UNION STATION to GEORGETOWN
Alternatives Analysis
for Premium Transit Service

PROPULSION STUDY

SEPTEMBER 2013
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Executive Summary

The Union Station-Georgetown Alternatives Analysis, also referred to as USGT throughout this document, is an effort intended to conduct the analysis and evaluation of a diverse range of alternatives, including mode, alignment, station/stops and potential vehicle technologies, for the introduction of premium transit service in the K-Street Corridor from Union Station, on the east side, to the Georgetown Waterfront, on the west side.

As a part of the AA study, an evaluation of alternative propulsion and Streetcar technologies to determine the feasibility of catenary-free operations along the K-Street Corridor, connecting the east and west terminus noted above was also conducted. This report summarizes the findings of such analysis and evaluation and is intended to provide a factual, practicable and updated perspective for the implementation of catenary-free operations.

With this in mind, the primary objective effort undertaken as a part of this alternative propulsion and technologies evaluation was to objectively assess the state of catenary-free technologies to determine the feasibility of the application of such technologies in the District of Columbia, including key elements and implications related to procurement and availability of each technology. The effort performed; therefore, revolved around the following:

- **Data Collection** - including research and data gathering from vendor websites, white papers, industry forum records, and technical interviews with a diverse group of car-builders, including SIEMENS, ALSTOM, Bombardier, CAF, Kinki Sharyo, and Brookville.

- **Validation**, evaluation and applicability of available technologies, including wayside infrastructure requirements, as well as operations and maintenance requirements.

- **Implication** of applicable regulations, standards and guidelines, including ADA and Buy America compliance.

- **Procurement implications**, including cost, demand and supply.

Findings and Conclusions

It is important to note that this propulsion report is intended to provide an independent assessment of the feasibility and applicability of catenary-free technologies. However, the introduction of such technologies for the DC Streetcar System would require the development of a comprehensive and complete technology program, beyond the scope of this effort. As such, this report does not provide specific recommendations with regard to the selection of a specific technology, but rather establishes the framework needed to create an appropriate platform for the implementation of a strategy necessary for the development of a comprehensive and complete technology program, as deemed
appropriate by the District Department of Transportation (DDOT). To that end, the following highlights the key findings of the effort.

**Alternative Propulsion Technologies**

Catenary-free technologies have advanced significantly over the past 5-10 years. In fact, whereas 10 years ago the number of systems in operation was limited to a couple of systems in France, today there are a few systems around the world using different technologies with many possibilities for potential application in DC. The technologies evaluated as a part of this effort can be grouped in two main categories:

1. **Energy Storage Systems (ESS)** – these technologies make use of power sources installed on the vehicle to allow for catenary-free operations. As such, these technologies may also be referred at times as On-Board/On-Tram technologies. Vehicles using this technology are powered by batteries, super capacitors, flywheels, fuel cells, diesel and/or alternative fuel sources or a combination of these power devices.

2. **Ground Level Continuous Power Supply Systems (GLCPSS)** – these technologies use ground level power sources instead of Overhead Contact Systems (OCS) to allow for catenary-free operations. As such, these technologies may also be referred at times as Infrastructure/Wayside and/or Off-Tram technologies. These systems distribute power to the vehicle via induction, as it is the case with Bombardier’s PRIMOVE and Ansaldo’s TramWave technologies, or direct contact with a power-rail installed between the running rails, in the case of ALSTOM’s APS technology.

Some of the key advantages and disadvantages of each technology, for each of the categories noted above are included in Section 6 of this report. Before it can be determined that the introduction of catenary-free operations for the DC Streetcar Network is feasible, the ultimate implementation strategy has to be developed for the deployment and implementation of such technology that takes into account the key elements that in the end will drive the application of any alternative propulsion technology, including the following:

- **Implication of proprietary systems and subsystems**, this is particularly important when considering warranty, operations and maintenance of the new system and vehicles. Ground Level Continuous Power Supply Systems are usually proprietary systems and could result in significantly higher costs over the life of the asset.

- **Technical Specifications and Procurement**, the level of detail required to appropriately procure the right technology for the implementation of catenary-free operations needs to be such that appropriate performance criteria are clearly defined while allowing some room for flexibility and innovation, required to trigger a competitive bid setting without compromising the long-term benefits of the investment.
**Utility Relocations**, catenary-free technologies may significantly reduce the need for utility relocations as the potential for stray-current leakage is minimal. This benefit would translate into significant infrastructure cost savings.

**Wayside Infrastructure Requirements**, irrespective of the technology, traction power substations would be required for any system. The location, power and distribution requirements associated with these units need to be evaluated to determine the infrastructure required for charging on-board systems or installation of a ground level continuous power supply.

**Alignment Characteristics and Constraints**, the technology selection is greatly dependent on the alignment characteristics and constraints, including horizontal and vertical geometry, as well as the availability of exclusive ROW. The maximum length of a catenary-free segment is a key driver in the selection of the right technology, with ESS having more limiting factors when compared to ground level systems. Similarly, shared lanes could present a problem for ESS applications as the storage capacity is limited to the type, size and number of storage devices (i.e., super capacitors, batteries, etc.) that can be accommodated on the vehicles. To that end, the ability to accurately predict running times between charging locations/stations is a key part of the ESS technology approach and the unpredictability of running shared lane operations could result in significant delays, thereby, compromising the reliability of this type of technology. Grades exceeding 7% could prove challenging for any technology as steeper grades would translate into much higher energy requirements.

**Maximum Length of Catenary-Free Segment**, based on the results of the data collection, there appears to be no limit to the maximum length for ground level systems as they use a ground level power-rail for power distribution. On the other hand, ESS technologies, based on the research of existing systems around the world, appear to have a maximum length in the range of ¼ mi-2.5 mi, contingent upon the specifics of the technology being used.
Vehicle Dimensions, the width and length of the vehicles are critical parts of the decision when selecting a catenary-free technology, given that storage space, either above or below the vehicle, would be limited when considering all other equipment needs, including HVAC. To that end, the American standard width of 2.65 m allows for much needed space for other equipment and energy storage devices. Similarly, a 30 m vehicle length would also allow for more storage space above and below the vehicle.

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1.0 Introduction

An overview of the basic technologies and their history is presented first. Technologies which are proprietary and will require the District to remain with one supplier to maintain a common operating platform across all routes are referenced by including the name of the supplier. Other technologies, primarily for on-board storage, where the wayside supplier has no proprietary encumbrances and vehicles from several manufacturers can operate without proprietary encumbrances are referred to generically, such as flywheels.

The third section characterizes the alignment into three types based on the maximum distance travelled between recharging of the systems and associates specific off-wire technologies with each type. The first type places no restriction on the maximum distance off-wire and addresses technology options which provide continuous power to the streetcar as it travels. The second type addresses off-wire segments of 1 mile (1.6 km) or less with recharging of the system while operating for a minimum on-wire. The third type considers operation off wire with recharging only while berthed at a passenger station. The advantages and disadvantages of each operational type are discussed. Furthermore, comparison tables including some of the key advantages and disadvantages of each technology are also provided in this section along with a comprehensive discussion on the Operations and Maintenance implications, including a maintenance facility.

The fourth section briefly touches on Buy America compliance and the fifth section highlights a couple of issues related to the existing Streetcar Design Criteria for further consideration, including recommended changes to maximize the number of potential suppliers with existing vehicle designs qualified to bid on a future procurement. This section includes a discussion of the possibility of retrofitting the District’s current streetcars and those on order with the selected technology to enable off-wire operation.

The report concludes with findings and conclusions, including some of the key advantages and disadvantages of each technology evaluated as a part of this effort.

No part of this report is intended to provide endorsement of any manufacturer or vendor.
2.0 Propulsion Technologies

In the last decade new technologies have been developed by several streetcar manufacturers to satisfy the desire to eliminate overhead wiring in visually and historically sensitive areas and increase sustainability through maximizing the recovery of braking energy. A wide variety of technologies are being developed with some readily available for revenue service and others falling by the wayside. The review of these technologies, including alternative propulsion options and readiness for deployment, is critical for the planning of a future Union Station-Georgetown Streetcar system that includes catenary-free segments. This said and acknowledging the rapid changes occurring in this technology arena, this study provides a snapshot of the state of these technologies at this period in time rather than a definitive assessment of the best technology available for application in DC.

The importance of selecting the appropriate technology for the alignment cannot be overstressed. National and international standards for the application, fabrication, certification, and operation of these vehicles are virtually nonexistent and the characteristics of each alignment are used to develop a semi-custom solution based on the best available technology. When developing a complete system it is valuable to consider not only the current alignment, but also try to envisage the worst case future alignment on the projected complete system.

Most of the technologies reviewed are not applicable only to rail transit but also are being developed for buses and automobiles. Pertinent information from these two modes has been included where applicable.
2.1 Ground Level Power Supply

Currently two systems are being marketed that are able to provide continuous power to the vehicle at ground level while in motion without the use of an overhead line and pantograph. The two systems were developed by ALSTOM (APS) and Ansaldo STS (TramWave). One supplier, Bombardier, has demonstrated the ability of their system to provide power while in motion, but is currently deploying the system to provide in-ground recharging capability only at stops and short sections when the vehicle is accelerating from a stop. Additional systems are in varying stages of development by suppliers with and without transit experience.

Continuous power systems offer the advantage of full vehicle performance under all normal operating conditions, including full acceleration and braking, as well as the ability to climb hills or bridge approaches and maintain high capacity passenger area cooling. The systems are immune to the possibility of being stranded without power during long delays due to traffic conditions or other events in the off-wire portion.

In systems where power is supplied to the vehicles continuously, traction power substation locations and sizes will remain the same as for a traditional streetcar system. The cost of the ground level distribution system can be up to six times the cost of an equivalent overhead contact wire due to factors such as the use of independently switched sections which must be of a shorter length than the vehicle to avoid exposing the public to high voltages in the street.

2.1.1 ALSTOM APS

The ALSTOM APS (variously Alimentation par Sol or Aesthetic Power Supply) is the most widely deployed ground level power supply. The system is currently operating in revenue service in Bordeaux (2003), Angers (2011), Reims (2011) and Orleans (2012). It is also under construction in Tours (opening Sept. 2013) and Dubai (opening Nov. 2014). Problems with the start-up of the first installation in Bordeaux have been resolved and the City has extended the original wire-free segment of the line from 1.8 mi (3 km) in 1999 to 16.8 mi (28 km) today. Overall the system is currently in operation on 22.9 track-miles (38.2 track-km) with an additional 14.3 track-miles (23.8 track-km) under contract.

The ALSTOM APS system uses vehicle mounted power pick-up shoes in direct contact with a series of switched power rails installed between the running rails. These sections are only energized upon receipt of a low power, specially coded signal from the vehicle transponder which indicates the vehicle is over that section. At all other times, the power rail segments are grounded.
Each streetcar is equipped with the following items for operation on the APS system:

- One roof mounted Emergency Battery Set to allow the streetcar to transition through any dead power segments.
- Two sets of center truck mounted Retractable Power Pickup Shoes for current collection mounted approximately 10 ft (3 m +) apart.
- One Pickup Shoe Control Box to activate the pickup shoes and interlock with the pantograph controls.
- One roof mounted Power Control Box with additional contactors and controls for switching the power from the pickup shoes and the emergency battery set.
- Additional Cab Controls and Monitoring equipment inputs to monitor and control the vehicle APS related equipment.
- Additional Safety Grounds under the low floor section of the vehicle to suppress any possible fault conditions.

The wayside installation of the APS system is made up of the following elements:

- Low profile, sectional Power Rails – 36 ft (11m) long sections fitted with 26.25 ft (8 m) of conductor rail and 9.84 ft (3 m) of insulating rail with integral duct bank and vehicle detection loop.
- Modular, quick replacement Power Rail Control Contactors – one is located every 72.2 ft [22 m], controlling two segments of power rail.
- Insulating Joint Boxes - one is located every 72.2 ft [22 m] and joins the ends of power rails not joined at the contactor boxes.
- Substation Grounding Contactor and System Monitoring Cabinet – one is added to each substation.

In the APS system the lengths of the conductor/insulator rail segments are matched to the length of the streetcar. The lengths are set such that two adjacent active segments, followed by an inactive section at each end, are always covered by the streetcar. For a 100 ft (30 m) Citadis streetcar or longer the lengths of the individual segments and shoe spacing on the vehicle correspond to the values provided above. The current APS design will not accommodate shorter streetcars, such as the Citadis Compact, and would require redesign to shorten the segments. Shorter segments would increase the number of segments, power rail control contactor boxes and insulating joint boxes.

A variety of safeguards are designed into the system to prevent any single point failure from causing a hazardous condition. Key among these is a condition monitoring system in each substation that detects faults in any power rail segment within 200 milliseconds, disconnects and grounds the
main feeder, automatically isolates the faulty segment and restores the system power to the remainder of the system in less than 2 seconds.

Electrically dead zones caused by an occasional faulty power rail segment contactor are traversed using vehicle on-board emergency battery sets with automatic transition to battery power when needed.

The proprietary APS system could in principle be retrofitted to many existing streetcars, but ALSTOM to date has not offered this system independent from procuring their matching Citadis streetcars, hence little information on the system is available directly from ALSTOM sources. Future orders of non-ALSTOM vehicles may be capable of being fitted with transponders, controls and pick-up shoe gear similar to that used on the Citadis vehicles to allow operation on an APS equipped system, but such a supplier would be at a competitive disadvantage due to the up-front engineering cost required to design and integrate the additional equipment.

The APS system does not support regenerative braking.

All active elements of the system are fully modularized, easily accessible, and quickly changed out in case of a fault.

The APS system has been utilized in areas with snow, including Reims, France. However, road salt is not used for de-icing in cities where the APS
in-street conductor technology is currently operating, a biodegradable de-icing fluid is used instead. To that end, coordination is required between the local municipality and the LRT operator to ensure there is no salt exposure of the portions of the alignment equipped with the APS in-street conductor technology. The use of snow plows equipped with a special rubber end, over portions of the rail alignment with the APS in-street conductor technology is also acceptable and it is currently used in the Bordeaux tram system.

The APS power rail, like any power rail, cannot operate when it is covered by water, because such a situation would lead to current leak when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit. Flooding of the track bed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

2.1.2 **Ansaldo STS**

The TramWave system by Ansaldo Signaling and Transportation Solutions (STS) is a second generation system incorporating lessons learned from an earlier system, known as Stream, which began development in 1994. A joint development venture with the local operator was previously installed to power electric buses through 2.0 mi (3.3 km) of historic old streets in Trieste, Italy in 1998, but abandoned due to problems with sinking resulting from an inadequate sub-base and political issues. More recent testing in Naples on a 0.25 mi (0.4 km) elevated track section on Ansaldo property has progressed to a revenue service operating track of 0.37 mi (0.6 km) in-street section on a seldom used route in Naples. Short segments of the TramWave system are also being installed on three streetcar routes in Florence.

Ansaldo STS’ TramWave System uses a continuous conduit duct embedded in the ground running between the rails. Power is provided by segmented, insulated conductor strips ranging between 3 and 5 meters in length with each segment activated as the train passes overhead to be powered. A ferromagnetic belt in the conduit lets electricity flow to the streetcar when contact is made with the power collector shoe. Gravity causes the magnetic belt to fall back into place once a train passes by, thereby cutting off the power supply. TramWave can be installed on a variety of vehicles, and can be integrated with traditional catenary lines. The fixed installation part of the TramWave system is made up of the following elements:

- Low profile, sectional Power Contact Modules – 9.84 to 16.4 ft [3.0 to 5.0 m] long sections with integral duct bank.
- Insulating Joint Boxes - one is located every 9.84 to 16.4 ft [3.0 to 5.0 m] and joins the ends of sectional Power Contact Modules.
• Substation System Monitoring Cabinet – one is added to each substation.

Every rail vehicle to be used on the TramWave system is equipped with the following additional items:

• One set of truck mounted Retractable Power Pickup Shoes for current collection.

• One Pickup Shoe Control Box to activate the pickup shoes and interlock with the pantograph controls.

• Additional Cab Controls and Monitoring equipment inputs to monitor and control the vehicle TramWave related equipment.

All active elements of the system are fully modularized, easily accessible and quickly changed out in case of a fault. The modules can be fitted to various types of track installation, including ballasted track.

The track modules also contain a return conductor instead of using the running rails as the return path. This can have substantial benefits by eliminating concerns over the corrosive effects of stray dc currents on underground utilities.

The system is covered by several worldwide patents, but Ansaldo STS advertises the TramWave system as being able to fit almost any light rail vehicle or streetcar.

Figure 2.2: Ansaldo STS’ TramWave – Power Rail Cross Section
Because it uses a contact system, TramWave is susceptible to ice, snow or sand on the lines. However, sweepers can be installed to clear lines as the train moves over them, and optional heating elements are available for cold climates where freezing is a concern.

TramWave power rail cannot operate when it is covered by water, because such a situation would lead to current leaks when the rail is powered up, and thus tripping of the circuit breaker protecting the traction power circuit. Flooding of the track bed is an exceptional situation which should be prevented by an appropriate drainage arrangement embedded in the track.

2.1.3 **Bombardier PRIMOVE**

Bombardier has developed a ground level, off-wire power system which uses non-contact inductive power transfer known as PRIMOVE. The initial testing of the PRIMOVE system began at the Bombardier facility in Bautzen, Germany in 2009 and moved to an urban environment on a seldom-used branch line in Augsburg, Germany in 2010. Testing on the streets of Augsburg was completed in 2012. In February of this year Bombardier announced plans to initiate revenue service testing of the static charge system on two electric buses in Montreal, Canada and Mannheim, Germany. Montreal is expected to begin testing at the end of this year, the Mannheim test is expected to begin in the second quarter of 2014.

Similar to the above continuous power transfer systems, PRIMOVE power segments are installed parallel to the track, but utilize contact-less inductive power transfer. The PRIMOVE system features 29.5 ft (9.0 m) long coiled cable segments laid between the rails. Inverters alongside the track are connected to a 750 Vdc power distribution network. The ground level segments are installed along 10-25% of the right-of-way and only powered when the train is present overhead, making it safe for pedestrians and other vehicles. When a ground level segment is energized, a 20 kHz, three phase magnetic field is created. Trains are equipped with pickup coils to receive this energy, which they convert into an electrical current that powers the tram. An energy transfer efficiency of 95 to 99% is claimed by Bombardier.

The fixed installation part of the PRIMOVE system is made up of the following elements:

- **Contactless Power Cabling Segments** – 29.5 ft (9.0) long sections installed underneath the street surface to generate the magnetic field for energy transfer with magnetic shielding underneath.
- **Vehicle Detection and Segment Control cable** - switches the individual segment on and off.
• High Voltage Inverter – one is installed for each power segment to convert the 750 Vdc distribution network to 20 KHz ac.

• Supervisory Control and Data Acquisition Interface – one is utilized for each power segment.

Every rail vehicle to be used on the PRIMOVE system is equipped with the following additional items:

• One Power Receiver System with Compensation Capacitor mounted underneath the vehicle to convert the magnetic field to an ac current.

• One Ac to Dc Converter to provide Dc current to the propulsion and energy storage systems.

• One on-board energy storage system, typically supercapacitors.

• One Vehicle Detection and Segment Control Antenna to energize the wayside Power Cable Segment.

Because the system is contact-less, PRIMOVE is able to operate in all climates. Snow, ice, sand and salt on the rails do not impact its ability to run.

However, this advantage causes a unique set of challenges. High power, high frequency EMC/EMI emissions can potentially cause safety problems with electronic devices, possibly including a passenger’s pacemaker, electrical cabling parallel to the power transfer segment, and vehicle controls. Bombardier has carefully engineered the system to minimize this risk and meet all applicable EMC codes and standards.

The track modules also contain a return conductor instead of using the running rails as the return path. This can have substantial benefits by eliminating concerns over the corrosive effects of stray dc currents on underground utilities.
2.1.4 **Other Inductive Charging Systems**

Numerous other companies are developing inductive charging solutions for automobiles and transit vehicles. The list of companies includes industry mainstays such as the German firm Wampler, new start-ups such as HaloIPT of Great Britain, and university spin-offs such as WAVE in Utah. Many of these systems are showing promise for future applications.

The diversity of power transfer methods and lack of national and international standards defining the power transfer interface means each wayside system must be paired with an on-board vehicle system from the same manufacturer.

2.2 **On-Board Energy Supply**

On-board energy supply systems can store energy electrically, chemically, or mechanically. The diversity of devices used includes supercapacitors, batteries, flywheels, fuel tanks, and fuel cells. All of these systems store energy on-board the vehicle and that energy must be periodically renewed from wayside facilities. There is a great variation in distance that can be travelled prior to renewal as well as the readiness of the different systems to be installed on an operating streetcar system.

The systems may offer either full or reduced performance depending on the maximum charge/discharge rates permitted. The number of recharge cycles in the useable lifetime of some of these devices is limited. Additionally, since the amount of energy stored is finite, a vehicle may be left stranded without power if long delays are encountered due to traffic conditions or other events on the off-wire portion.

The vehicles may have no impact on a traditional traction power supply system, may alter the system substantially, or eliminate it completely with the new requirements for fuel storage and handling.

2.2.1 **Supercapacitors**

Supercapacitors (sometimes referred to as ultra-capacitors) have been installed on revenue service vehicles by almost all major international car builders. Their primary purpose has been to increase regeneration and lower energy consumption though they are also used for off-wire operation. Vehicles with supercapacitors designed for off-wire operation are normally also provided with a small battery bank to extend the off-wire time and/or provide for hotel loads such as HVAC.

Bombardier was the first to demonstrate supercapacitors in revenue service in Mannheim, Germany from 2003 to 2007. Mannheim followed in
2007 with the first supercapacitor equipped vehicle order for 19 additional cars and another 11 cars in 2011. ALSTOM has supplied a tram in 2009 to Paris which is equipped with supercapacitors that currently runs in revenue service off-wire on two sections of line T3: Georges Brassens to Brancion and Porte de Choisy to Porte d'Italie. Ansaldo STS has a supercapacitor equipped Sirio tram undergoing evaluation in Florence, Italy. The Spanish firm Construcciones y Auxiliar de Ferrocarriles SA (CAF) initially supplied vehicles with supercapacitors for off-wire operation to Seville in 2010 to accommodate a religious procession where overhead wires would have interfered. Subsequently CAF supplied off-wire vehicles to Zaragoza, Spain in 2011, and won additional orders for Granada, Spain in 2010 and Kaohsiung, Taiwan in 2012. SIEMENS offers supercapacitors as part of their standard Mobile Energy Storage (MES) designed to fit on the roof of any vehicle. Additionally Vossloh Kiepke is building streetcars equipped with supercapacitors for Leon, Spain and Rostock, Germany.

In the United States a demonstration project funded by a TIGER III grant is being conducted by Tri-Met in Portland, Oregon. Supercapacitor banks from American Maglev Technologies are being fitted to twenty SIEMENS LRVs which will operate in revenue service. The installation is intended primarily to increase efficiency and reduce substation demand during peak periods. Off-wire operation will also be tested at speeds up to 25 mph with distances of 2500 ft (762 m) on level track being expected.

Supercapacitors, or double-layer capacitors, store their energy electrically in an electrostatic field. These units are basically very large versions of the well-known capacitors used in electronic circuits. Like normal capacitors,
they basically consist of two metallic plates isolated from each other by a non-conducting dielectric material. The main difference is that these units are much larger in size and capacity, with unit ratings of up to 160 farads and 45 Kilojoules of energy storage capacity at 300 to 500 volts. Supercapacitors have wide-ranging applications other than rail transit and available virtually off the shelf.

The supercapacitor system charging/discharging rate is very fast, measured in seconds, and they can withstand repeated charge/discharge cycling without significant degradation over time. Design life does vary somewhat depending on the degree of cycling but has been claimed to be on the order of 23 to 30 years.

2.2.2 Batteries

Batteries have been installed on revenue service vehicles since the beginning of horse-less operation in the mid 1800’s which predates the use of an overhead contact wire. Batteries are also the most diverse type of on-board energy storage and include the traditional lead-acid, widely-used nickel cadmium types, as well as the newer nickel-iron, nickel-metal hydride, nickel-zinc, sodium-sulfur, lithium-iron disulfide, lithium-ion, lithium-polymer, lithium-thionyl chloride, lithium-sulfur dioxide, lithium-manganese dioxide, zinc-air, zinc-dibromide and numerous other types. Due to this wide variety, generalities concerning their performance characteristics, cost, weight, safety, maintenance and space requirements are difficult. Each battery type must be considered independently.

All types of batteries store energy chemically. The requirement of a chemical reaction results in a longer time to charge and discharge the battery with charging usually measured in hours, rather than seconds. The slow discharge rate usually results in a lower vehicle acceleration and overall performance. On the plus side, batteries can store more energy per unit weight than other on-board storage devices such as supercapacitors and flywheels. For long distances off-wire batteries are far superior to either supercapacitors or flywheels.

All batteries also show a reduction in life based on the number of charge/discharge cycles and the depth of the discharge. Battery capacity is often oversized to minimize the depth of discharge in normal service. Typical expected lifetimes will be in the 5 to 10 year range.

Improvements in battery performance are continuously emerging, driven mostly by developments for the automotive and cell phone industries.

Lead Acid

Lead acid batteries have been used on rail vehicles since the 1800’s and are widely distributed throughout the transportation industry, including...
almost all automobiles. However, they are very heavy compared to the energy they can store and rely on an environmental contaminant, lead. These batteries, until recently, have been used by ALSTOM as a back-up to the APS system in cities such as Bordeaux.

The design life of lead acid batteries is typically 3 years based on the experience of electric buses.

**Nickel Cadmium**

Nickel cadmium (NiCad) batteries are widely used as rechargeable batteries for consumer electronics and are widely used as back-up to the low voltage distribution system on rail transit vehicles. NiCad batteries can store more energy per unit of weight than lead acid, but also contain a serious environmental contaminant, cadmium. There is no known use of these batteries in a high voltage drive application on rail vehicles.

**Nickel Metal Hydride**

Nickel Metal Hydride (NiMH) batteries first appeared on the market in 1989. NiMH batteries are able to store three to four times the energy of an equivalent sized NiCad battery. Their energy density is comparable to some lithium-ion chemistries. Generally seen as environmentally friendly, they have a wide distribution across the electrical/electronic device markets.

Applications of NiMH electric vehicle batteries include all-electric plug-in vehicles such as the General Motors EV1, Honda EV Plus, Ford Ranger EV and Vectrix scooter. Hybrid vehicles such as the Toyota Prius, Honda Insight, Ford Escape Hybrid, Chevrolet Malibu Hybrid, and Honda Civic Hybrid also use them. Currently over 2 million hybrid automobiles worldwide are using NiMH batteries.

The first modern battery-driven off-wire streetcar uses NiMH batteries. The ALSTOM Citadis streetcar entered service in Nice, France in 2007. Since then these batteries have gained widespread acceptance from the larger streetcar manufacturers including ALSTOM, Ansaldo, Bombardier, CAF, Kawasaki, and SIEMENS.
NiMH batteries require both a battery management and a thermal management control system. Charging currents, particularly fast charging, need to be controlled to prevent over-charging and damage to the cell. Damage and reduced life may also occur with “trickle charging” a fully charged battery. The operational temperature range of a streetcar typically exceeds the operational temperature range of the battery requiring the use of both heating and cooling of the battery to achieve the performance and lifetime specified by the manufacturer. Overcharging or overheating of a NiMH battery may result in the release of hydrogen gas.

**Lithium-ion**

Lithium-ion (Li-) batteries are very promising because they are lighter, more compact, and can store more energy at sufficient power, but they are a diverse family of chemistries, each with their own strengths and weaknesses. The newer lithium-iron phosphate batteries have high storage capacity, but not as high as the more common lithium cobalt-oxide batteries. However, the latter tend to overheat and may catch fire or explode due to runway oxidation reactions of the graphite electrode. Nano lithium-titanate batteries store sufficient energy and power with greater chemical stability and improved thermal safety. Emerging lithium-polymer, lithium-sulfur, and lithium-air batteries are expected to bring noticeable improvements in energy storage/recharging capabilities which are double or quadruple today’s capabilities. These future batteries are expected to be lower weight, smaller in size, with longer life and a higher temperature operating range. Each chemistry has specific application, handling, and storage requirements and the continued production and availability of a specific chemistry is not a certainty. Until a preferred chemistry is established by the automotive or transit industries, it is not possible to recommend one specific type.

Applications of Li-batteries in the automobile industry have been primarily limited to all electric and “plug-in” hybrids. All electric vehicles include the
Nissan Leaf and upstarts such as Fisker Automotive. The “plug-in” hybrids include the General Motors Volt and the Toyota Prius. Detailed information on these batteries is difficult to obtain and often considered proprietary, however the general chemistry is known. Fisker Automotive is using lithium cobalt oxide which is the same chemistry used in the Boeing 787 batteries which have had fire/safety problems. The Nissan Leaf is using manganese dioxide technology but is expected to change to nickel manganese cobalt in the near future. Nickel manganese cobalt is also used in the Prius plug-in. The GM Volt uses lithium manganese spinel. Which, if any, of these chemistries will be used going forward is impossible to predict.

The use of Li-batteries in modern streetcars is a new development with the only examples in service being small trolleys used in shopping centers such as The Grove in California and custom built by Gomaco Trolley or TiG/m. Stadler Rail has demonstrated operation of a Li-battery equipped streetcar in Munich, Germany and the local transit authority has ordered four of the vehicles. In this country Kinki Sharyo has built a demonstrator prototype, the ameriTRAM, which has toured several cities though no orders are known to be forthcoming. Two car builders have orders to supply streetcars with off-wire running based on Li-batteries. Inekon of the Czech Republic is supplying six “Buy America” qualified streetcars to the City of Seattle and Brookville Equipment Corp of Pennsylvania is supplying two Liberty streetcars with Li-batteries to Dallas.

![Image of GS Yuasa's LIM30H-8A lithium-ion battery module selected by the Kinki Sharyo Co. for the ameriTRAM LRV](image)

<table>
<thead>
<tr>
<th>External dimensions</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>l, w, h: 389, 231, 147 (mm)</td>
<td>19.5Kg</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>Nominal cell voltage</td>
</tr>
<tr>
<td>29.8V</td>
<td>3.6V</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>Operating voltage range</td>
</tr>
<tr>
<td>30Ah</td>
<td>23.2–33.2V</td>
</tr>
<tr>
<td>Maximum pulse current</td>
<td>Continuous current</td>
</tr>
<tr>
<td>600A</td>
<td>100A</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>Monitoring system</td>
</tr>
<tr>
<td>0–45 °C</td>
<td>Monitors each cell voltage and module temperature</td>
</tr>
</tbody>
</table>

Figure 2.6: GS Yuasa's LIM30H-8A lithium-ion battery module selected by the Kinki Sharyo Co. for the ameriTRAM LRV
Li-batteries require rigorous care with both battery management for charge/discharge control and thermal management for both heating and cooling. The different chemistries impose different conditions for these systems on the vehicles. Two of the most stable chemistries, lithium titanate (proprietary to A123) and lithium iron phosphate (several suppliers) have widely different cell voltages with lithium titanate having a maximum cell voltage of 2.8 V and lithium iron phosphate having a maximum cell voltage of 3.65 V. The nickel manganese cobalt type currently being deployed on automobiles has a maximum cell voltage of 4.2 V. Any change in battery type is likely to require replacement of the battery and thermal management systems also. This could be very problematic if the battery management systems are incorporated into the propulsion system controls.

Currently both the National Fire Protection Association (NFPA) and the National Highway Traffic Safety Administration (NHTSA) are developing standards for the use of high voltage battery sets in vehicles. In January of 2012 the NHSTA released a document titled “Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped with High Voltage Batteries”. The document is in response to fires in the General Motors Volt during crash testing. While re-affirming that Li- are not unsafe it does note that fires and release of toxic flammable gases after a crash are possible. Detailed requirements for the physical protection of Li-batteries may be forthcoming. In terms of applicability to streetcars, it is advisable for the owner to seriously review designs such as the Kinki Sharyo’s ameriTRAM where batteries are mounted on the side of the vehicle and protrude into the passenger compartment. This location will be highly susceptible to impacts from traffic accidents. The proposed retrofits to the Boeing 787 airliner in response to fire in the Li- batteries include housing the batteries in an explosion-proof container and venting any gases to the outside of the airplane.

2.2.3 Flywheels

Flywheels store their energy mechanically as rotational kinetic energy. Modern flywheels store kinetic energy in a high speed rotating drum which forms the rotor of a motor generator. When surplus electrical energy is available it is used to speed up the drum and thus store more kinetic energy. When electrical energy is required, the drum gives up some of its kinetic energy by driving the generator.

The use of flywheels in transit vehicles is an area that has been under active development for some years, especially in Europe. This technology has been applied to a number of demonstration vehicles, especially buses, although always in a hybrid configuration with another power source. The most widely known application is the Parry People Mover Ltd. (PPM) in England, which has built 12 units for demonstration. ALSTOM
also continues to prototype flywheel equipped Citadis vehicles but has not yet marketed a model for revenue service operation.

The total amount of energy that can be stored in a flywheel arrangement is not large and is comparable to its electrical equivalent, supercapacitors. While future developments may result in a very attractive technology, flywheels are not ready for revenue service applications.

![Image of Kinergy flywheel technology used by PPM in the U.K.]

Figure 2.7: Kinergy flywheel technology used by PPM in the U.K.

### 2.2.4 Fuel Tanks

Storing energy on board the vehicle as a combustible fuel used to power an engine or turbine is a technology more traditionally used for long distance interurban rail travel. The fuel is typically diesel or liquefied natural gas (LNG). Urban applications of this technology are well established in bus operations with fueling facilities incorporated into the maintenance yards. Adapting this technology to modern low floor streetcars based on electric drive technology is difficult, and not cost effective considering the wide availability of buses.

The one known application of this technology was the adaptation of a SIEMENS Combino streetcar to run on diesel outside the urban core where an overhead electrical supply was not available. Three vehicles in Nordhausen, Germany were outfitted with a diesel engine and fuel tank inside the passenger compartment. They have been performing well with the exception of a fire in the passenger compartment caused by a leaky fuel line in 2010.

Compressed Natural Gas (CNG) is a mature technology for buses, but does not appear to have had much success in the streetcar world.
2.2.5 **Fuel Cells**

Fuel cells are a promising technology for direct conversion of a fuel to electrical power without the need for an engine or turbine. In 2012 there were 25 active bus demonstrations in eight locations. The two most common fuels have been hydrogen and methanol. Methanol was used in the local demonstration project at Georgetown University that ended in July 2011 due to a lack of funding. Almost all work on this technology has been performed on buses with no known applications to streetcars.

2.2.6 **Car Builders’ Perspective**

As noted in the Executive Summary, the data collection effort conducted as a part of this study included a series of interviews with a diverse group of car builders. To that end, the list of potential car builders with the ability and capacity to provide DC with catenary-free technologies is included below. Due to the limits of the scope of this effort, technical informative sessions were held with only six car builders, including SIEMENS, Bombardier, Brookville, Kinki Sharyo, CAF and ALSTOM. A robust and comprehensive industry forum and outreach program should be considered as the catenary-free technology program is further defined in the next stages of the project development process. The text below is intended to provide some insight into the state of catenary-free technologies from the car builder’s perspective. Additionally, meeting notes and information collected during the informative sessions noted previously are included in the Appendix Section of this report. No part of this report is intended to provide endorsement or preference for any car manufacturer or vendor.

2.2.6.A **SIEMENS**

SIEMENS is a multinational engineering company based on Munich, Germany with services on rail-based mobility; from trams, light rail and metro services, to commuter rail lines up to regional services. They have been building trams since they provided the world with its first electric tram powered from overhead wires in Berlin in May 1881. SIEMENS currently offers catenary-free trams using their Sitras HES (Hybrid Energy Storage). This system has been in use in Lisbon, Portugal since November 2008 and has been selected for the turnkey construction of a tram system for the Qatar Education City campus located in the capital city of Doha. The scope of supply also includes signaling and communication systems, electrification as well as the depot equipment. The Qatar Education City tram will be the first 100% catenary-free system in the world and will extend approximately 11.5 km with 25 stops (for an approximate spacing of 0.5 km between stations) which will serve as charging points. The Qatar Education City tram system will enter service in autumn 2015.
HES is a modular system that can either be built into new vehicles or installed in existing trams, enabling them to run for distances up to 2.5 km without wires. It comprises two roof mounted units: a Nickel-Metal Hydride cell (NiMH) battery and an MES (Mobile Energy Storage) unit using double-layer “super capacitors”. Batteries have a higher energy density than super-capacitors but take longer to charge. In the HES unit the respective stored energy of batteries and super-capacitors is 18 kWh and 0.85 kWh whilst the respective power output is 105 kW and 288 kW. For this reason, HES uses super-capacitors for acceleration and batteries for steady speed.

SIEMENS HES trams require an overhead supply. This may be conventional overhead wires on part of the network or a Sitras LCU (Local Charging Unit). The LCU is a short length of overhead conductor rail placed at stations or other stops that can deliver a 1,000 amp charging current during a typical 20-second station dwell time. HES is also charged from regenerative braking, which SIEMENS claim can reduce energy consumption by 30%.

![Figure 2.8: SIEMENS Cars](image)

(1) Lisbon Tram (2) SIEMENS’ Avenio Prototype (100% Low Floor Car)

### 2.2.6.B Bombardier

Bombardier is multinational Aerospace and Transportation Company with headquarters in Montreal, Canada. Their PRIMOVE system provides a contactless power source solution for all types of electric transport, from light rail and bus networks to commercial vehicles and cars, by using the principles of inductive power transfer. This system has the advantage of being entirely hidden as the inductive loops between the tracks used to transmit power to trams are safely contained underground. These loops need to be covered by a 40mm layer of non-conductive material such as resin, asphalt base or non-reinforced concrete which may need to be carefully installed or it might be vulnerable to heavy traffic. Each looped cable segment is eight meters long and transmits 200kw. It is fed by an inverter which transforms 750 volt DC into 200 kHz AC. This system has
transmission efficiencies of between 90% and 95%, which Bombardier advises is only 2% less than contact systems. PRIMOVE is only switched on when the tram is above it by a maintenance-free solid-state unit. Power transmission loops are generally located at stations and gradients as required by the tram network. The PRIMOVE system allows electric vehicles to be wirelessly recharged either in motion (dynamic charging) or at rest (static charging) without affecting journey times and it can be recharged completely in about 30 seconds. The loops fit above sleepers and so involve no additional civil engineering costs. This system does not continuously power the tram so energy storage is an essential aspect of the PRIMOVE system. Bombardier’s MITRAC Energy Saver uses super-capacitors and was originally designed to store energy from regenerative braking. Trials have shown savings of up to 30% of traction energy.

The PRIMOVE concept has been successfully demonstrated in Augsburg, Germany where Bombardier low-floor trams have been tested on an 800 m spur line to the city’s exhibition center for operation in sand, snow, and salty slush conditions. Further testing has been done at Bombardier’s hub in Mannheim which opened in September 2011 and which has also tested PRIMOVE buses, minivans, and cars.

Bombardier Transportation has successfully completed the testing of its PRIMOVE catenary-free power system on a branch of the Augsburg tram network as mentioned above. Nonetheless, Augsburg transport operator AVG, does not plan to deploy PRIMOVE trams, but the federal government has awarded funding for Bombardier and Braunschweig transport operator BSVAG to undertake in-service trials with two electric buses which will run on a 12 km route.

![Figure 2.9: Bombardier’s PRIMOVE Car Testing at Augsburg, Germany](image-url)
2.2.6.C Brookville

Brookville is an American streetcar builder based on Pennsylvania, founded in 1918, focused on manufacturing, engineering, product safety, customer care, and expert craftsmanship. They have over 10 years of experience in restoration of historical Presidents' Conference Committee (PCC) streetcars and modernization of vintage cars in Philadelphia and San Francisco but are also now offering new modern streetcars and new replica streetcars. They recently got awarded with their first contract for the production of two 70% low floor off-wire capable Liberty Modern Streetcars for the downtown Union Station to Oak Cliff streetcar extension project by the Dallas Area Rapid Transit (DART). This light rail vehicle (LRV) system will be the first-ever American designed and manufactured off-wire capable streetcar to be delivered to a US public transit agency.

The Brookville Liberty Streetcars will operate along a four-stop, 1.6-mile track that provides access for citizens of Dallas' urban core to the downtown Union Station hub, which connects to DART's Red/Blue/Green light rail lines and the Trinity Railway Express with service to Fort Worth.

Brookville Liberty Modern Streetcars in Dallas will utilize an innovative battery energy storage system (ESS) to power the car's four traction motors when off-wire and will charge by overhead wire or by non-contact inductive transfer charging. When operating off-wire, the batteries will be periodically charged through induction coils that are located in critical areas along the route to incrementally charge the batteries located on the streetcar. Approximately one mile of the 1.6-mile track will require ESS power, allowing the LRV to cross the city's historic Houston Street Viaduct over the Trinity River without the use of catenary. This bridge has a maximum gradient of 4%.

Figure 2.10: Brookville’s Liberty Car Prototype
2.2.6.D  Kinki Sharyo

Kinki Sharyo International is a subsidiary of Kinki Sharyo Company, a manufacturer of railroad vehicles based in Osaka, Japan. In 2011 Kinki Sharyo unveiled the prototype LFX-300 100% low-floor hybrid streetcar developed for the US market and named it the ameriTRAM. The three-section vehicle is 20 m long and 2,650 mm wide and is powered by four 120 kW motors. The ameriTRAM has a modular design allowing the length of the cars to be increased; thereby increasing passenger capacity without increasing the total fleet size. The modular design allows it to be supplied with up to seven sections.

The ameriTRAM vehicles use an Electro-Hybrid (e-Brid) propulsion technology that enables the vehicle to be propelled by overhead catenary or on-board lithium-ion batteries. The e-Brid system charges the batteries while running on catenary power. In battery mode, the e-Brid system uses electricity stored from regenerative braking. Depending on conditions, with e-Brid technology the ameriTRAM vehicle can run on battery power for up to five miles.

The Metropolitan Transportation Authority (MTA) of Los Angeles has approved a contract to buy 78 light rail cars from the Japanese company and the option to purchase additional 157 cars. The light rail cars will be deployed on the Expo Line Phase II, Gold Line Foothill Extension, Crenshaw Line and the Blue Line to replace 69 ageing rail cars, which are expected to go out of service by 2018. Kinki Sharyo will deliver 28 of the new rail cars by 2015 and a further 62 by May 2016.

Figure 2.11: Kinki Sharyo’s ameriTRAM Car
2.2.6.E  CAF

CAF (Construcciones y Auxiliar de Ferrocarriles) is a company based in Beasain, Spain with a worldwide market that constitutes approximately 82% of their sales. The core of their business is the design, manufacture, and supply of rolling stock. CAF has extensive experience producing vehicles for high speed rail, commuter rail, light rail, and streetcar applications worldwide. As part of their efforts to expand internationally, CAF-USA operates a manufacturing facility located in Elmira, NY, which produces railcars for the US market including Amtrak, the Houston Light Rail, and the Cincinnati Streetcar. For the Houston light rail project CAF will be providing thirty nine (39) 70%-low floor cars whereas the Cincinnati streetcar project has an order of five (5) 100%-low floor cars. The Cincinnati streetcar will be the first 100%-low floor system to operate in the US.

In Spain, CAF streetcars are currently in operation in cities like Seville and Zaragoza (Freedrive). The Seville streetcar was the first ACR system to be built and it has been under operation for approximately 3 years. An approximately 1.6 km (1 mile) long section of the Seville system was converted to catenary-free for the purpose of religious ceremonies. The Zaragoza streetcar has been operating for about one year and it includes a catenary-free section through a historical area of the city. For the systems currently under operation, the typical spacing between tram stations is 1.0 km. The cities of Málaga and Granada are also planning on having segments of their tram network operate without overhead wires.

The ACR (Rapid Charge Accumulator) system is based on the use of super capacitors and batteries which supply the vehicles with power. The ACR system is also equipped with a battery that is used as a backup in case of system failure. The backup battery can provide an approximate travel distance of 60 meters. CAF has developed two types of onboard energy (ACR) systems for catenary-free operation: the Evodrive and the Freedrive. Evodrive is an energy efficient brake regenerative system whereas the Freedrive systems recharge at stations. The Freedrive system has the capability to charge in 20 seconds and can travel as far as 1.4 km without charging, in ideal conditions. For the worst-case scenario (i.e. extreme weather conditions, HVAC use, steep grades, etc.), this system could probably travel as far as 800 meters without the need to be charged. The maximum horizontal curvature for these vehicles is 15 meters.

The photos below show the two systems in operation: Seville which uses the Evodrive system and Zaragoza which uses Freedrive technology.
2.2.6.F ALSTOM

ALSTOM is French company which supplies rolling stock, transport infrastructure and signaling, maintenance equipment, and global rail systems. ALSTOM’s APS (Aesthetic Power Supply) system was the first second-generation catenary-free tram system. It began operation in Bordeaux, a UNESCO world heritage site, in 2003. Up until 1958, Bordeaux’s trams used the conduit system, and it had been assumed that the new trams would operate similarly. However it was decided that, as the old conduit system was not suitable, the new trams would have overhead wires. Protests from both the public and the French Ministry of Culture on the use of overhead wires for the Bordeaux’s tram resulted in the development of the APS system which is used for 12 km of the total 44 km of Bordeaux’s tram network.

The APS system had some initial issues that have been resolved and now the Bordeaux tram system is a reliable system the city is satisfied with. ALSTOM’s APS consists of a conduit, flush with the ground, on top of which are 8 meter long contact strips alternating with 3 meter long insulated segments. Inside this conduit are the supply cables and an antenna. There is a power supply box adjacent to every other insulated segment that feeds the adjacent contact strips. These are energized only when the antenna detects that the tram is wholly above the contact strip. To maximize power transfer time, contact shoes are in the center of the
The power rails and power units used in this system are also manufactured by ALSTOM who can also provide the maintenance. These parts are shipped and assembled on site. APS allows for catenary-free sections of any length or for the entire line.

ALSTOM vehicles can also operate with an on board battery energy storage system. In this case, energy is stored in Nickel Metal Hydride (Ni-MH) batteries when the tram runs on sections equipped with OCS (Overhead Contact System) and this energy is used on OCS-free sections. The distance that can be covered while running on an OCS-free section with this solution depends on the battery capacity and the length of the preceding OCS section. Note that battery operation reduces the achievable rate of acceleration and speed.

APS is also now in use as part of the tram systems in French cities including Tours, Orleans, Angers, Nice, and Reims. The APS system used in the Nice tram has an on board battery for two half-kilometer low-speed segments with no power input; the rest of the network is APS and OCS. Outside France, work has started on APS tramways in Brasilia and Dubai which are planned to open in 2014. In Dubai the trams will have brushes to keep the contact strips clear of sand.

All catenary-free systems are to be used on vehicles 30 to 40 meters long since the power and battery equipment for these systems will not fit on a 20 meter, four-axle car. The current ALSTOM's vehicles are the Citadis and dual-voltage Dualis. These cars can travel on maximum grades of 6%. Vehicles equipped with the APS technology can run on a minimum horizontal radius of 20 meters and a minimum vertical radius of 250 meters. For a 20 meter radius horizontal rail, ALSTOM uses a pre-curved APS/conductor rail in three segments which is assembled on site. The photos below show the Bordeaux and Reims trams Citadis vehicles.
3.0 Application and Selection

3.1 Selection of Alternate Propulsion System

Designing a system for off-wire operation using periodic power transmission/energy storage devices is a complex task which must dynamically balance the energy stored on the vehicle against the energy requirements of the areas to be operated without an overhead distribution system. In order to optimize the type and size of the vehicle on-board energy storage devices to be used, a rigorous set of engineering calculations must be performed.

The first step in this process is to accurately define the route and fully identify the areas where wireless operations are required and/or desired. This information is used to perform standard propulsion system simulations that calculate energy consumption of both the propulsion performance and auxiliary power loads such as HVAC. Such simulations typically include:

- speed limits and maximum operating speed,
- acceleration and braking performance,
- station dwell times,
- number and location of station stops,
- number and location of traffic lights,
- vertical grade details, and
- any other alignment details and/or characteristics which may affect vehicle operations.
For the USGT Alternatives Analysis several assumptions have been made to assess the potential application of catenary-free operations currently in revenue operations in other cities. To that end, we've classified existing systems in revenue operations into three categories, based on the maximum distance traveled off wire. The three categories are:

- Distances greater than one mile (1.6 km);
- Distances greater than one half mile (0.8 km); and
- Distances shorter than one half mile (0.8 km).

The classifications are intended to be very conservative and actual distances may be greater after an engineering analysis is performed. For example, the Czech cars currently owned by the District of Columbia will also be used in Seattle for a 2.5 mi (4 km) off-wire segment. However, this off-wire segment will only be used on the downhill inbound track and the cars will only operate with ventilation and no air-conditioning loads.

Reserve capacity of the storage system will also need to be established during preliminary engineering for the line. The reserved capacity is needed for:

- Limiting the “depth-of-discharge” for the storage devices to achieve maximum lifespan (the deeper the discharge, the shorter the life);
- Allow for delays due to traffic without stranding a vehicle without power; and
- Allow for system faults which may reduce the available power.

The table below summarizes some relevant technology applications around the world that could be used for comparisons for potential applications in DC.
## Table 3.1: Relevant Catenary-Free Systems in Revenue Operations or In-Progress for Potential Application in DC

<table>
<thead>
<tr>
<th>System</th>
<th>Catenary-free Distance &gt; 1 mile</th>
<th>Catenary-free Distance &lt; 1 mile</th>
<th>Catenary-free Distance &lt; .5 mile</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bordeaux – ALSTOM</td>
<td>●</td>
<td></td>
<td></td>
<td>APS – ground level</td>
</tr>
<tr>
<td>Ansaldo STS</td>
<td>●</td>
<td></td>
<td></td>
<td>Induction – ground level</td>
</tr>
<tr>
<td>Lisbon - SIEMENS</td>
<td>●</td>
<td></td>
<td></td>
<td>Batt. &amp; Super Capacitors</td>
</tr>
<tr>
<td>*China–PRIMOVE</td>
<td>●</td>
<td></td>
<td></td>
<td>Induction – ground level</td>
</tr>
<tr>
<td>Nice - ALSTOM</td>
<td></td>
<td>●</td>
<td></td>
<td>Battery</td>
</tr>
<tr>
<td>Munich - Stadler</td>
<td></td>
<td>●</td>
<td></td>
<td>Battery</td>
</tr>
<tr>
<td>Seattle - Inekon</td>
<td></td>
<td>●</td>
<td></td>
<td>Battery</td>
</tr>
<tr>
<td>*Dallas - Brookville</td>
<td>●</td>
<td></td>
<td></td>
<td>Battery</td>
</tr>
<tr>
<td>Seville – CAF</td>
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<td>●</td>
<td>●</td>
<td>Batt. &amp; Super Capacitors</td>
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<tr>
<td>Zaragoza - CAF</td>
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<td>●</td>
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<tr>
<td>Doha - SIEMENS</td>
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<td>Batt. &amp; Super Capacitors</td>
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<tr>
<td>*Qatar – SIEMENS</td>
<td>●</td>
<td></td>
<td></td>
<td>Battery</td>
</tr>
</tbody>
</table>

* Currently in development, vehicle orders in place and system expected to start revenue operations by 2015.
### 3.2 Comparison of technologies

#### Table 3.2: Advantages and Disadvantages of Energy Storage Systems (ESS)

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Batteries</td>
<td>- ability to operate w/o wires for lengths of up to 1-1.5 miles</td>
<td>- weight could become an issue with higher power requirements</td>
</tr>
<tr>
<td></td>
<td>- can serve as back-up to OH traction power in the event of a power failure</td>
<td>- limited battery life could be a concern</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- potential high maintenance requirements</td>
</tr>
<tr>
<td>Flywheels</td>
<td>- improved energy efficiency</td>
<td>- not yet commercially available for rail applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- technology still at an early stage of evaluation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- perhaps better use as a means of improving energy efficiency and not off-wire capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- maintenance and safety implications still not quite defined</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>- ability to deliver high levels of power as required</td>
<td>- not yet commercially available for rail applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- likely to be expensive when available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Life cycle and maintenance costs not available</td>
</tr>
<tr>
<td>Super Capacitors</td>
<td>- Potential to deliver significant energy savings on a network basis</td>
<td>- additional cost and weight</td>
</tr>
<tr>
<td></td>
<td>- have been in revenue service on a limited basis for a few years and proven reliable</td>
<td>- limited performance away from OH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- life cycle of units not quite defined</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- some maintenance implications are unclear</td>
</tr>
<tr>
<td>Diesel</td>
<td>- completely independent of power infrastructure</td>
<td>- additional costs, weight and maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- loss of passenger space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- increased cost and complexity of depot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- not available in low-floor configuration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- not compatible with alignment geometric constraints in urban settings</td>
</tr>
<tr>
<td>Diesel as Auxiliary Power</td>
<td>- could be used in conjunction with one of the other alternative propulsion systems</td>
<td>- loss of performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- disadvantages listed for diesel option also applicable to this option</td>
</tr>
<tr>
<td>Liquid Petroleum Gas</td>
<td>- alternative fuel source with “greener” characteristics</td>
<td>- not realistically available and a sub-option to diesel traction</td>
</tr>
</tbody>
</table>
### Table 3.3: Advantages and Disadvantages of Ground Level Continuous Power Supply Systems (GLCPSS)

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetic Power Supply (APS) by ALSTOM</td>
<td>-allow for catenary-free operations for relatively long distances. Bordeaux System in operation for over 10 years has over 16 miles of single track. -minimal visual impacts</td>
<td>-proprietary system would limit competition -operating and maintenance cost may be significantly higher compared to other non-proprietary systems -climatic conditions in DC, snow and ice, are certainly different when compared to those conditions in Bordeaux, France -Safety certifications may require additional work when compared to ESS systems</td>
</tr>
<tr>
<td>Non-Contact Inductive Power System – PRIMOVE by Bombardier</td>
<td>-could allow for catenary-free operations for relatively long distances as technology has been in use in the auto industry for many years -minimal visual impacts -expected to perform well under DC climate conditions</td>
<td>-proprietary system would limit competition -operating and maintenance cost may be significantly higher compared to other non-proprietary systems -currently not in revenue operations. A 7.5mi bus system has been approved in Germany by the federal government, but beginning of revenue operations is unknown at this time</td>
</tr>
<tr>
<td>Non-Contact Inductive Power System – STS by Ansaldo</td>
<td>-could allow for catenary-free operations for relatively long distances, given its similarities with the APS system noted above -minimal visual impacts</td>
<td>-proprietary system would limit competition -operating and maintenance cost may be significantly higher compared to other non-proprietary systems -climatic conditions in DC, snow and ice, are certainly different when compared to those conditions in Bordeaux, France -Safety certifications may require additional work when compared to ESS systems</td>
</tr>
</tbody>
</table>

### 3.3 Wayside Impacts

The wayside impacts associated with catenary-free technologies include the location of electrical substation units and power distribution infrastructure elements required to provide the electrical power necessary to energize the system. These impacts are beyond the scope of this study and will need to be evaluated as part of future efforts of the project development process. It is important to note that most catenary-free systems use station areas to recharge ESS, such as batteries through the use of super capacitors or allow for recharging of battery packs at the...
ends of the line, accounting for longer periods for recharging of the ESS. In either case, the station area is used to accommodate the necessary equipment for recharging of the system.

3.4 Capital Costs

A more detailed discussion of capital costs is included in the AA report for the system components, including vehicles and incremental cost for the implementation of catenary-free technologies. To that end, our research has led us to the conclusion that the cost of deploying these alternative technologies would result in an approximate cost per vehicle of no more than $5.0-5.2M. This incremental cost per vehicle translates into an additional cost of approximately 5-7% when compared to the cost of using a traditional catenary system. As noted in the previous section, however, the need for utility relocations may be significantly reduced, as stray-current is not an issue, resulting in substantial cost savings. In the end, we expect the capital costs for the implementation of catenary-free technologies to be somewhat higher, but within an acceptable range.

3.5 Vehicle Maintenance and Storage Facility

Overview

The primary objective of this analysis is to determine and document requirements for vehicle maintenance, operational support, wayside maintenance and managerial / administrative support for the District of Columbia Department of Transportation’s (DDOT’s) Union Station to Georgetown Streetcar Line. This analysis addresses yard and shop requirements to support the fleet size and operational service envisioned.

Assumptions

In the absence of a complete definition of the specific route alignment and type(s) of vehicles to be used, this analysis was performed using the following assumptions:

1. Fleet Size will be set at twelve (12) streetcars
2. Service frequency is assumed 10-minutes (peak) and 20-minutes (off-peak)
3. Preliminary projections for scheduled operation will be 18 hours per day Monday through Thursday, 19 hours on Friday, 17 hours on Saturday, and 10 hours on Sunday, as follows:
   a. Monday through Thursday – 6:00 a.m. to 12:00 a.m. (midnight)
b. Friday – 6:00 a.m. to 1:00 a.m.

c. Saturday – 8:00 a.m. to 1:00 a.m.

d. Sunday – 10:00 a.m. to 8:00 p.m.

4. Four mile alignment

5. Power supply will be through a combination of overhead catenary and off-wire technologies.

6. Maintenance-of-Way facilities may or may not be co-located with streetcar maintenance and storage facilities

**Maintenance Philosophy**

The maintenance philosophy for the Union Station to Georgetown streetcar service consists of replacing the Lowest Level Replaceable Units (LLRU) in order to minimize the out-of-service time. Scheduled maintenance programs will be based upon manufacturer’s recommendations, and will be monitored and revised as necessary in order to minimize the potential for in-service failures.

**Vehicle Maintenance and Storage Facility (VMSF)**

The Vehicle Maintenance and Storage Facility (VMSF) will be located in close proximity of the streetcar service alignment to minimize construction costs and operational dead-head time while meeting economic constraints and community concerns. Conceptual layouts will be developed as appropriate sites are identified.

The basic functional requirements for the Union Station to Georgetown VMSF will primarily consist of:

- Yard area with vehicles storage tracks, temporary track for vehicle delivery and acceptance testing, automobile parking lot, and additional vehicle storage space for future growth
- Vehicle exterior wash facility, and
- Vehicle maintenance shop building for scheduled maintenance, unscheduled maintenance and repair, warranty repairs, component repair, vehicle interior cleaning, parts and material storage, administrative offices, and employee facilities.

Security and environmental considerations must also be identified and addressed.
Functional requirements for the VMSF should be addressed as listed below.

Vehicle storage yard: It is recommended that yard storage be provided for a minimum of 12 vehicles, if possible. This will allow maximum flexibility for the vehicle movement in-and-out of the vehicle maintenance shop building; for dispatching vehicles to revenue service and bringing back for storage into the yard during non-peak hours; and for other activities such as vehicle testing, recovery, etc. The number of tracks will depend on the yard configuration, but an ideal situation would be to have no more than three cars on each storage track. A “run-around” track, in addition to four (4) storage tracks (for three cars each), would provide maximum flexibility; and, a loop from the “run-around” track to storage tracks would also be desirable to provide even wear on the vehicle wheels and other components. The following factors should be considered in the design of the yard vehicle storage area:

- Yard storage tracks capable of holding a minimum fleet size of 12 streetcars. Ideally, tracks should be double-ended and level tangent to allow for sufficient space between the turnouts and the cars. If practical, the track design should allow for a maximum of three streetcars to be stored on each track.
  - Alternating storage track spacing of 14 ft where no access aisle is required between tracks and 17 ft where an access aisle is required in order to accommodate service aisles and/or overhead contact system (OCS) poles.
  - Yard run-around / bypass track, including a loop or other method for reversing streetcar direction.
  - Two yard lead tracks to the revenue service main line with sufficient length to allow at least one streetcar between the first yard switch and the main line signal.
  - Blue flag protection must apply for all storage and shop tracks.
  - Yard turnouts with manual ground throw switch machines and trailable switch points for all yard turnouts.
  - Vehicle exterior wash facility with recycled water system (non-automated per design criteria) – ideally, at least 200 ft long, in order to accommodate two streetcars.
  - Vehicle undercar cleaning capability and sanding capability should be provided in conjunction with, or as a supplement to, the wash facility.
  - Vehicle interior cleaning capability.
• Temporary track for vehicle delivery, testing, and acceptance (including space assigned to vehicle contractor and subcontractors’ field personnel).

• Daily and other manufacturer-recommended inspections, tests, and maintenance (including periodic or preventive maintenance).

• Parking spaces for transportation, vehicle maintenance, and administrative employees as well as for rubber-tired support vehicles.

• Yard security, fire protection, and environmental systems, storm-water retention and wastewater treatment.

• Utilities including water, sewer, electrical, gas, communications, compressed air, etc.

• Site roadways and service aisles.

• Site protective fencing and lighting.

• Site capability to accommodate fleet expansion in the future.

**Vehicle maintenance shop building:** This facility must be able to accommodate the following:

• One streetcar-length inspection pit with roof access platforms.

• One floor-level track with roof access platforms, and an inspection pit with roof access platforms at the other streetcar position.

• One floor level track with the capability for jacking vehicles, using in-floor vehicle hoists and car-body supports (preferred) or portable electric jacks for wheel and truck lifting, and other large component removal at two streetcar-length positions.

• Each shop track capable of accommodating two streetcars with at least 20 ft between vehicles and shop doors. Shop tracks should be double-ended.

• Operations Control Center (OCC).

• Traction power substation.

• Limited Overhead Catenary System (OCS) with power isolation capability in sections and lockout capability inside the shop; or use of an optional remote controlled electric car mover on selected tracks.

• Two backup power sources, one for limited shop activities and one for the OCC.
Utilities including water, sewer, electrical, gas, communications, compressed air, etc.

Vehicle shop power and compressed air to be provided at all work/pit locations.

Overhead safety support equipment during work on vehicle roof equipment

Parts, material, supplies, and spares storage (including separate storage for hazardous materials) with shipping and receiving dock area.

Location(s) for vehicle repairs due to failures (including warranty and non-warranty).

Secure space for special tools and technician tool storage.

Component change-out, repair, and overhaul areas.

Provisions for future body and paint booths, if possible.

Maximum use of natural light throughout the shop.

Facilities for administrative, vehicle maintenance, transportation and other support personnel and management; consisting of offices, restrooms, lunch room, locker rooms, conference rooms, training rooms, etc. (included on the second floor or optionally a mezzanine level).

Electrical/mechanical rooms, sprinkler systems, and security/surveillance systems.

Based upon shop designs for recent streetcar projects, it is estimated that approximately 20,000 sq. ft. will be needed for streetcar maintenance and an additional 8,000 sq. ft. for transportation, maintenance support, OCC, administrative and auxiliary functions. Some of the 8,000 sq. ft. may be distributed on a mezzanine level or a second floor level, dependent upon plot space or other constraints on building configuration.

**Shop Equipment**

Major shop equipment should be procured either with the maintenance shop building construction or, if deemed advantageous, as a separate contract. Major shop equipment to be considered is listed in the table below:
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-floor vehicle hoists with car body</td>
<td>1</td>
<td>Electric, 2 or 3 hoists with 12 car body stands, or</td>
</tr>
<tr>
<td>stands, or Portable jacks with car body</td>
<td></td>
<td>12 portable electric jacks with 12 car body stands</td>
</tr>
<tr>
<td>stands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck Turntables, Manual</td>
<td>2</td>
<td>One for each flat track</td>
</tr>
<tr>
<td>Wheel Truing Machine Provisions</td>
<td>1</td>
<td>Procure, if funding is available</td>
</tr>
<tr>
<td>Overhead Bridge Crane, 10 ton</td>
<td>1</td>
<td>Over vehicle jacking track and to service the Wheel and Truck Shop</td>
</tr>
<tr>
<td>Tire Press</td>
<td>1</td>
<td>As part of the Wheel Shop</td>
</tr>
<tr>
<td>Jib Crane, 5 ton</td>
<td>1</td>
<td>For component Repair</td>
</tr>
<tr>
<td>Dock Levelers</td>
<td>1</td>
<td>At loading/unloading dock</td>
</tr>
<tr>
<td>Vehicle Mover, electric, remote control</td>
<td>1</td>
<td>For moving cars in the shop (optional)</td>
</tr>
</tbody>
</table>

In addition, smaller support equipment will also be required, such as lathes, parts cleaners, pallet lifts, etc.

**Operations Control Center (OCC)**

An Operations Control Center (OCC) will be located at the Vehicle Storage and Maintenance Facility. The OCC shall have responsibility for the operation, control, coordination, and monitoring of all vehicle movements on revenue and yard tracks, station operations, and any revenue track activities that may affect rail operations.

Transit security, passenger information, CCTV, revenue control activities, and designated local police and emergency response agencies shall be coordinated, and monitored at the OCC, as appropriate. Access to the secured control room shall be restricted to authorized personnel only and shall be located to minimize the disturbance to staff communications or their view of the operations overview display. OCC staff shall utilize consoles and wall displays to supervise streetcar system activities. It is estimated that OCC will require approximately 1,000 sq. ft. of floor space. The computer and communications equipment room will require approximately 150 sq. ft. (10’ x 15’) of climate-controlled floor space.

An emergency backup room (10’ x 15’ minimum) with a console capable of performing the basic functions of the Operations Control Center should also be provided at a remote location.
Facility Foot Print

Based on the fleet of 12 streetcars, it is estimated that a plot of approximately 2 - 3 acres will be required for vehicle yard storage, to provide storage track capacity including turnouts, adequate clearance, fencing and yard leads.

Additionally, dependent upon the terrain and access, it is likely that at least 6 or more acres plot will be needed to accommodate facilities and storage for a 12 car fleet with allowance for some future expansion, MOW facility, automobile parking, and vehicle maintenance shop building.

Location

Information on specific locations will be completed as part of later stages of the project development process.

4.0 Vehicle Design Criteria

4.1 Suggested Changes

Vehicle width: 2.46 m is a Czech (CZ) standard and may not result in an industry-wide response. Only two suppliers may be interested in providing vehicles with these dimensions with Inekon being one of them. A more standard US width of 2.65 m would allow for a more competitive setting and provide much needed space on the vehicle to accommodate additional equipment necessary for catenary-free operations.

Vehicle length: 20 m may be too short to accommodate the needed storage. Most suppliers have standard models of 30 m (100 ft). To that end, all car-builders interviewed as a part of this propulsion effort strongly suggested a minimum width of 30 m.

Platform interface: Widen to accommodate more standard vehicles.

5.0 Conclusion

5.1 Conclusions

- Ground Level Continuous Power Supply Systems (GLCPSS, aka APS systems) – This system is by far the oldest system in
operation around the world, with revenue operations over 10 years in Bordeaux, France. This is a proprietary system developed by ALSTOM and uses an in-ground contact rail/third rail, installed between the running rails, to distribute power and a shoe power collector on the vehicle. Electrical power is transmitted to the vehicle as the shoe collector makes contact with the power-rail. A loop detector installed on the vehicle allows only those segments of third-rail directly below the vehicle to be energized; thereby minimizing the risk for accidental contact between an electrified third-rail segment and pedestrians and/or any other objects. This is certainly proven technology, given the years in revenue operation, however, special attention and careful evaluation of the proprietary implications, including O&M costs over the life of the asset, must be performed to determine its applicability to the DC Streetcar Network. Equally important, weather conditions must be carefully evaluated to ensure that winter conditions, including plowing of streets and salting operations do not create additional maintenance issues.

- Inductive Systems – Similar to the APS system described above, inductive systems use a Ground Power Supply by either installing a third-rail between the running rails or other electrical hardware for contactless induction; however, unlike the APS system, inductive systems do not use a shoe collector, but rather rely on an electro-magnetic field formed between the third-rail and a magnet on the vehicle to provide electrical power to the vehicle. This system is not currently in revenue operations. Similar to the APS system, this type of inductive system is proprietary and was developed by Ansaldo and Bombardier. Bombardier was recently awarded a contract in China for the construction of the first catenary-free system of its kind in that country, but revenue operations are not expected to begin until 2015-2016. Additional evaluations need to be conducted to confirm the applicability of this technology in the US.

- Energy Storage Systems (ESS), including batteries and super capacitors, appear to have gained some popularity in Europe and today there are a few systems using these technologies. Similarly, Brookville, an American Manufacturer, will be using ESS based on advanced battery technology to provide catenary-free operations in Dallas. With this in mind, today ESS technologies offer a reliable catenary-free option and battery technology continues to improve, in many cases driven by the auto industry. Having said this, some concerns regarding overheating of batteries have been mitigated, but the history of systems using these technologies is somewhat limited. Therefore, ESS is certainly a technology that warrants further study, but careful evaluations of the subsystems must be
performed to confirm applicability of this technology to the DC Streetcar Network.

- Irrespective of the technology, one of the key questions we set out to answer as part of this study was the maximum length of a catenary-free segment to be assumed for the DC Streetcar network. Our evaluation of the technologies and other systems around the world leads us to a range of 0.25-1.5 miles. This range may be somewhat conservative, and we expect it to improve as the definition of the technology for the DC Streetcar is further developed during the next stages of the project development process.

As noted in the executive summary included at the beginning of this report, the deployment strategy for the use of catenary-free technologies in DC need to take into account the following key items:

- **Implication of proprietary systems and subsystems**, this is particularly important when considering warranty, operations and maintenance of the new system and vehicles. Ground Level Continuous Power Supply Systems are usually proprietary systems and could result in significantly higher costs over the life of the asset.

- **Technical Specifications and Procurement**, the level of detail required to appropriately procure the right technology for the implementation of catenary-free operations needs to be such that appropriate performance criteria are clearly defined while allowing some room for flexibility and innovation, required to trigger a competitive bid setting without compromising the long-term benefits of the investment.

- **Utility Relocations**, catenary-free technologies may significantly reduce the need for utility relocations as the potential for stray-current leakage is minimal. This benefit would translate into significant infrastructure cost savings.

- **Wayside Infrastructure Requirements**, irrespective of the technology, traction power substations would be required for any system. The location, power and distribution requirements associated with these units need to be evaluated to determine the infrastructure required for charging on-board systems or installation of a ground level continuous power supply.

- **Alignment Characteristics and Constraints**, the technology selection is greatly dependent on the alignment characteristics and constraints, including horizontal and vertical geometry, as well as the availability of exclusive ROW. The maximum length of a catenary-free segment is a key driver in the selection of the right
technology, with ESS having more limiting factors when compared to ground level systems. Similarly, shared lanes could present a problem for ESS applications as the storage capacity is limited to the type, size and number of storage devices (i.e., super capacitors, batteries, etc.) that can be accommodated on the vehicles. To that end, the ability to accurately predict running times between charging locations/stations is a key part of the ESS technology approach and the unpredictability of running shared lane operations could result in significant delays, thereby, compromising the reliability of this type of technology. Grades exceeding 7% could prove challenging for any technology as steeper grades would translate into much higher energy requirements.

- **Maximum Length of Catenary-Free Segment**, based on the results of the data collection, there appears to be no limit to the maximum length for ground level systems as they use a ground level power-rail for power distribution. On the other hand, ESS technologies, based on the research of existing systems around the world, appear to have a maximum length in the range of ¼ mi-2.5mi, contingent upon the specifics of the technology being used.

- **Vehicle Dimensions**, the width and length of the vehicles are critical parts of the decision when selecting a catenary-free technology, given that storage space, either above or below the vehicle, would be limited when considering all other equipment needs, including HVAC. To that end, the American standard width of 2.65 m allows for much needed space for other equipment and energy storage devices. Similarly, a 30 m vehicle length would also allow for more storage space above and below the vehicle.
REFERENCES

Figure 2.1: ALSTOM APS System Components: ALSTOM Technical Presentation to RK&K (March 8, 2013, Fairfax, VA, USA)

Figure 2.2: Ansaldo STS’ TramWave – Power Rail Cross Section: Feasibility of Alternative Power Supply Systems for the LUAS BXD (February 2011, Systra)

Figure 2.3: Bombardier PRIMOVE Inductive Technology: Bombardier Technical Presentation to RK&K (April 18, 2013, Fairfax, VA, USA)

Figure 2.4: Supercapacitor Energy Storage Unit being installed at Tri-Met in Portland, OR: News from Portland Article (June 6, 2013) and Technical Presentation at APTA 2012 Rail Conference (John Swanson, PB, Oceanside, CA)

Figure 2.5: NiMH battery technology (34 Ah) in ALSTOM’s Citadis Tram in operation since 2007 in Nice, France: ALSTOM Technical Presentation to RK&K (March 8, 2013, Fairfax, VA, USA)

Figure 2.6: GS Yuasa’s LIM30H-8A lithium-ion battery module selected by the Kinki Sharyo Co. for the ameriTRAM LRV: News from GS Yuasa Lithium Power Inc, (March 11, 2011, Kyoto, Japan)

Figure 2.7: Kinergy flywheel technology used by PPM in the U.K.: CAF Presentation to RK&K (March 22, 2013, Fairfax, VA, USA)