# DRAFT

# Fort Worth Modern Streetcar

# TRACTION POWER SUPPLY AND DISTRIBUTION

**JUNE 17, 2010**

## 1. General Requirements

The traction power supply and distribution system consists of traction power substations located along the system route and the overhead and underground wiring needed to move power from the substations to the operating vehicles. All components, from the power utility supply to the vehicle pantograph's point-of-contact with the overhead wire, are included in this system. Also addressed are issues related to ensuring the integrity of the return circuit from the vehicle wheels to the substation,

The traction power substations are connected to the distribution circuits of the local power utility company. Each substation includes all the equipment necessary to transform and rectify the utility ac three-phase voltage to the dc distribution voltage required by the vehicles. The individual units are connected in parallel to form a multiple-feed system where revenue operations can continue even in the event of an outage of any one of the substations.

The streetcars will collect power from a contact wire by means of pantographs and return power to the substations via the running rails. The overhead contact wire can be either a single wire (trolley wire) system or a catenary system incorporating a parallel conductor to increase the amount of power delivered via the substations. The return rails are ungrounded on the revenue service line to minimize the potential for stray currents resulting in possible corrosion of metallic structures along the trackway.

The traction power supply and distribution system must maintain the system voltage at the streetcar's pantograph within an allowable range for operation. For a 750 Vdc nominal system, this is typically 525 to 950 volts. The system must also operate within the allowable capacity of the substations. These conditions include the capability of operating the intended service with any one substation out-of-service.

The functional requirements need to be based on the intended service and the possible anticipated future expansion of the system. At this stage, the service frequency of the streetcar operations has not been determined. However, we should anticipate that future expansions of the system might result in headways as short as five minutes. The traction power system can be difficult and expensive to upgrade in the future if service expands, however, the incremental cost in supplying a system initially that can support the heavier potential future loads is much smaller. Therefore, it is recommended that the initial system be designed to support single vehicles operating at 5-minute intervals.

## 2. System Configuration

The configuration of the traction power supply and distribution system can have a major impact on the right-of-way and system construction costs. Three basic configurations are typically used for the operation of streetcars and light rail vehicles. Each option has advantages and disadvantages based on local conditions and requirements. These can be identified as:

**(1) High power substations with overhead feeders;**

**(2) High power substations with underground feeders; and**

**(3) Low power substations without feeders.**

Each of theses systems is described more detail in the sections on traction power supply and traction power distribution, below. It is critical that the traction power supply be coordinated properly with the distribution method to achieve an efficient system.

## 3. Traction Power Supply

### 3.1 High Power Substation Option

High power substations are defined as having a rated power of over 500 kW. The utility supply is typically medium voltage, 12.5 to 15 kV, with full load current outputs of over 1,000 amps. Either they can be provided as pre-fabricated units ready to set in place and connect or as individual assemblies of equipment which can be installed in a specially built enclosure. If service using multiple-car consists is desired, high power substations must be used to provide the electrical current required by the vehicles.

The high voltage utility service and resultant larger fault currents available require a large ground mat to be installed under the building for safety. The ground mat needs to be able to dissipate the available fault currents without allowing the voltage of the ground near the enclosure to rise above safe levels of “step and touch” potentials. The area adjacent to the substation normally includes crushed rock to limit exposure to higher potentials. The area requirement for such a substation is shown below:

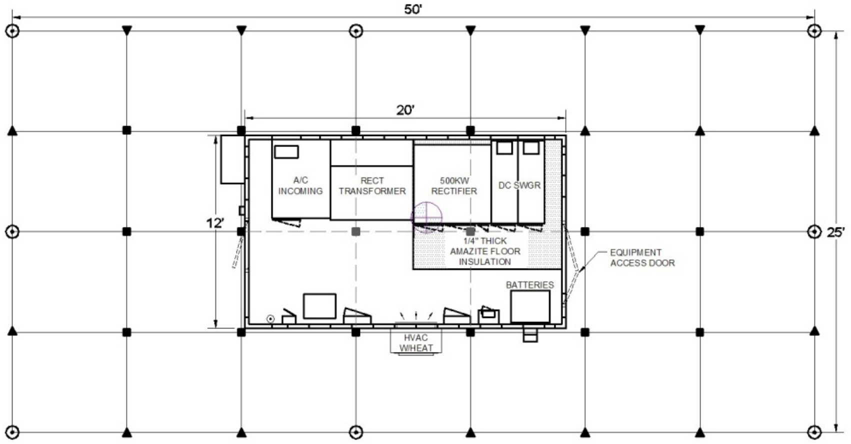

Fig. 1 Typical High Power Site Plan

The spacing of high power substations on the alignment is generally one 1-MW unit per mile of double track plus one unit to reduce the distance at the end of the line in the event of a substation outage. This is a general rule of thumb and analysis during preliminary engineering would result in a more accurate number for the Fort Worth alignments.

Some of the advantages of incorporating the use of high-powered substations are that fewer units are required and, if a catenary system with overhead parallel feeders is used, lower overall cost.

For alignments in urban cores, like portions of the Fort Worth system, the high power option has disadvantages in the cost of utility service at higher voltage levels and the greater land area required to site the substations. If an overhead distribution is unwanted for aesthetic reasons, the cost of installing underground parallel feeders with high-voltage taps to the overhead can be expensive.

### 3.2 Low Power Substation Option

Low power substations are defined as having a rated power of 500 kW or less. The utility supply is typically low voltage, 480 Vac, with full load current outputs of 700 amps or less. Similar to their high power cousins, they can be provided as either pre-fabricated units ready to set in place and connect or as individual assemblies of equipment which can be installed in a specially built enclosure.

The low voltage utility service and lower fault currents available generally do not require a large ground mat be installed under the building for safety. A grounding ring around the perimeter of the building, similar to low power commercial/industrial installations, is normally sufficient. The land area necessary for siting the building is also reduced. Installations have been made in such locations as underground vaults, building basements, and parking garages. For dense urban areas, the flexibility in location can be advantageous. The figure below shows the approximate dimensions for a freestanding low power substation:

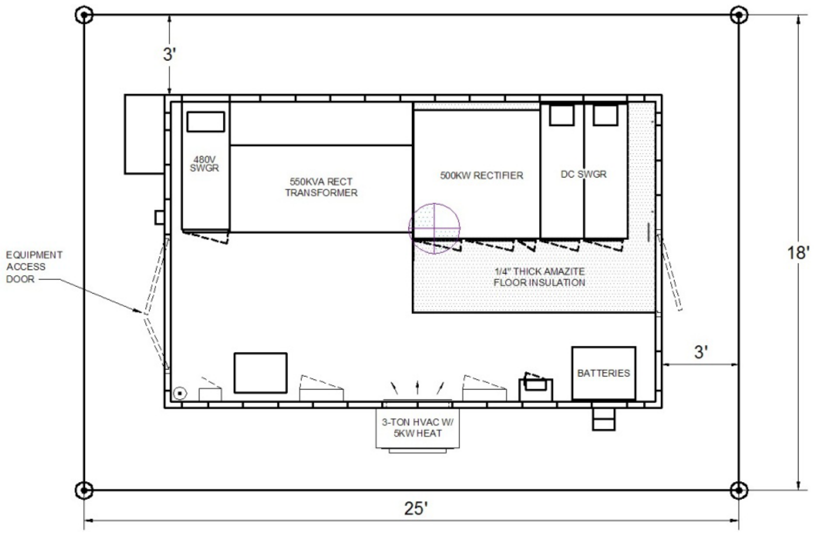

Fig. 2 Typical Low Power Site Plan

The spacing between low power substations along the alignment is less than for the high power option. Typical spacing is approximately one unit per one-half mile, or double the number of high power substations that would be required for the same alignment. However, significant cost savings may result from using low voltage switchgear on the utility feed, using a 6-pulse rectifier instead of a 12-pulse rectifier, and the advantages listed below:

**(1) No underground or overhead parallel feeder wires;**

**(2) Utility service from common distribution circuits;**

**(3) Lower return rail voltages and lower stray current levels reducing utility relocations;**

**(4) Smaller land acquisition requirements; and**

**(5) Greater flexibility in the siting of substations.**

The primary disadvantage is the increase in the number of individual units along the trackway.

### 3.3 Substation Enclosures

Substation enclosures may have a visual impact along the trackway and their location and styling may play a role in their selection. The least expensive alternative is typically the procurement and installation of pre-fabricated enclosures. These are usually sheet metal “sheds” like that shown in the photo below. Often these are set behind fences to prevent graffiti or unauthorized access.

Figure 3 – Low Power Pre-fabricated Enclosure

Alternatively, the substation equipment may be purchased separately and installed in a structure built on site. The structure either can be a stand-alone building or may be a modification of an existing structure. The photos below show a freestanding high power substation installed in a brick building along a light rail line and an application where two parking spaces of an existing parking garage were modified to accommodate a low power substation.

Fig. 4 – Building for High Power Substation

Fig. 5 – Parking Garage Enclosure for Low Power Substation

It is also possible to build a façade around a sheet metal pre-fab unit. However, these types of applications have experienced problems with the interpretation of building codes and can be more expensive than simply constructing a stand-alone building to house the traction power equipment. The enclosure of a pre-fab unit generally means you are paying for a building with the substation equipment then paying for a second building on site.

### 3.4 Substation Power Rating

The power rating of the substations will be determined during the future preliminary design phase by calculations and computer simulations of the alignment operating at the minimum design headway. This rating will be used to specify the full load rating of the substations required at the locations identified along the trackway. The actual operation of the streetcars will exceed the full load rating for short periods such as when the vehicle accelerates from a station platform or more than one streetcar is operating in the area of the same substation. To accommodate these overloads, a load cycle for the substations will be specified.

A typical mainline substation should be capable of supplying the following transit load cycle in accordance with NEMA and ANSI standards:

**(1) Constant temperature of all equipment shall be reached following operation at 100% rated power for a minimum of 2 hours.**

**(2) Equipment shall then be able to sustain a 150% overload for 2 hours with five evenly spaced periods of one minute each at 300% of rated load and one 15 second period at 450% of rated load, followed by a maximum short circuit current with duration equal to substation protective device clearing time.**

**(3) Equipment shall be capable of sustaining such an overload twice a day – once in AM peak and once in the PM peak periods.**

### 3.5 Substation Incoming Service

Incoming primary ac power to the traction power substations will be determined by the system configuration selected. If high power substations are used, the supply will most likely be provided at a nominal 12.5 to 15 kV, 3 phase, 3 wire, and 60 hertz. If the low power option is selected the supply will be provided at a nominal 480 Vac, 3 phase, 3 or 4 wire, 60 hertz. Coordination with the local utility and the performance of a cost analysis after the preferred locations for the substations are selected will finalize the parameters of the incoming electrical service.

Cable ductbanks, conduits, raceways and manholes are typically constructed from the point of utility interface to the meter with cabling installed by the utility. From the meter to the incoming service cubicle in the substation, both the ductbank and cabling are typically constructed by the Agency. The design will be fully coordinated with the utility requirements and interfaced with the utility overhead and/or underground facilities. The feeder rating shall permit the substations to supply the specified load cycle and short circuits without exceeding the allowable equipment temperatures.

### 3.6 Negative Return

The negative return path for electrical current from the substation will be via the running rails in the street. These rails will be isolated from earth ground as a stray current control method. The isolated rails will be monitored by a potential relay in the substation that will not allow the voltage difference between the return rails and earth ground to exceed 50 volts in normal operation or 75 volts with a substation outage. See section E for more details on corrosion control and stray current.

### 3.7 Substation Grounding

Each traction power substation shall be provided with a grounding system to limit step and touch potentials in the event of a fault. Typically, this will be a mat with high power substations, as shown in Fig. 1, or a ring arrangement for low power substations, as shown in Fig. 2. Special locations may require a special design approach such as the installation of a remote ground if the substation is situated in an existing structure.

The safety grounding system shall be designed so that the step and touch potentials at the rated short circuit current do not exceed the recommended safety limits of IEEE standards. An average body weight of 125 lbs shall be used in calculating the tolerable step and touch potentials. Where the surface soil layer covering the ground mat is coarse, clean gravel or asphalt over gravel, the grounding shall be designed in accordance with IEEE Standard 80.

The traction power grounding system shall be designed and installed in a manner that obtains a ground resistance of 5 ohms or less when tested in accordance with IEEE 81.

### 3.8 Substation Equipment

Each traction power substation will be equipped with a lineup of high voltage conversion equipment cubicles to transform the incoming ac power to nominal 750 Vdc power for operation of the streetcars. The cubicles will be arranged in a lineup of dead front enclosures housing the ac incoming service, power rectifier transformer, rectifier, disconnect switches, and dc high-speed feeder breakers.

Power for auxiliary loads, including lighting, HVAC, battery backup, battery charger, and convenience outlets, will be derived from the incoming ac supply.

Based on the magnitude of load, overload and short circuit currents, a comprehensive protective scheme shall be designed to protect the substation equipment and the overhead distribution system as well as provide back up for the transit vehicle protective devices. All protective relays shall be high quality utility-type draw-out devices enclosed in rustproof, dust-proof, high-impact cases with integral test switches. The protective relays shall be self-reset and have seal-in, hand-reset targets indicating relay operation. The relays shall be arranged to be visible, accessible for maintenance and logically grouped, with devices of related functions located in proximity to each other.

### 3.9 Emergency Shutdown

Each substation shall be equipped with traction electrification emergency shutdown buttons. One button shall be located on the exterior of the enclosure or nearby pole and shall be accessible to local fire department personnel, or other approved safety personnel, by key-switch only. The other emergency shutdown shall be located inside near an entry on the interior. Actuation of the button shall trip the ac incoming service breaker on the substation.

Tripping the incoming ac service breaker on one substation will not de-energize the overhead contact line unless a transfer trip system is installed which will also trip the two adjacent substation’s dc feeder breakers. Without transfer trip capability, the overhead contact line will need to be de-energized by opening the manual disconnect switches for the overhead contact system at the two adjacent substations or using the emergency shutdown buttons at the two adjacent substations.

The method of emergency shutdown activation will be coordinated with the local fire/life safety agencies during the future preliminary design phase.

## *4. Traction Power Distribution*

Traction power is distributed from the substations to the vehicles via an overhead contact system (OCS). The OCS is one of the elements that is highly visible to the public and may have a large impact on the streetscape. This section discusses the design criteria and options for the OCS and its components. The options can be intermixed, for example, constructing part of the line with cantilever poles and part with span wire.

### 4.1 Overhead Feeder (Simple Catenary) Option

A simple catenary consists of a messenger wire supporting a contact wire by the means of hangers. With this system, each pole will use two cantilevers, one for the contact wire and one for the messenger wire. The picture below shows a long cantilever arrangement that would be used for crossing a parking lane.

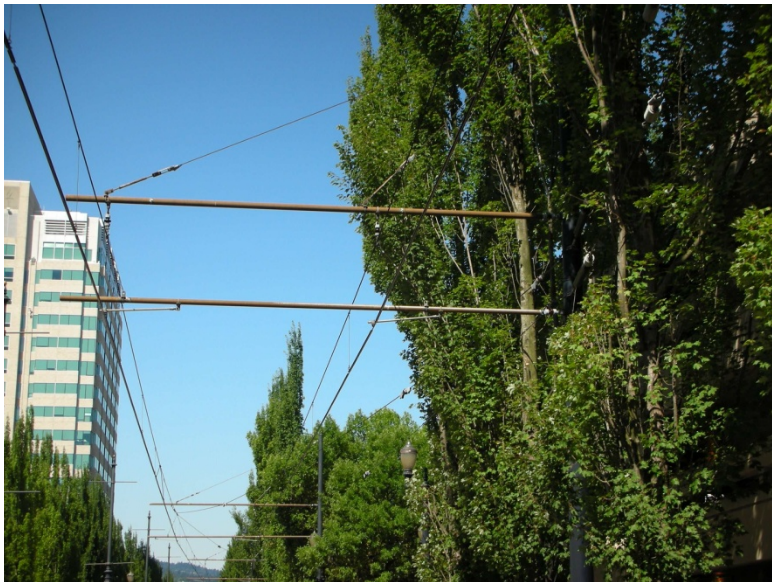

Fig. 6 - Typical Simple Catenary Cantilever

This style of catenary is paired with the high power substation option and provides sufficient copper wire capacity to move the required current at sufficient voltages over a mile along the trackway. Generally, this is the least expensive option to implement.

Simple catenary usually uses an auto-tensioning system where counterweights at each end of a tension segment adjust the wire tension, and consequently wire height, to accommodate the lengthening or shortening of the wire with ambient temperature changes. A typical tension segment extends for a mile with a fixed mid-point anchor.

The “system height” or distance between the messenger and contact wires will determine the distance between poles as discussed in section 4, below.

### 4.2 Trolley Wire with Underground Feeder Option

A trolley wire system uses a single contact wire suspended over the city streets. This option must supplement the single overhead contact wire with a parallel wire running in an underground ductbank along the trackway. The combination of the two wires provides sufficient capacity to use the high power substation option. However, this configuration is much more costly than using an overhead messenger wire. The advantage of this type of system is that it reduces the amount of "hardware in the air" and provides a more esthetically minimalist design.

The underground parallel feeder is spliced approximately every 200 feet and routed up a pole to feed the single overhead contact wire. The required spacing for the connections is determined using computer simulations performed during the future preliminary design phase. The picture below shows a typical connection on a trolley wire suspended on span wires across the trackway.

Fig. 7 – Connection of parallel feeder to trolley wire

A trolley wire system can be installed either as an auto-tensioned system, as discussed in the previous section, or as a fixed-termination system. A fixed-termination system does not attempt to adjust the wire tension or height to compensate for changes in ambient temperature. It is stretched tight during cold weather and allowed to sag between the supports in hot weather. This design is appropriate for low speed operation in climates without large temperature variations.

### 4.3 Trolley Wire without Feeders Option

A feederless trolley wire system relies on a single contact wire to distribute power to the vehicles and does not incorporate an overhead messenger wire or an underground parallel feeder. Historically it has been used with older trolley systems with smaller vehicles that do not use electronic controls for propulsion or auxiliary power generation. Modern streetcars carry more passengers, draw higher currents, and have low voltage limits to protect the solid-state devices. This type of system can be used with the low power substation option and its closer spacing of the substations efficiently delivers power to the vehicles. The picture below shows a trolley wire suspended from a cantilever extending over the parking lane.

Fig. 8 – Trolley wire suspended by cantilever

The feederless trolley wire design allows the single wire to limit visual impacts and saves the cost of relocating existing utilities to install an underground ductbank in city streets.

### 4.4 Poles

The style of poles and their integration into the existing streetscape is important to the overall appearance of the project. The poles can be either a simple tapered tubular pole or an ornamental pole designed to interface aesthetically with other structures along the alignment. Less expensive options would include a wide flange (I-beam) pole or a round pole with steps reducing the diameter from bottom to top of pole. The noted less expensive pole options are not recommended where visual appearance is important; however, they could be used in areas such as the storage yard.

If reducing the number of poles along the street is important, the OCS support poles may be combined with the street lighting poles or other structures such as traffic signal poles. Figures 7 and 8, above, show a tapered tubular pole enclosed in an ornamental cladding with lamps. The picture below shows a pole incorporating a typical Cobra-style streetlight.

Fig. 9 – Joint use pole with Cobra heads

The spacing of the poles along the trackway is dependent on both the choice of simple catenary or trolley wire and whether the contact wire is suspended from cantilevers or a span wire. The designer will attempt to space the poles at regular intervals along the entire alignment with a resulting design standard of two or three poles per block depending on the maximum span length of the OCS and the length of the blocks. If the poles are integrated with street lighting infrastructure, generally the photometrics of the lighting determines the distance between poles.

Span lengths are determined by the type of OCS used and the local climatic conditions. Generally, for a trolley wire system the maximum span length is 120 feet for auto-tensioned systems and 100 feet for fixed-termination systems. For simple catenary, the maximum span length depends on the system height, ranging from 115 feet with an 18-inch system height to 220 feet with a 48-inch system height. The distance actually used in the design is 10 feet less than the maximum span length to permit flexibility in citing the poles and foundations to avoid underground structures found during construction of the line.

When the OCS is suspended using cantilever arms, as shown in Fig. 9 above, poles are only needed on one side of street. Some localities desire to minimize the amount of hardware in the air and therefore a span wire system is used. The span wires utilize poles in pairs set on opposite sides of the street. The resultant suspension system is almost invisible as shown in Figures 10 and 11 below where traffic signal poles provide support.

Fig. 10 – Span wires support by traffic signal poles

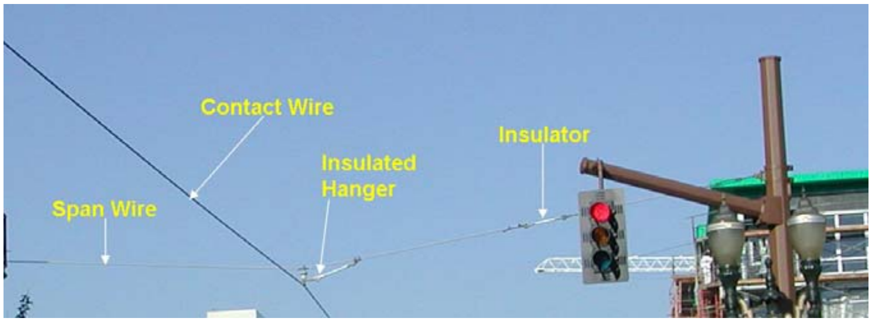

Fig. 11 – Detail of span wire arrangement

In specific areas where poles are difficult to locate, other suspension methods need to be utilized. An example of this situation is shown below in Figure 12 where basement extensions from the buildings under the sidewalk prevent the installation of a pole and foundation. In this instance, an attachment to the building face was used after obtaining an easement from the owner.

Fig. 12 – Building Attachment

### 4.5 Electrical Clearances

The overhead contact wire is a bare copper wire energized at 750 volts and will rise to 925 volts during regeneration from the vehicles. The establishment and maintenance of clearances in relation to wayside structures and the public are critical. Established standards for these clearance dimensions are addressed by American Railway Engineering and Maintenance-of-Way Association (AREMA), National Fire Protection Agency (NFPA), Institute of Electrical and Electronics Engineers (IEEE), and Occupational Health and Safety Administration (OHSA). Additionally, the design needs to incorporate a minimum of two levels of insulation between the energized contact wire and supporting structures, and all structures that the contact wire may touch in a failure mode need to be solidly grounded.

The clearance of the OCS above the roadway is regulated by the National Electrical Safety Code (NESC) as published by the IEEE. The minimum height of the contact wire above the roadway under worst case conditions is required to be 18 feet with mixed traffic.  To maintain this clearance under all conditions the design height for the system will need to be between19 and 19½ feet. In specific areas where structures such as overpasses restrict the clearance above the roadway, lower clearances may be approved by the local governing agency. In such instances, appropriate restrictions need to be placed on traffic, particularly trucks.

The recommended clearances for the energized contact wire and pantograph to grounded structures, such as an underpass of an overhead structure, is included in the AREMA Manual Chapter 33.  For dynamic passing conditions, the recommended clearance is a minimum of 3 inches. For static clearance, a minimum of 4 inches is required. For design standards, it is recommended to use 4 inches for the passing clearance and 5 inches for the static clearance.

Clearances for overhead electrical lines above the OCS system are specified in NESC. These clearances are particularly important when overhead utilities cross the trackway/street.

Generally, insulated conductors of less than 750 volts nominal require a minimum of 4 feet of clearance when calculated at their maximum sag, including ice, and wind loads. For conductors between 750 and 22,000 volts a clearance of 6 feet will apply and conductors over 22 kV will require special calculations. Relocation of the existing utilities may be required in the event the required clearance is not achieved.

On urban streets, special attention must be given to overhead traffic signals. In addition to the static and passing clearances noted above, these signals need to be maintained by city traffic departments according to OSHA rules. OSHA requires a minimum of 10 feet of clearance to the energized contact wire for non-qualified personnel to access the traffic signals. If the maintenance personnel are qualified to work near high voltage lines and are provided with specialized equipment, such as isolated lift trucks, this clearance may be reduced to 3’-8”. With mast arm mounted signal heads, one method of providing the clearances is shown in Fig. 10 above. The picture below shows another method when the signal heads and train warning sign are mounted on a span wire.

Fig. 13 – Traffic signal interface

### 4.6 OCS Design Study

The design of the OCS is based on an engineering analysis initiated during the future preliminary engineering phase and is continually updated through the issuance of the system bid package. The analysis includes calculations of the OCS design parameters, pantograph security analysis, pantograph operations analysis, conductor tensions and maximum tension length analysis for the design wire height. It shall take into account all factors that contribute to displacement of the contact wire with respect to the pantograph, including:

- Climatic data
- Conductor data

- Vehicle clearance envelope
- Pantograph dimensions
- Allowable contact wire wear
- Pole deflection due to loads imposed
- Erection tolerances
- Maintenance tolerances
- Vehicle roll and lateral displacement
- Sway of pantograph
- Static pantograph centerline variation from vehicle centerline
- Dynamic pantograph centerline variation from track centerline due to vehicle displacement on curves

The result of this study shall define the following parameters:

- Maximum structure spacing as a function of track curvature
- Conductor blow-off, stagger effect and allowable static offset
- Conductor rise and fall
- Conductor along-track movement, stagger variation and wire elongation
- Conductor tensions, sags and factors of safety under various climatic conditions
- Contact wire deviation due to movement of hinged cantilevers
- Conductor profile, hanger lengths and spacing
- Equipment vertical and radial loads
- Loss of conductor tension along the system
- Conductor temperature range for auto tensioning
- Pantograph sweep criteria
- Catenary system height criteria
- Minimum hanger length criteria
- Pantograph clearance envelope

The parameters listed above will form the criteria to be used for the development of the system layouts plans and details of the hardware to be incorporated.

## 5. Stray Current Control

The control of stray earth currents to reasonable levels is an important corrosion control aspect of a direct current powered, rail return transit system. To construct and operate a system without adequate control of stray currents may result in corrosion damage leading to premature failure of underground utility structures and elements of the project itself. An effective program for the limitation of stray currents from the return rails limits potential damages and minimizes the relocation of existing underground utility structures.

The design for stray current control, and its implementation, shall meet the following objectives:

- Realize the design life of system facilities by avoiding premature failure caused by corrosion;
- Minimize annual operating and maintenance costs associated with material deterioration;
- Provide continuity of operations by reducing or eliminating corrosion related failures of systems and subsystems; and
- Minimize detrimental effects to facilities belonging to others as may be caused by stray earth currents from transit operations.

Stray current corrosion control includes measures installed with the traction power system and trackwork to ensure that stray traction currents do not exceed maximum specified levels. During the preliminary engineering phase, engineering calculations and computer simulations of the streetcar system in operation are used to establish the anticipated voltage potentials along the trackway. From these voltage potentials, and the distributed resistance to earth of the return rails, anticipated levels of stray currents are established as design criteria for the project. These levels are used to determine the need to relocate some underground utilities or provide mitigation measures such as sacrificial anodes to protect these and other fixed facilities along the trackway.

The primary means of stray current control is isolation of the negative return system, the running rails. Isolation of the negative return system is accomplished by maintaining “floating” traction power substations, and using state of the art trackwork isolation systems. Trackwork isolation systems are installed to ensure that the track maintains a high level of track-to-earth resistance. Typical values for track-to-earth resistance are as follows:

- Ballasted Trackwork – 500 Ohms per 1,000 Track Feet
- Direct Fixation Trackwork – 500 Ohms per 1,000 Track Feet
- Embedded Trackwork – 250 Ohms per 1,000 Track Feet

Stray traction current monitoring devices are installed in the traction power substations for use in determining the levels of stray current. These facilities can be further utilized to mitigate noted stray traction current, if required, using resistors and/or diodes.

Embedded trackwork is typically installed with a rubber boot surrounding the track, such as the Rail Boot manufactured by Iron Horse Engineering Company, as shown below. The rubber boot completely encapsulates the rail, preventing the traction power current from flowing off the rail and into the earth, thus reducing the levels of stray traction current.

Fig. 14 - Rail boot embedded trackwork isolation system

Additional secondary measures may be applied to mitigate any observed stray traction current, if necessary. These measures typically include making the track slab reinforcing steel in embedded sections electrical continuous. The electrically continuous reinforcing steel acts as a low resistance path for the accumulation and safe mitigation any stray traction current. By creating a low resistance path at a location close to the tracks, any stray traction current would tend to flow along the reinforcing steel instead of along other buried electrically continuous structures adjacent to the trackwork, such as utilities. Test facilities may be installed along the electrically continuous track slab to monitor both the magnitude and direction of stray current flow and to help determine the location of loss of track-to-earth resistance. New utility structures associated with the transit system are typically isolated from existing structures and may be cathodically protected to reduce any impacts from stray traction current.