampacity of bare overhead conductors. This is based on desert like worst-case conditions. However, for urban rail transit systems there is better convection cooling due to street traffic, as well as air turbulence created by the trains themselves. In recognition of this, and to avoid being overly conservative, there are indications that the American Railway Engineering and Maintenance-of-Way Association (AREMA) is moving towards adopting higher (probably 4 ft/sec) wind velocity for the calculation of OCS ampacity and wire temperature for urban rail transit systems. For the study 3 ft/sec wind velocity was assumed, for both outdoors and tunnel conditions.

For the stated conditions the ampacity calculations for the 350 kcmil copper contact wire and 500 kcmil copper messenger wire resulted in the following currents:

<table>
<thead>
<tr>
<th>Environment</th>
<th>Contact Wire</th>
<th>Messenger Wire</th>
<th>Simple Catenary OCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoors</td>
<td>525</td>
<td>789</td>
<td>1314</td>
</tr>
<tr>
<td>In Tunnel</td>
<td>578</td>
<td>875</td>
<td>1453</td>
</tr>
</tbody>
</table>

Comparing the RMS current in an OCS section to the OCS ampacity is not very accurate, however, for determining whether the maximum OCS temperature is below the acceptable limit, and is appropriate only if the RMS current is significantly lower than the OCS ampacity. There are several reasons for this, such as the non-linear current distribution between CW and MW (the current is collected from the contact wire only), the impact of the spacing and locations of the equalizing jumpers, and the tendency of the conductor's temperature to be elevated due to the high form factor of the train current.

The following approach is used in the study with respect to thermal capacity evaluation of the OCS. First, the maximum RMS currents in the electrical sections and corresponding timing offsets are determined via statistical run. If the maximum RMS current in a section is below the 88 % level of the OCS ampacity, it is deemed sufficient indication that there is no overheating of the OCS. Otherwise, a more accurate dynamic temperature analysis of the subject OCS section will be carried out via a simple run of extended duration, with DTO leading to the maximum RMS current in the target positive feeder/ OCS section.

It should be noted that once the OCS reaches thermal equilibrium the wire temperature is not constant but oscillates with a cycle matching the headway. The oscillations are more pronounced in the contact wire, especially if worn, due to its lower mass and the fact that in the vicinity of the train all of the current passes just through the contact wire. The OCS temperatures discussed so far (the 75 °C limit and temperature for comparison from the simulations) are interpreted as the mean value over a headway cycle, known also as effective temperature. There is also the crest temperature, which is the peak temperature reached within the headway cycle. The crest temperature is important for ensuring that there is no annealing and subsequent loss of tensile strength of the OCS wires, as commercial copper begins to anneal at about 100 °C and the process is cumulative (repeated exposures do add up).
5.0 ANALYSIS OF SIMULATION RESULTS

5.1 General

Each TP simulation has two stages. The first stage is used to saturate the system with trains at the required headway and DTO, assuming nominal 750 V dc throughout. In the second stage the electrical network is solved at standard 1-second time intervals, each interval followed by update to the trains’ status and locations. At this stage train performance is voltage-sensitive, depending on the performance characteristics of the vehicle. Automatic forced reduced performance at low voltage and regenerative braking, if active at some trains, are accounted for in the solution of the electrical network.

In the model the train’s propulsion system is not shut down if the voltage falls below the minimum acceptable, as would happen in actual operations. Instead, all trains remain connected to the TES and the excursion of the train voltage below the minimum acceptable is used as an indicator of the severity of the under-voltage condition.

The minimum voltages summarized in this section are absolute minimum voltages from statistical runs. The absolute minimum voltage is the lowest voltage from the set of multiple simulations (covering all timing offsets between trains in opposing directions for the study) comprising a statistical run. As such it reflects the most adverse train configuration with regards to line voltage for the simulated headway pattern and TES status. For the RMS and peak TPSS currents, it is the maximum current also from a statistical run that is used to confirm whether the load is within the capability of the TPSS. Same for the RMS currents in the dc feeders, used for sizing new feeders or checking up existing feeders for overload.

Four service routes were set up for the overall LRT system included in the model, each operating at 5-minute headway as follows:

<table>
<thead>
<tr>
<th>Route</th>
<th>Description</th>
<th>Origination Station</th>
<th>Destination Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long Beach – Pasadena</td>
<td>San Pedro</td>
<td>French Ave</td>
</tr>
<tr>
<td>2</td>
<td>Pasadena – Long Beach</td>
<td>French Ave</td>
<td>San Pedro</td>
</tr>
<tr>
<td>3</td>
<td>Culver City – East LA</td>
<td>Expo Park/USC</td>
<td>Indiana St</td>
</tr>
<tr>
<td>4</td>
<td>East LA – Culver City</td>
<td>Indiana St</td>
<td>Expo Park/USC</td>
</tr>
</tbody>
</table>

The four service routes can be traced on the TP model’s map shown on Figure 1-1. Trains on Routes 1 and 3 become the Eastbound trains on Regional Connector, while those on Routes 2 and 4 are the Westbound. Departure times from the origination stations were determined so that trains entering the trunk line via the same junction arrive staggered about 2.5 minutes apart, resulting in almost uniform 2.5 minute headway on the trunk line, which includes Regional Connector.

To our knowledge Metro doesn’t have a comprehensive labeling scheme, acronym type, for the traction power substations on their LRT lines. On some lines there are such designations while on others the substations just have names of nearby streets or prominent landmarks. As TPSS labels are convenient for presentation of the results in table form and for reference, such labels were set up for the study if originally unavailable. The TPSS labels and locations for the studied part of the existing system and RC are provided in Table 5-1.

REGIONAL CONNECTOR TRANSIT CORRIDOR PROJECT

December 1, 2011
Table 5-1: Substation Designations

<table>
<thead>
<tr>
<th>TPSS Label</th>
<th>TPSS Location</th>
<th>System Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>JS</td>
<td>Junction Substation. At the Flower Junction, located at the corner of Washington Blvd and Flower St, interfacing the Blue and Expo Lines.</td>
<td>Assumed as Existing</td>
</tr>
<tr>
<td>PICO</td>
<td>PICO Substation. At the corner of Flower St and PICO Blvd. On the Blue Line.</td>
<td>Existing</td>
</tr>
<tr>
<td>RC1</td>
<td>TPSS #1 on Regional Connector. At the 2nd/Hope passenger station.</td>
<td>New</td>
</tr>
<tr>
<td>RC2</td>
<td>TPSS #2 on Regional Connector. At the 2nd/Broadway passenger station.</td>
<td>New</td>
</tr>
<tr>
<td>TPS01</td>
<td>Metro label for the Red Line Yard TPSS supplying the Gold Line (Eastside segment)</td>
<td>Existing</td>
</tr>
<tr>
<td>TPS02</td>
<td>Metro label for the 1st Street/Breed St TPSS supplying the Gold Line (Eastside segment)</td>
<td>Existing</td>
</tr>
<tr>
<td>P110</td>
<td>Metro label for the Union TPSS, supplying the Gold Line (Pasadena segment)</td>
<td>Existing</td>
</tr>
<tr>
<td>P120</td>
<td>Metro label for the Baker Street TPSS, supplying the Gold Line (Pasadena segment)</td>
<td>Existing</td>
</tr>
</tbody>
</table>

Even though four more substations were included in the model they are in parts of the system that are not studied. Their inclusion was for the purpose of avoiding artificial end-of-line effects in the central part of the system subject to analysis.

The track numbering convention of the model, used for reference purposes in this section as well, is as follows:

Track 1: Northbound on Blue Line; Eastbound on RC; towards East LA from Alameda Junction (Gold Line); towards Pasadena from Alameda Junction (Gold Line); and Westbound on Exposition Line

Track 2: For trains in the opposite direction on the same line segment

For the statistical runs service routes 1 and 3 were used as anchors, with fixed train dispatch times from the end-of-line stations for the simple simulations comprising a statistical run. Service routes 2 and 4 were set up with varying dispatch times from their origination stations, the dispatch times delayed by extra 3 seconds per simple simulation. The duration of each simple simulation was set to match the 5-minute headway, as there is no need to continue the simulation beyond the headway cycle (the load pattern repeating itself in the absence of operational disturbances). With the selected 100 simple simulations per statistical run, the resulting range of variation of the directional timing offset (DTO) is 3*100 = 300 seconds. It matches the headway cycle and so covers the full range of possibilities as to where trains on the same route but moving in opposite directions meet.

The scope of the study is limited to the Regional Connector and the following adjacent existing substations: PICO substation to the South (Blue Line), Red Line Yard (TPS01) substation on the Eastside segment of the Gold Line, and Union Substation (P110) on the Pasadena segment of the Gold Line. In contingency operations with one of these substations out-of-service, the area of interest extends further out into the existing system to the next healthy substation.
5.2 Train Performance and Energy Use

Speed vs. distance plots for trains on service routes 1 and 2, normal operations, are provided on Figures 5-1A and 5-2A for illustration. Figures 5-1B and 5-2B show the corresponding train currents, while Figures 5-1C and 5-2C the train voltages. The simulation from which the plots were recorded was with a randomly chosen DTO of 0 sec.

The run times between existing stations bracketing RC, including the 30-sec station dwell on each of the three passenger stations of Regional Connector, are as follows:

<table>
<thead>
<tr>
<th>Service Route</th>
<th>From Departing</th>
<th>Till Arrival At</th>
<th>Trip Time (mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7th/Metro Center</td>
<td>Union Station</td>
<td>8:21</td>
</tr>
<tr>
<td>2</td>
<td>Union Station</td>
<td>7th/Metro Center</td>
<td>8:40</td>
</tr>
<tr>
<td>3</td>
<td>7th/Metro Center</td>
<td>Pico/Aliso</td>
<td>7:29</td>
</tr>
<tr>
<td>4</td>
<td>Pico/Aliso</td>
<td>7th/Metro Center</td>
<td>7:36</td>
</tr>
</tbody>
</table>

For the entire modeled system the specific car energy use, including the car’s auxiliary (hotel) loads, was recorded at 9.45 kWh/car-mile.

The energy losses in the TES, which include losses in the traction power substations and the dc distribution system, came to about 8.2% of the overall energy consumption (with 6.6% of the losses incurred in the dc distribution system, and 1.6% in the substations).

The load flow simulations also showed that the energy recovered by regenerative braking is about 24% of the overall energy usage of the traction power system. It should be noted, however, that in off-peak operations when the headways will be longer and the trains spaced further apart, the effectiveness of the regenerative braking will be reduced.

5.3 Decision on System Configuration

Given the 1.7-mile length of Regional Connector and its position between the existing lines (see Fig. 1-1) it appears a question of whether it requires one or two traction power substations. The feasibility of the first option, that is a system with one TPSS, was determined by simulating a contingency scenario with this TPSS out of service. In such case all power to trains on the Regional Connector will have to come from adjacent substations on the existing lines.

For the “single TPSS out of service” scenario it was assumed that the standard OCS on Regional Connector is reinforced by a supplemental feeder sized 2-750 kcmil copper cables per track. This was considered the largest such feeder for practical purposes, as further increase of this feeder’s size is likely to invoke the law of diminishing returns.

The statistical run with the above-described conditions resulted in the following key results.

Absolute minimum train voltage: 425 V dc
Maximum RMS load of adjacent substations:
71 % at PICO
110 % at Red Line Yard (TPS01)
115 % at Union (P110)

Maximum RMS currents in positive feeders:
For PICO TPSS, 1905 A in feeder #3
For Red Line Yard TPSS, 1979 A in feeder #1
For Union TPSS, 1208 A in feeder #2

The above results indicate that while the existing substations have adequate capacity and would not be overloaded (as a TPSS can support 150 % load during the peak period) there is severe low voltage problem on RC, and overload on some of the existing positive feeders providing power to RC. The OCS near Red Line Yard TPSS and PICO TPSS supplied by these dc feeders would also be overloaded. For these reasons the alternative with a single TPSS was deemed not feasible.

For the second alternative, the two substations were located at the 2nd/Hope and 2nd/Broadway Stations, which are about 2000 ft apart and in a near central position relative to the existing substations. The reason for this choice was to minimize the RMS load on the positive feeders and OCS in contingency operations with one of these two substations out of service; as well as for better voltage support in such operations, given the favorable results with a single centrally located, in-service TPSS on RC.

Simulations with two substations at the selected locations, one of them out-of-service, and standard OCS on Regional Connector, resulted in absolute minimum voltage of 536 V dc and thermal overload on the OCS between the two substations, RC1 and RC2. Based on these results, a supplemental 500 kcmil copper conductor was added to the OCS in the form of a second messenger wire. The resulting double messenger wire was assumed as extending from the beginning of RC near the 7th/Metro Station to the track split point at the Alameda junction at the other end of RC. The reasons for this greater length of the double messenger wire than strictly needed from OCS loading point of view are covered in the Executive Summary and Section 6, Conclusions and Recommendations, of the report.

Subsequent simulation results and analysis in this section are for the above-described TES of RC: two traction power substations located at the 2nd/Hope and 2nd/Broadway Stations, and simple, low-profile OCS with 2-500 kcmil copper double messenger wire, with the second MW extending along most of the RC alignment (from the OCS interface with the Blue to the track turnout for Union Station after the 1st/Central Station).

5.4 Minimum Train Voltages
The minimum voltages for operations with normal TES are summarized in Table 5-2.
Table 5-2: Minimum Train Voltages in Normal Operations

<table>
<thead>
<tr>
<th>#</th>
<th>Zone</th>
<th>System Part</th>
<th>Absolute Minimum Voltage (V dc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PICO – RC1</td>
<td>Existing &amp; RC</td>
<td>623</td>
</tr>
<tr>
<td>2</td>
<td>RC1 – RC2</td>
<td>RC</td>
<td>678</td>
</tr>
<tr>
<td>3</td>
<td>RC2 – Alameda Junction (AJ)</td>
<td>RC</td>
<td>625</td>
</tr>
<tr>
<td>4</td>
<td>AJ – TPS01</td>
<td>Mostly Existing</td>
<td>642</td>
</tr>
<tr>
<td>5</td>
<td>AJ – P110</td>
<td>Mostly Existing</td>
<td>610</td>
</tr>
</tbody>
</table>

As seen from Table 5-2, the 525-volt criteria threshold is easily met in normal system operations.

For contingency operations with one TPSS out-of-service the absolute minimum voltages are summarized in Table 5-3.

Following the statistical run for a contingency scenario, a simple run was also performed with DTO that results in the absolute minimum voltage, the program output including a system status snapshot at the time of its occurrence. A brief description of what causes the absolute minimum voltage is provided in the last column of Table 5-3.

Table 5-3: Minimum Train Voltages in Contingency Operations

<table>
<thead>
<tr>
<th>#</th>
<th>TPSS Off-Line</th>
<th>Absolute Minimum Voltage</th>
<th>Trains In Outage Zone at Time of Occurrence of the Absolute Minimum Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PICO</td>
<td>575</td>
<td>SB train accelerating from PICO (33 mph, 587 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NB train accelerating from PICO (29.7 mph, 575 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SB train stopped at 7th/Metro (0 mph, 652 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NB train accel. from 7th/Metro (35.5 mph, 602 V)</td>
</tr>
<tr>
<td>2</td>
<td>RC1</td>
<td>563</td>
<td>SB train braking towards PICO (3.5 mph, 731 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NB train accel. from 7th/Metro (15.6 mph, 563 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SB train accelerating after curve from 2nd/Hope (43.4 mph, 568 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EB train accel. from 2nd/Hope (13.5 mph, 586 V)</td>
</tr>
<tr>
<td>3</td>
<td>RC2</td>
<td>571</td>
<td>EB train accel. from 2nd/Hope (10.5 mph, 679 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB train approaching 2nd/Hope (15 mph uphill, 678 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EB train accel. from 2nd/Broadway (44.7 mph, 609 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB train accel. from 1st/Central (19 mph, 571 V)</td>
</tr>
<tr>
<td>4</td>
<td>TPS01</td>
<td>499</td>
<td>EB train accel. from 2nd/Broadway (26.8 mph, 694 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB train running on the curve West of 1st/Central (25 mph, 681 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EB train accel. to 35 mph after tunnel exit on First St (34.6 mph, 517 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB train accel. from Pico/Aliso (31.2 mph, 499 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Train accel. from Union Station, Pasadena direction (26.6 mph, 606 V)</td>
</tr>
<tr>
<td>5</td>
<td>P110</td>
<td>474</td>
<td>EB train accel. from 2nd/Broadway (41.8 mph, 671 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB train accel. from 1st/Central (21.3 mph, 578 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Train accel. from Union Station, Pasadena direction (32 mph, 498 V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Train accel. from Chinatown Station, RC direction (29.2 mph, 474 V)</td>
</tr>
</tbody>
</table>

The outage zone referenced in Table 5-3 is limited by the adjacent healthy substations located on either side of the one out of service. For substations around Alameda Junction, the outage
zone is limited by three substations given the line configuration as shown on Figure 3-3. Additional details, such as currents and voltages at the substations, and exact locations, acceleration rates and currents of the trains at the moment of occurrence of the absolute minimum voltage are available on the program printouts.

As seen from Table 5-3, there are at least four trains in the outage zone at the occurrence of the minimum voltage in each scenario. With three or four trains at full, or near full, power. Also of note is that in some cases there are other trains drawing maximum current near the outage zone, thus increasing the load on the substations that support operations inside it, and lowering further the TPSS dc bus voltage. Excepting perhaps the PICO TPSS out-of-service contingency, none of the minimum voltages are due to a simple “two trains accelerating simultaneously from the same station” scenario.

As Table 5-3 shows, the absolute minimum voltages for the first three contingency scenarios – substations PICO, RC1 and RC2 out of service – are above the 525-volt criteria by a comfortable margin. The last two contingency scenarios don’t meet the criteria, however. In both cases the train at which the absolute minimum voltage occurs is on the Gold Line. And in both cases there is also a second train in the area at line voltage below 525 V dc.

Speed, current and voltage plots for the trains experiencing the minimum voltage in the last two scenarios in Table 5-3 are shown on Figures 5-3A, 5-3B and 5-3C (Red Line Yard TPSS out-of-service) and Figures 5-4A, 5-4B and 5-4C (Union TPSS (P110) out-of-service) at the end of this section.

Based on the statistical runs, the probability of the minimum voltage falling below 525 V dc as a function of the DTO for the Red Line Yard TPSS out-of-service is 17 %, while for the Union TPSS out-of-service scenario it is 46 %. The software calculates these probabilities on the assumption that all directional timing offsets between trains in the opposing directions on the same line are equally likely.

### 5.5 Maximum Substation Loading

The heaviest load on a transformer/rectifier unit (TRU) occurs in contingency operations. For a substation with one TRU this happens when an adjacent TPSS is taken out of service.

The maximum RMS and momentary currents of the evaluated substations are summarized in Table 5-4. These are loads that would occur if for the simulated operations plan and system configuration the train departures from the opposing end-of-line stations entail the most adverse DTO with respect to the RMS load on a given substation.

The percent load in Table 5-4 is calculated as ratio of the maximum RMS and peak currents from the simulations to the nominal dc current of the TRU.
Table 5-4: Maximum TPSS Load

<table>
<thead>
<tr>
<th>TPSS</th>
<th>TRU Rating (kW)</th>
<th>Nominal TPSS Current (A dc)</th>
<th>Normal Operations</th>
<th>Contingency Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max RMS Current (%)</td>
<td>Max Peak Current (%)</td>
</tr>
<tr>
<td>PICO</td>
<td>3000</td>
<td>4000</td>
<td>44</td>
<td>162</td>
</tr>
<tr>
<td>RC1</td>
<td>2000</td>
<td>2666</td>
<td>67</td>
<td>206</td>
</tr>
<tr>
<td>RC2</td>
<td>2000</td>
<td>2666</td>
<td>72</td>
<td>207</td>
</tr>
<tr>
<td>TPS01</td>
<td>1500</td>
<td>2000</td>
<td>69</td>
<td>234</td>
</tr>
<tr>
<td>P110</td>
<td>1500</td>
<td>2000</td>
<td>90</td>
<td>281</td>
</tr>
</tbody>
</table>

The results in Table 5-4 show that the RMS and peak load currents in contingency operations are well within the acceptable limits for all substations. Therefore, the selected TPSS rating for the substations on Regional Connector is appropriate, and the existing adjacent substations will not be overloaded. It should be noted, however, that the simulated contingencies for the existing substations PICO, TPS01 and P110 include taking only the adjacent RC substation out-of-service (and not the existing substation on the opposite side).

Plots of substation RC2’s dc bus voltage and dc currents through the TRU and dc feeder circuit breakers in contingency operations with RC1 out-of-service, at a DTO that results in the maximum RMS load on RC2, are shown for illustration purposes on Figures 5-5A through 5-5F at the end of this section.

As can be seen on Figures 5-5A and 5-5B, occasionally the bus voltage rises above the no-load voltage thus blocking the rectifier. This is due to the presence of trains in regenerative braking mode in the vicinity. Positive value for the dc feeder current means that the current is flowing from the TPSS bus towards the OCS. Negative value means the current flows in reverse direction towards the dc bus. The latter can occur in case of a feed-through from an adjacent TPSS, or if a train in regenerative braking is supplying power to other trains through the substation’s bus.

### 5.6 Positive DC Feeder Currents and Feeder Sizing

The maximum RMS currents in the positive feeders of the traction power substations on Regional Connector, and in those feeders of adjacent existing substations that face RC, are summarized in Table 5-5. The table also includes the feeder sizes (recommended size in case of a new TPSS) and the estimated feeder ampacity for assumed two feeders per common underground duct-bank.
Table 5-5: Positive DC Feeder Currents and Feeder Sizes

<table>
<thead>
<tr>
<th>Feeder ID</th>
<th>Size</th>
<th>Ampacity (A)</th>
<th>Normal Operations</th>
<th>Contingency Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICO-3</td>
<td>2-750 kcmil</td>
<td>1230`</td>
<td>1303</td>
<td>1467 (RC1 Off)</td>
</tr>
<tr>
<td>PICO-4</td>
<td>2-750 kcmil</td>
<td>1230`</td>
<td>1168</td>
<td>1327 (RC1 Off)</td>
</tr>
<tr>
<td>RC1-1</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>1254</td>
<td>1432 (PICO Off)</td>
</tr>
<tr>
<td>RC1-2</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>1115</td>
<td>1212 (PICO Off)</td>
</tr>
<tr>
<td>RC1-3</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>655</td>
<td>1122 (RC2 Off)</td>
</tr>
<tr>
<td>RC1-4</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>649</td>
<td>1182 (RC2 Off)</td>
</tr>
<tr>
<td>RC2-1</td>
<td>4-750 kcmil</td>
<td>2250</td>
<td>1182</td>
<td>1563 (RC1 Off)</td>
</tr>
<tr>
<td>RC2-2</td>
<td>4-750 kcmil</td>
<td>2250</td>
<td>1193</td>
<td>1696 (RC1 Off)</td>
</tr>
<tr>
<td>RC2-3</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>1028</td>
<td>1404 (TPS01 Off)</td>
</tr>
<tr>
<td>RC2-4</td>
<td>3-750 kcmil</td>
<td>1680</td>
<td>1024</td>
<td>1493 (P110 Off)</td>
</tr>
<tr>
<td>TPS01-1</td>
<td>3-750 kcmil</td>
<td>1680`</td>
<td>829</td>
<td>1101 (RC2 Off)</td>
</tr>
<tr>
<td>TPS01-2</td>
<td>3-750 kcmil</td>
<td>1680`</td>
<td>605</td>
<td>879 (P110 Off)</td>
</tr>
<tr>
<td>P110-1</td>
<td>2-750 kcmil</td>
<td>1230`</td>
<td>924</td>
<td>1145 (TPS01 Off)</td>
</tr>
<tr>
<td>P110-2</td>
<td>2-750 kcmil</td>
<td>1230`</td>
<td>713</td>
<td>794 (RC2 Off)</td>
</tr>
</tbody>
</table>

* Raceway routing data for the dc feeders of the existing substations was not available, and therefore the assumption carried over from RC of “two circuits per duct-bank” for dc cable ampacity estimate may not be correct. If more than two circuits share a common duct-bank then further de-rating of the cable ampacity will be needed, and the feeder ampacity in Table 5-5 will be lower than shown.

The last column in Table 5-5 shows also the TPSS outage resulting in the cited maximum RMS current. For feeders supplying power to the area of the Alameda Junction, two different TPSS out-of-service conditions are possible and the listed maximum current is the higher from the two contingencies. For details on the traction power system configuration in the vicinity of Alameda Junction, refer to Figure 3-3.

The maximum RMS currents of feeders RC2-1 and RC2-2 show that one of them would be slightly overloaded in contingency operations, if sized at 3-750 kcmil. As this is a new system the next higher size was used for these two feeders. The 4-750 kcmil cables per feeder will be installed in two 4-inch conduits (two cables per conduit). For the positive feeder numbering convention on RC, refer to Figure 3-4.
As seen from Table 5-5, feeders PICO-3 and PICO-4 will be overloaded in contingency operations, with PICO-3 possibly slightly overloaded even in normal service, the latter depending on the DTO inherent in the train schedule.

5.7 Negative DC Feeder Currents and Feeder Sizing

The negative return (NR) from the running rails to the TPSS negative bus may be considered as two feeders (one per track for the 2-track system), or alternatively, it may be treated as one common feeder. The latter approach is used by the study, because at the connections of the negative feeders to the tracks on RC, the tracks will be also cross-bonded for current equalization purposes. This approach was adopted after initial simulations showed that without such a measure, with the standard 3-750 kcmil cables per track the maximum RMS current in contingency operations in the cables providing return for one of the tracks is either very close to, or slightly exceeding, the cable ampacity.

The maximum RMS currents in the NR feeders, along with the feeder size and ampacity, are summarized in Table 5-6.

<table>
<thead>
<tr>
<th>Negative Return Feeder</th>
<th>Maximum RMS Current (A)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Operations</td>
<td>Contingency Operations</td>
</tr>
<tr>
<td>PICO</td>
<td>6-750 kcmil</td>
<td>3360</td>
</tr>
<tr>
<td>RC1</td>
<td>6-750 kcmil</td>
<td>3360</td>
</tr>
<tr>
<td>RC2</td>
<td>6-750 kcmil</td>
<td>3360</td>
</tr>
<tr>
<td>TPS01</td>
<td>6-750 kcmil</td>
<td>3360</td>
</tr>
<tr>
<td>P110</td>
<td>6-750 kcmil</td>
<td>3360</td>
</tr>
</tbody>
</table>

The last column of Table 5-6 contains the maximum RMS currents in the TPSS negative return feeder when different adjacent substations are taken out-of-service. As seen, all NR feeder sizes are adequate.

Cross bonding of the two tracks ties all four running rails for dc current return. As such it helps equalize the traction power current between the two tracks, as well as between different cables of the TPSS negative return feeder. The current equalization between all four running rails results in lower negative voltage rise along the tracks, and consequently lower rails-to-ground potentials and stray currents. For these reasons the two tracks on RC will be cross-bonded.

The Regional Connector tracks are proposed to be cross-bonded at seven locations as indicated in Table 5-7. As mentioned, two of the locations are at the substations RC1 and RC2 negative returns in order to equalize the current in the feeder cables. The maximum RMS currents in the cross bonding links obtained from the simulations are listed in Table 5-7.
Table 5-7: Cross Bonding Locations and Currents

<table>
<thead>
<tr>
<th>Cross Bonding Locations on RC (by civil stationing)</th>
<th>Maximum RMS Current Through Cross Bond (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8+18</td>
<td>964</td>
</tr>
<tr>
<td>32+75 (at NR of TPSS RC1)</td>
<td>416</td>
</tr>
<tr>
<td>49+57 (at NR of TPSS RC2)</td>
<td>778</td>
</tr>
<tr>
<td>69+00</td>
<td>494</td>
</tr>
<tr>
<td>90+80 (on Eastside branch of Alameda Junction)</td>
<td>345</td>
</tr>
<tr>
<td>91+85 (on Pasadena branch of Alameda Junction)</td>
<td>344</td>
</tr>
</tbody>
</table>

Given the maximum RMS current of 964 A in Table 5-7, the cross bonding connections between the two tracks can be made with 3-500 kcmil copper cables, installed in one 4-inch diameter conduit, concrete-embedded between the tracks, linking the corresponding impedance bonds.

### 5.8 OCS Wire Temperatures

Special simulations for dynamic temperature analysis were carried out to determine the maximum OCS temperatures on the Regional Connector and parts of the existing system - where deemed necessary due to high RMS currents in the positive feeders. These simulation were performed with the following conditions:

- Detailed ladder type model of the OCS between two substations, including specific equalizing jumper locations. For the remainder of the system the OCS was modeled with the standard equivalent conductor method.

- Initial equalizing jumper spacing on RC between 350 and 400 ft, depending on the distance between the feeder connection points. For the portion of the existing Blue Line included in this analysis the locations of the equalizing jumpers were obtained from record drawings. The equalizing jumpers connect electrically the messenger wire with the contact wire.

- Equalizing jumper size of 500 kcmil bare copper for the catenary segments, and 750 kcmil copper cable for risers from the parallel underground feeder in the single contact wire segment near PICO substation. For details on the latter, see Figure 3-2.

- Multi-point representation of the trains when inside the detailed OCS model zone, where each car is represented individually, separated by one car length from the adjacent car of the consist

- DTO of the train operations for the simulation the same as the one resulting in the maximum RMS current in the positive feeder in the vicinity of which the OCS temperature is of greater interest.

- 45 minutes duration of the simulation, which is deemed sufficient for the OCS wires to reach stable temperature
• Ambient conditions as stated in Section 4.5 of the report, for tunnel operations, or for open
  air, as appropriate
• Contact wire assumed worn by 25 %.

5.8.1 RC1 – RC2 Segment

As seen from Table 5-5 the two highest RMS currents in the positive feeders on Regional
Connector occur during contingency operations in feeders RC2-1 and RC2-2 when substation
RC1 is out-of-service. They are 1563 A and 1696 A, respectively, and both exceed the
estimated ampacity of the standard OCS in the tunnel, which is 1453 A.

These feeders, however, have a 560-ft offset from the sectionalizing gap of substation RC2,
which is not negligible (see Figure 3-4 for details). Therefore, the RMS current at the beginning
of the main OCS segment for each track, which is to the West of the respective feeder’s
connection point, will be somewhat lower than the current in the positive feeder.

The main results for the OCS temperature from the simulations for the line segment between
substations RC1 and RC2, with RC1 out-of-service, are summarized in Table 5-8.

<table>
<thead>
<tr>
<th>#</th>
<th>Case Description</th>
<th>Track</th>
<th>Contact Wire</th>
<th>Messenger Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RC1 out-of-service; DTO for max RMS current in feeder RC2-2; standard OCS; uniform equalizing jumper (EJ) spacing of 400 ft; quoted maximum currents and temperatures are for first OCS ladder cell West of RC2-2.</td>
<td>WB</td>
<td>703</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>101.5 mean 112.3 crest</td>
<td>60.0 mean 62.9 crest</td>
</tr>
<tr>
<td>2</td>
<td>As in Case 1 above, but with double messenger wire</td>
<td>WB</td>
<td>591</td>
<td>426</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81.8 mean 89.9 crest</td>
<td>38.3 mean 39.2 crest</td>
</tr>
<tr>
<td>3</td>
<td>As in Case 2 above, but with one extra EJ dividing the first OCS cell West of RC2-2 in two (resulting in 200 ft spacing of the first two jumpers)</td>
<td>WB</td>
<td>479</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>65.7 mean 70.9 crest</td>
<td>42.4 mean 43.8 crest</td>
</tr>
</tbody>
</table>

As noted in Table 5-8, the maximum OCS temperature on the WB track occurs in the first OCS
ladder cell on the West side of feeder RC2-2’s connection point, which is logical given that it is
the area where trains accelerate Westbound from the 2nd/Broadway Station and draw maximum
current.

The high RMS current in the contact wire on the West side of feeder RC2-2’s connection, and
high CW temperature (101.5 ºC mean over the headway cycle, and 112.3 ºC crest temperature)
indicates a need for another conductor to the OCS, which was done in Case 2 with the addition
of a second messenger wire. To note, the MW current in Table 5-8 is given on a per wire basis,
rather than the combined current in the two messenger wires.

The results for Case 2 indicate that there is still a hot spot in the first OCS ladder cell (400 ft
long with the initial EJ spacing), as the contact wire temperature exceeds the limit of 75 ºC.
Case 3 includes adding another equalizing jumper to split the first cell West of feeder RC2-2 in two shorter 200 ft long cells. And as the results show, this measure is sufficient to finally bring the maximum CW temperature below the criteria limit.

The results for the RMS currents in the equalizing jumpers showed that in the final configuration (Case 3 in Table 5-8) the RMS current in the EJ at the feeder RC2-2’s connection point is 778 A, which is high enough to require two side-by-side jumpers. Elsewhere, a single 500 kcmil copper EJ is adequate.

Plots of OCS currents and temperatures in this line segment, for Cases 2 and 3 as described in Table 5-8, are shown at the end of this section.

Figure 5-6A shows the OCS temperature profile along the length of the RC1-RC2 segment for both tracks for the conditions of Case 2.

Figure 5-6B shows the currents in the contact wire and messenger wire at Probe 1, which as indicated is located just to the West of feeder RC2-2’s connection (WB track). Figure 5-6C shows the temperature of the contact wire vs. time at Probe 1. As seen, the contact wire’s mean temperature over the headway cycle (let alone the crest temperature) exceeds the 75 ºC limit.

Figures 5-7A through 5-7D show OCS currents and temperatures for Case 3, which is similar to Case 2 except that an extra equalizing jumper (EJ) has been added on the WB track near the feeder RC2-2’s connection, which reduces the jumper spacing from 400 ft to 200 ft in the area.

As seen on Figure 5-7A, the closer EJ spacing has the desired effect and the mean temperature of the contact wire is now within acceptable limits.

Figure 5-7B shows the contact wire and messenger wire currents v. time at Probe 1 near the feeder RC2-2’s connection point, with the extra EJ on the WB track, while Figures 5-7C and 5-7D show the contact wire and messenger temperatures over time at the same location.

### 5.8.2 PICO – RC1 Segment

Substation PICO out-of-service results in the next highest RMS feeder currents on Regional Connector, occurring in the positive feeders on the West side of the sectionalizing gaps of RC1. These are feeders RC1-1 and RC1-2, with their maximum RMS currents listed in Table 5-5. Of the two, RC1-1 supplying the OCS of the EB track on the West side of the sectionalizing gap of RC1 is with the heavier load and hence the associated OCS of the EB track West of the 2nd/Hope Station was chosen for temperature analysis.

Given the assumed RC1-1 and RC1-2 connections at 29+50 on the West side of the 2nd/Hope station platform, and first existing EJ on the Blue Line located at 3+26 in the present tailrack of the 7th/Metro Station, the resulting distance is 2624 ft and uniform EJ spacing of 375 ft was assumed for this OCS segment (375*7 = 2625 ft).

For the existing OCS of the Blue Line in the tunnel, EJ locations were obtained from record drawings. Outside the tunnel, South to the PICO TPSS, the OCS is of the single contact wire (SCW) type with parallel underground feeder sized 2-750 kcmil copper cables per track. The locations of the cable risers in this segment, connecting the parallel feeder to the SCW were
also obtained from as-built drawings of the Blue Line. The details of the dc distribution system in the area of the PICO TPSS and PICO Station, as modeled, can be seen on Figure 3-2.

The main results for the OCS temperature in the PICO-RC1 segment, in contingency operations with a TPSS out-of-service, are summarized in Table 5-9.

<table>
<thead>
<tr>
<th>#</th>
<th>Case Description</th>
<th>Track</th>
<th>Contact Wire</th>
<th>Messenger Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>PICO out-of-service; DTO for max RMS current in feeder RC1-1; standard OCS; uniform EJ spacing of 375 ft on new OCS; quoted max currents and temperatures are near EJ at 7+00 for the CW, and near RC1-1 feeder for the MW.</td>
<td>EB (NB)</td>
<td>483</td>
<td>804</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>65.6 mean</td>
<td>71.9 mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>71.8 crest</td>
<td>75.6 crest</td>
</tr>
<tr>
<td>5</td>
<td>RC1 out-of-service; DTO for max RMS current in feeder PICO-3; double MW along RC; the max CW temperature is on the N. side of the first tap of feeder PICO-3.</td>
<td>NB</td>
<td>445</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>73.6 mean</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>79.3 crest</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>As in Case 5 above, but with DTO for the maximum RMS current in feeder PICO-4. The maximum CW temperature is on the S. side of the first tap of feeder PICO-4.</td>
<td>SB</td>
<td>605</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>88.2 mean</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>97.5 crest</td>
<td></td>
</tr>
</tbody>
</table>

The OCS temperature results from Case 4 in Table 5-9 show that from strictly OCS temperature point of view a single messenger wire would be adequate on the West side of RC1.

Figure 5-8A shows the OCS temperature profile for Case 4, from the beginning of the tunnel (the transition point between SCW and simple catenary) to substation RC1 at the 2nd/Hope Station. As seen, the OCS temperature is within acceptable limits both near the 2nd/Hope Station and in the existing tunnel around the 7th/Metro Center Station.

However, as a conservative approach and especially to improve the voltage margin in contingency operations - given possible operation of other cars on RC with higher propulsion current than the P2550, as well as irregular headway patterns rather than uniform 2.5-minute headway - a double MW was assumed for a greater length, from the RC/Blue Line interface to the track split point at Alameda Junction.

The contact wire temperatures in the PICO Station area were determined for contingency operations with RC1 out-of-service. Case 5 describes the conditions for the maximum CW temperature on the North side of the first feeder tap to the SCW of feeder PICO-3, and the results show that the maximum CW temperature is within the acceptable limit.

Case 6, which is used to determine the maximum CW temperature to the South of the first tap to the contact wire of feeder PICO-4, showed however that the CW temperature on the SB track at that location (just South of 145+87 by civil stationing) exceeds the 75 °C limit. It is a hot spot in the contact wire created by the relative long SCW-only segment to the substation’s sectionalizing gap without another cable riser in an area where accelerating trains draw peak current and the headway is short.

The contact wire temperature profile in the PICO Station area is shown on Figure 5-9A.
5.8.3 Segments on the Gold Line

As seen from Table 5-5, the maximum RMS currents in contingency operations in the positive feeders of Red Line Yard (TPS01) and Union (P110) TPSS facing Regional Connector, are 1101 A, and 1145 A, respectively. These currents are comfortably below the estimated OCS ampacity of 1314 A for open-air operation, and therefore it is concluded that there is no OCS temperature problem on the Gold Line in the vicinity of the RC interface.

5.9 Sample Graphics Outputs

Figure 5-1A: Train on Route 1, Normal System, Speed v. Distance
Figure 5-1B: Train on Route 1, Normal System, Current v. Distance
Figure 5-1C: Train on Route 1, Normal System, Voltage v. Distance
Figure 5-2A: Train on Route 2, Normal System, Speed v. Distance

Train on Route 2 [Pasadena - Long Beach]

![Graph showing train speed vs distance along Route 2 with stops at PICO Station, 7th St/Metro, 2nd/3rd Hope, 2nd/Broadway, 1st/Central, Union Station, and Chinatown. The graph indicates varying speeds across different stops.]

Train Speed (mph) vs Location (mi)
Figure 5-2B: Train on Route 2, Normal System, Current v. Distance

Train on Route 2 [Pasadena - Long Beach]

Simulation at DTO = 0

Train Current (A)

Location (mi)

PICO Station 7th St/Metro 2nd/Hope 2nd/Broadway 1st/Central Union Station Chinatown

Train 206

December 1, 2011
Figure 5-2C: Train on Route 2, Normal System, Voltage v. Distance

Train on Route 2 [Pasadena - Long Beach]

- Simulation at DTO = 0
- TPSS

Train Voltage (V dc) vs. Location (mi)
Figure 5-3A: Train on Route 4, Red Line Yard TPSS Out-of-Service, Speed v. Distance

Train on Route 4 [East LA - Culver City]
Contingency Operations

Train Speed (mph)

Simulation at DTO = 279

Location (mi)

1 2 3 4 5 6

PICO Station 7th St/Metro 2nd/Hope 2nd/Broadway 1st/Central Pico/Aliso Mariachi Pl. Solo

Train 403

REGIONAL CONNECTOR TRANSIT CORRIDOR PROJECT
December 1, 2011
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Figure 5-3B: Train on Route 4, Red Line Yard TPSS Out-of-Service, Current v. Distance

Train on Route 4 [East LA - Culver City]
Contingency Operations

Simulation at DTO = 279

Train Current (A)

Location (mi)

PICO Station
7th St/Metro
2nd/Hope
2nd/Broadway
1st/Central
Pico/Aliso
Mariachi Plaza
Soto

Train 403

-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
5000

Train 403

1 2 3 4 5 6

December 1, 2011
Figure 5-3C: Train on Route 4, Red Line Yard TPSS Out-of-Service, Voltage v. Distance

Train on Route 4 [East LA - Culver City] Contingency Operations

Simulation at DTO = 279

TPSS In Service
TPSS Off-Line

Train Voltage (V dc)

Location (mi)

Train 403
Figure 5-4A: Train on Route 2, Union TPSS Out-of-Service, Speed v. Distance

Train on Route 2 [Pasadena - Long Beach]  
Contingency Operations

Simulation at DTO = 294  
Train 202

<table>
<thead>
<tr>
<th>Location (mi)</th>
<th>PICO Station</th>
<th>2nd/3rd Hope</th>
<th>2nd/3rd Hope</th>
<th>1st/4th Central</th>
<th>Union Station</th>
<th>Chinatown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Speed (mph)</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

December 1, 2011
Figure 5-4B: Train on Route 2, Union TPSS Out-of-Service, Current v. Distance

Train on Route 2 [Pasadena - Long Beach]
Contingency Operations

Simulation at DTO = 294

-4000 -3000 -2000 -1000 0 1000 2000 3000 4000 5000
Train Current (A)

1 2 3 4 5 6
Location (mi)

PICO Station 7th St/Metro 2nd/Hope 2nd/Broadway 1st/Central Union Station Chinatown

Train 202

REGIONAL CONNECTOR TRANSIT CORRIDOR PROJECT
December 1, 2011
Figure 5-4C: Train on Route 2, Union TPSS Out-of-Service, Voltage v. Distance
Figure 5-5A: DC Bus Voltage of TPSS RC2, Contingency Operations with RC1 Out-of-Service

Substation RC2 Contingency Operations

Operations at DTO = 114

No-Load Voltage

Full-Load Voltage

Elapsed Time (mm:ss)
Figure 5-5B: DC Current of TPSS RC2, Contingency Operations with RC1 Out-of-Service

Substation RC2
Contingency Operations

Operations at DTO = 114

Full-Load Current

DC Current (A)

Elapsed Time (mm:ss)
Figure 5-5C: Current in DC Feeder RC2-1, Contingency Operations with TPSS RC1 Out-of-Service

Operations at DTO = 114 sec
Figure 5-5D: Current in DC Feeder RC2-2, Contingency Operations with TPSS RC1 Out-of-Service
Figure 5-5E: Current in DC Feeder RC2-3, Contingency Operations with TPSS RC1 Out-of-Service

Positive Feeder RC2-3
Contingency Operations
Operations at DTO = 114 sec
Figure 5-5F: Current in DC Feeder RC2-4, Contingency Operations with TPSS RC1 Out-of-Service

Positive Feeder RC2-4
Contingency Operations

Operations at DTO = 114

Elapsed Time (mm:ss)
Figure 5-6A: RC1-RC2 Segment, Contingency Operations, Double MW, Uniform 400-ft EJ Spacing, OCS Temperature Profile
Figure 5-6B: RC1-RC2 Segment, Contingency Operations, Double MW, Uniform 400-ft EJ Spacing, Currents in CW and MW at Probe 1
Figure 5-6C: RC1-RC2 Segment, Contingency Operations, Double MW, Uniform 400-ft EJ Spacing, CW Temperature v. Time at Probe 1

Contact Wire Temperature v. Time
Uniform 400 ft EJ Spacing
At Probe 1, WB Track

CW: 350 kcmil copper @ 25% wear

Temperature (deg C)
Elapsed Time (mm:ss)
Figure 5-7A: RC1-RC2 Segment, Contingency Operations with RC1 Out of Service, Double MW, Uniform 400-ft EJ Spacing Plus Extra EJ on WB Track, OCS Temperature Profile

OCS Mean Temperature Profile
Double Messenger Wire
400 ft EJ Spacing, With Extra EJ on WB Track
Figure 5-7B: RC1-RC2 Segment, Contingency Operations with RC1 Out of Service, Double MW, Uniform 400-ft EJ Spacing Plus Extra EJ on WB Track, Currents in CW and MW at Probe 1

Currents in Contact Wire and Messenger Wire (Individual) With Extra EJ on WB Track At Probe 1, WB Track

Elapsed Time (mm:ss)
Figure 5-7C: RC1-RC2 Segment, Contingency Operations with RC1 Out of Service, Double MW, Uniform 400-ft EJ Spacing Plus Extra EJ on WB Track, CW Temperature v. Time at Probe 1

Contact Wire Temperature v. Time
With Extra EJ on WB Track
at Probe 1, WB Track

CW: 350 kcmil copper @ 25 % wear
Figure 5-7D: RC1-RC2 Segment, Contingency Operations with RC1 Out of Service, Double MW, Uniform 400-ft EJ Spacing Plus Extra EJ on WB Track, MW Temperature v. Time at Probe 1

Messenger Wire Temperature v. Time
With Extra EJ on WB Track
At Probe 1, WB Track
Figure 5-8A: PICO – RC1 Segment, PICO TPSS Out-of-Service, Standard OCS, EJ Spacing of 375 ft on New OCS, OCS Temperature Profile in Tunnel

**OCS Mean Temperature Profile**

*Single 500 kcmil Messenger Wire in Shown Segment*

- **PICO (Off)**
- **RC1**
- **Feeders RC1-1 and RC1-2**
- **End of Tunnel**
- **Equalizing Jumper (Typ)**
- **CW on EB Track**
- **MW on EB Track**
- **Probe 1 Location**

**Location (ft)**

- **970+00**
- **980+00**
- **990+00**
- **1000+00**
- **1010+00**
- **1020+00**
- **1030+00**

- **CW on WB Track**
- **WB Direction**
- **2nd/ Hope**

**Temperature (deg C)**

- **100**
- **90**
- **80**
- **70**
- **60**
- **50**
- **40**
- **30**
- **20**

**Probe 1 Location**

- **7th/Metro**
- **FEEDERS RC1-1**
- **FEEDERS RC1-2**
- **1000+00**
- **1010+00**
- **1020+00**
- **1030+00**

**Location (ft)**

- **970+00**
- **980+00**
- **990+00**
- **1000+00**
- **1010+00**
- **1020+00**
- **1030+00**

**Temperature (deg C)**

- **100**
- **90**
- **80**
- **70**
- **60**
- **50**
- **40**
- **30**
- **20**
Figure 5-8B: PICO – RC1 Segment, PICO TPSS Out-of-Service, Standard OCS, EJ Spacing of 375 ft on New OCS, Currents in CW and MW at Probe 1

Currents in Contact Wire and Messenger Wire
At Probe 1, EB Track

Elapsed Time (mm:ss) vs Current (A) plot showing MW and CW currents.
Figure 5-8C: PICO – RC1 Segment, PICO TPSS Out-of-Service, Standard OCS, EJ Spacing of 375 ft on New OCS, MW Temperature v. Time at Probe 1

Messenger Wire Temperature v. Time
At Probe 1, EB Track

Temperature (deg C)

Elapsed Time (mm:ss)
Figure 5-9A: PICO – RC1 Segment, RC1 TPSS Out-of-Service, CW Temperature Profile neat PICO Station

Mean Temperature Profile of Contact Wire
PICO Station Area

- SCW Only
- SCW With Underground Feeder
- Catenary
- SI
- First tap to CW for positive feeders PICO-3 and PICO-4
- CW of SB Track
- CW of NB Track
- Cable Riser (Typ)
- NB Direction

Temperature (deg C) vs Location (ft)
6.0 CONCLUSIONS AND RECOMMENDATIONS

Following below are the main conclusions and recommendations based on the results from the traction power load flow study.

6.1 Regional Connector

Two traction power substations are needed for RC. Per present design the substations are located at the 2nd/Hope and 2nd/Broadway Stations at nearly central position in the downtown tunnel.

Both substations, labeled RC1 and RC2 for the purposes of the report, will have a single transformer/rectifier unit. Given the RMS loading results from the simulations a 2000 kW nominal rating is appropriate for each TPSS. Also, the substations should be specified with extra heavy-duty traction overload capability as defined in NEMA RI-9.

The substations should be specified with initial voltage regulation of 4.5 %, as used in the simulation analysis. This voltage regulation should be maintained up to minimum 350 % load. Nominal dc bus voltage at 100 % load is 750 V dc per Metro Rail Design Criteria.

Based on the results of the study, appropriate current ratings of the substation’s dc circuit breakers are 4000 A for the main circuit breaker, and 2000 A for the feeder circuit breakers.

The following dc feeder sizes were established based on the maximum RMS currents in contingency operations: 3-750 kcmil copper cables for the positive feeders, except for the WB feeders of TPSS RC2, which are sized at 4-750 kcmil; and 6-750 kcmil copper cables total per TPSS for the negative return feeder (three cables per track).

It is recommended that the two tracks of RC be cross-bonded, both at the TPSS negative return connections, as well as at several other locations as indicated. Cross bonding should be done with 3-500 kcmil copper cables, which as the study showed would be adequate and usually conservative given the RMS currents through them.

Double messenger wire is required at least between substations RC1 and RC2, to avoid overheating the OCS in contingency operations with the used ambient conditions in the tunnel summer time (see Section 4.5 for details). However, a longer extent of the double messenger - from the interface of RC with the Blue Line to the track turnout of the Alameda Junction - is recommended, to improve the train voltage margin in contingency operations. The larger difference between the minimum train voltage and 525 V dc criteria is desirable as the P865 vehicle in the Metro fleet, which may also operate on the Regional Connector, draws higher propulsion current than the P2550 car used in the study, and also does not feature forced reduced performance at low voltage.

With the recommended TES the minimum train voltage in contingency operations on the Regional Connector is 563 V dc, which could occur if substation RC1 is out of service.

6.2 Gold Line Near RC Interface

The study showed minimum train voltages below criteria in contingency operations if either the Red Line Yard TPSS on the Eastside, or Union TPSS on the Pasadena side, are taken out of service. The minimum train voltages in these scenarios are 499 V dc and 474 V dc,
respectively. The electrical interface between Regional Connector and Gold Line, given the OCS sectionalizing at the Alameda Junction, is via two-way conductivity, with dc circuits in a triangular configuration, as indicated on Figure 3-3.

The simulations showed that with one of the above substations out of service, given the headways and speed limit profiles in the area, there will be four trains in the outage zone limited by three healthy substations, one on each side. And that depending on the timing offset between trains running in the opposite directions on a given line, it is possible that all four trains are in acceleration mode (albeit at different speed) drawing nearly maximum current at the same time. The above quoted minimum voltages occur in such train configurations, as seen from the train status details listed in Table 5-3.

The study did not attempt to find a solution to the above low voltage problems. It was deemed appropriate to first discuss the issue with Metro, following Metro’s review of the report, and identify acceptable in principle solutions before evaluating their effectiveness. The latter could be done with a follow-up study.

One measure that could be considered is relocating TPSS RC2 from the 2nd/Broadway Station to the 1st/Central Station, as well as extending the double messenger wire along the branches of the Alameda Junction to the actual interface with the existing OCS of the Gold Line. This would reduce the outage zone and provide better voltage support from the Regional Connector side in such contingencies. It would further increase the RMS load on the NB feeders of TPSS PICO in contingency operations though, as well as the load on the single contact wire segment to the North of PICO, so such a measure would need to be evaluated with respect to its effectiveness and implications.

6.3 Blue Line Near RC Interface

The study identified a different type of problem at the interface of RC with the Blue Line, one of overload of existing dc circuits.

The two positive feeders of TPSS PICO supplying power to the North of the sectionalizing gap, and sized at 2-750 kcmil copper cables each, are at risk of overload, especially in contingency operations with TPSS RC1 out of service. In such contingency operations the maximum RMS current can be as high as 19 % above the feeder ampacity. The overloading is only in the segment from the substation’s dc feeder circuit breaker to the first connection to the contact wire (as the feeders continue underground with additional tap connections to the single contact wire).

Additional data for the routing of the positive and negative feeders of the PICO substation, and associated raceway details, is needed to fully evaluate the extent of the overload. The study’s estimate of 1230 A for the current carrying capability of the 2-750 kcmil dc feeder is based on the assumption of two such circuits per common underground ductbank. However, if more than two feeders are installed in a common ductbank between the substation and the tracks, additional de-rating of the cable ampacity would have to be taken into account, leading to worse overload.

A hot spot in the contact wire in the PICO Station area was also identified, where the contact wire temperature – on the SB track, and close to the South end of the station - exceeds the 75 ºC (167 F) limit. This is due to the 425-ft long “single contact wire only” segment from the first connection of the feeder to the sectionalizing gap further South, located in a train acceleration
zone at short (2.5-minute) headway. The OCS sectionalizing and feeder connection scheme in the area, based on available record drawings for the Blue Line, as modeled for the study is shown on Figure 3-2. It is advisable for Metro to confirm the accuracy of this scheme, and that it adequately represents the current conditions in the PICO Station area.