SECTION B

Wireless Operation in the District of Columbia

October, 2011

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District Department of Transportation

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Wireless Trolley Operation in the District of Columbia

INTRODUCTION

In the early 20th century, the transition from horse-drawn trolleys to self-propelled trolleys, or streetcars, required the development of a means to provide a constant source of power to the vehicles. Early efforts consisted of engine-driven vehicles powered by steam or fossil fuels which quickly fell out of favor due to the attendant noise and exhaust vapors. Electrically-powered vehicles replaced their predecessors with the development of power delivery systems both in the ground and suspended safely from aerial wires. Eventually, the overhead contact wire technology gained widespread acceptance. The wires were suspended from poles with cantilevered wire attachments or span wires attached to a pair of poles on opposite sides of the street. In some instances the span wires were attached directly to buildings adjacent to the alignment. The photographs in Figures 1-4 illustrate the different methods used to support the contact wire over the streetcar tracks.

Fig. 1 - Side Cantilevered Support Arms (Salt Lake City, UT)

Fig. 2 - Joint-use Center Cantilevered Supports (San Jose, CA)

Fig. 3 - Span Wire Support (Montpellier, France)

Fig. 4 - Building Attachment (Portland, OR)

Many cities have rich histories that continue to live in the form of monuments, classic buildings and treasured open spaces. It is the desire of these city leaders to maintain the site lines and view corridors for all to enjoy. In order for streetcar lines to introduce minimal visual obtrusiveness with these historical structures and open spaces, it is desirable to deliver power through means other than using overhead wires. The District of Columbia is a perfect example, where all utilities are buried, and site lines and/or view corridors are established to preserve the architectural features of the landscape. Introducing poles and overhead wires as part of a new urban streetcar project is naturally met with resistance. Some cities have taken advantage of, or are experimenting with, new technologies that will allow streetcars to operate through these view-sensitive areas without any overhead wire system.

This report provides an historical background for Washington, DC and an overview of current technologies in use or being developed, which may be utilized to continue the wireless tradition.

ALTERNATIVES IDENTIFICATION

The technologies substituting for overhead wire can be placed into three categories:

- Wayside Technology: those which are installed on the wayside and deliver power to the streetcars by means other than overhead wire;

- Onboard Energy Storage Technology: those which employ energy storage devices on the streetcars; and
- Onboard Power Source Technology: those which serve as an onboard power source.

Wayside Technologies

Wayside technologies include those applications by which electric power is brought to the vehicle by some means at or beneath the street level. These include conventional overhead contact wire systems, the District’s earlier system using sub-surface conduit rail, surface-mounted contact rail, and non-contact inductive power.

Sub-Surface Conduit Rail

The conduit rail system is not a currently deployed technology. It is described here as an historical reference because it did address a similar challenge in a previous era and the operation of the system can provide lessons for the application of new systems. The basic system was employed as early as 1895 in New York City and Washington, DC, in the United States and in London, England. Although the technology was tried by several localities, only the cities listed here used this sub-surface power supply system for an extended period of time. The last of these systems was operated in the District and was decommissioned in 1962.

The conduit system utilized underground positive and negative “rails” from which power was collected by a vehicle-mounted “plow”. The conductor rails were mounted on insulators attached to cast iron “yokes” positioned every 13.5 feet in Washington and 15 feet in New York. Handholes were provided to allow maintenance access to the insulators and drains installed to prevent flooding of the rail channels. The positive rail was attached to one side of the yoke and the negative rail was attached to the opposite side with a separation of about six inches. The plow extended about 16 inches below the street level through about a half-inch steel slot on the surface of the street. The yokes were installed below the street surface between the tracks and extended 38 inches below the surface of the street. Figure 5 shows a picture of the track and conduit rail in the street, while Figures 6 and 7 are drawings illustrating the conduit rail cross-section and the plow in the Washington, DC application (taken from the Electrical Engineer’s Pocket Reference published in 1918).

Fig. 5 - Photo of Rail in Street

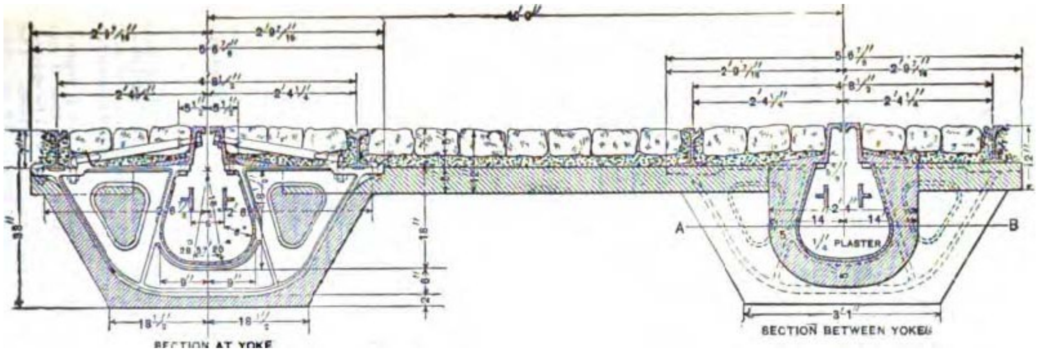

Fig. 6 - Cross-section of Conduit Rail in Washington, 1895

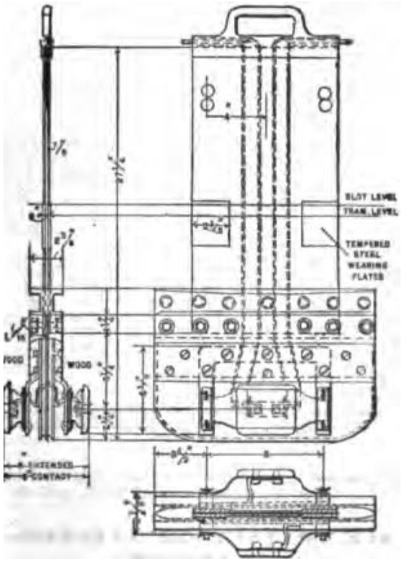

Fig. 7 - Section, Side, and End Elevation of Plow, New York, 1897/99

In Washington, DC, the streetcars were operated with a traditional trolley pole in contact with overhead wire in suburban areas and with conduit rail in the central area of the city (the old L'Enfant City) where overhead wires were banned. The changeover was accomplished by two people - one person in an underground pit to install or remove the plow and one person above to raise or lower the trolley pole. On lines with short headways, the changeover time was critical, as well as being labor intensive.

The limited number of installations of this system was primarily a result of the high construction, operating, and maintenance costs. Reliability of the system is believed to have been good despite the occasional dropped plow or frozen slot, which would cause major service disruptions, such as can be seen in Figure 8.

Fig. 8 - Line of Streetcars and Iced Slot

Surface Mounted Contact Rail

The delivery of power to the vehicle through an exposed conductor mounted on the surface of the street is of both historical and current interest. General Electric had a working system installed in Monte Carlo, Monaco, as early as 1898. Currently, Alstom and Ansaldo Breda have surface-mounted systems in service or in development. The Alstom system is operating in Bordeaux, Orleans, Rheims, and Angers in France, and in Dubai in the United Arab Emirates. The Breda system is presently undergoing testing at the Breda plant with plans to install this system on a portion of a streetcar line in Florence, Italy in the near future.

At the turn of the last century two US suppliers, General Electric and Westinghouse, were marketing solutions that used conductors mounted on the street surface and claiming the installation costs were one half that of an overhead conductor system. The systems were quite similar in that they both used two contact rails on the vehicle and two rows of cast iron “buttons” installed on the street surface. Two diagrams of the system, taken from the Electrical Engineer’s Pocket Reference, are shown in Figures 9 and 10.

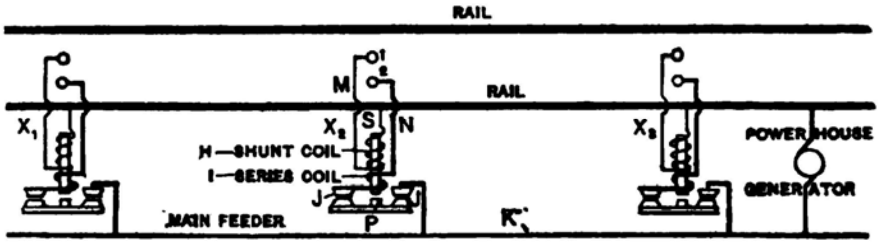

Fig. 9 - Diagram of Switch Connections

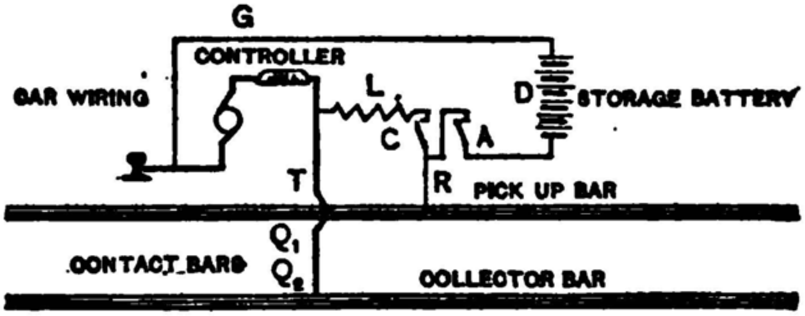

Fig. 10 - Diagram of Vehicle Connections

The buttons were connected to the power supply through electro-magnetically operated switches (Fig. 9) typically installed every 15 feet along the tracks. When a vehicle was over the buttons, a current would flow and electro-magnetically lift an armature to close the contacts that supplied power to the buttons. When the vehicle moved forward and there was no contact with the prior buttons, the armature would drop by gravity and open the circuit, de-energizing the surface-mounted buttons. This system required the establishment of two independent connections, and the force for opening the connection was provided by gravity.

Beginning In the mid-1990s, a system consisting of a magnetically-lifted power feed to contact a street-mounted rail to deliver power to the vehicle was developed by AnsaldoBreda. Originally called the STREAM system (the acronym in Italian for “magnetic pick-up electric transportation system”), the current designation is TramWave. The power collector on the vehicle was equipped with a strong magnet to lift the flexible conductor against the surface rail as the vehicle passed over it. That part of the conductor would drop with gravity when the vehicle moved past it.

The TramWave design uses a system of 19.7 inch (500 mm) plates which feed power at 750 Vdc from a positive feeder housed in a “box” mounted in the street to a collector mounted on the truck of the vehicle. Both positive and return conductors are incorporated in this arrangement, eliminating the need to use the running rails as the return path. Not using the running rails as the return path greatly reduces the need for electrical isolation of the rails and stray current mitigation issues. This concept is illustrated in Figure 11.

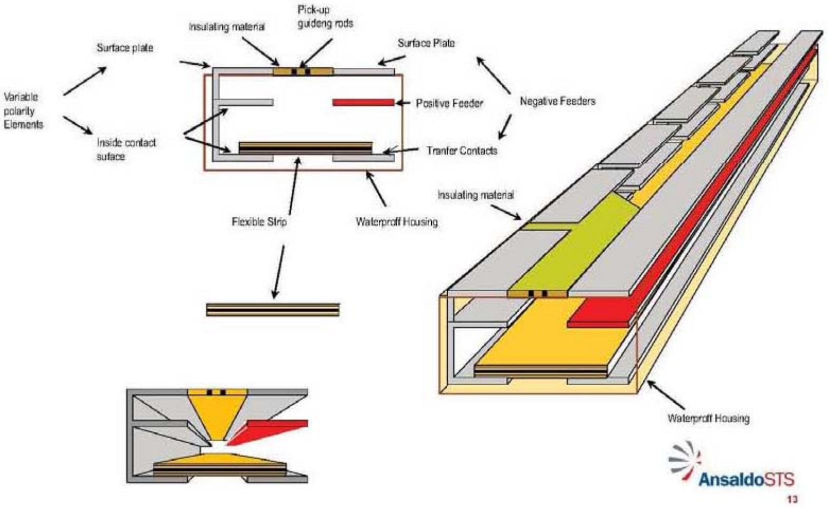

Fig. 11 - Diagram of Ansaldo Breda TramWave

This system was installed and tested on a trolley bus application in Trieste, Italy. It has also undergone some experimental testing in Naples at the Ansaldo facility. Currently a new streetcar system in Florence, Italy is planning to install the TramWave surface rail on two short sections.

As part of its new light rail system, the City of Bordeaux required that there be no overhead wire through its downtown historic district. The tender to accomplish this was won by Spie Enertrans, who had developed a unique surfaced contact system they dubbed Innorail. The system was developed in concert with Alstom Transportation who was providing the light rail vehicles. Alstom subsequently acquired the Innorail technology, made improvements to it, and renamed it APS, an acronym for Alimentation Par le Sol, which translates as 'ground power supply'. They have also referred to is as 'Aesthetic Power Supply'. The Bordeaux system has been in operation since 2003 and expansion of the system continues today. Despite initial start-up problems during the first year, the system has proven highly reliable.

Dramatic photographs of the rail system operating through the historic district are shown in Figures 12 and 13.

Fig. 12 - Bordeaux Wireless Operation

Fig. 13 - Bordeaux Wireless Operation

As shown in Figure 14, the APS system uses a segmented design with the contact bars mounted slightly above the surface of the street in the track centerline. Power conducting segments are 26½ ft (8 m) in length and are separated by insulating segments of 10 ft (3 m). Power supply boxes are located every 73 ft (22 m). Two power collector shoes are suspended from the underside of the vehicle. They are located slightly more than 10 ft (3 m) apart to bridge the insulating segment, assuring a continuous supply of power to the vehicle. The dimensions of the segments are dependent on the length of a vehicle such that two adjacent active segments, followed by an inactive section at each end, are always covered by the streetcar.

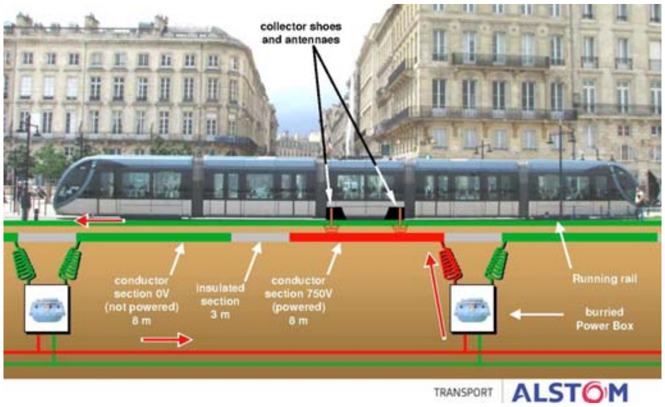

Fig. 14 - Alstom Sectionalizing Diagram

The embedded structure for the contact strips is installed in a shallow tray located in the center of the tracks as shown in Figure 15. This embedded structure also contains an inductive detection loop, power supply conductors, ground conductors, and communications conductors inside individual compartments, simplifying the installation work.

Fig. 15 - Installation of APS System

Individual segments are energized via the power boxes when the presence of a vehicle is detected by means of an inductive detection loop. Segments are switched by regular electro-mechanical contactors housed in the power boxes embedded in the street. After the vehicle's power rail shoes have passed and the inductive loop no longer detects the presence of a vehicle, the power is switched off and the rail connected to ground.

Fig. 16 - Power Box Installation

The APS system does have some drawbacks. It is currently only available from the French company, Alstom, as a proprietary design, and the willingness of Alstom to install the system in a US city is unknown. The cost differential between this system and a traditional overhead contact wire system is not precisely known, although various sources report that the APS is three to three-and-a-half times more expensive to install. The cost for the future purchase of streetcars may also be significantly more expensive, as the purchase will be “locked-in” to this carbuilder. The four French cities utilizing APS have applied it in very limited areas and over relatively short distances, typically urban historic districts, while installing overhead contact wire elsewhere on their rail networks.

Both of these surface contact systems which rely on direct contact between the vehicle-mounted shoe and the copper contact bar in the street can be anticipated to have problems with snow, ice, and corrosive de-icing chemicals. Historically winter weather has been an issue with underground rail in the District of Columbia as shown on Figure 8. For this type of system, the presence of road salt on the contact strips for an extended period of time may cause them to corrode, resulting in poor power transfer and accelerated replacement.

Non-Contact Surface Rail

A new technology is emerging which utilizes inductive transfer of power from the wayside to the vehicle through an air gap without the need for exposed conductors or physical contact. A small scale example of this is how a Sonicare toothbrush is recharged by simply setting it in its base which has no metallic contacts. An auxiliary benefit of this technology is that it uses alternating current (ac) instead of direct current (dc), which avoids the corrosive effects of stray current on nearby metallic objects such as building structures and underground utilities.

The inductive technologies have been implemented in two distinct styles. The first style uses discrete charging stations along the alignment with on-board energy storage during operation. The second style uses a continuous transfer of energy from the wayside during operation and stores a smaller amount of on-board storage for high demand activities such as streetcar acceleration or grade climbing.

An example of the discrete charging style is the battery-powered double-decker streetcar operating at The Grove, an outdoor shopping mall in the Hollywood area of Los Angeles. In addition to being recharged in the maintenance shop, the streetcar batteries are inductively recharged from power boxes embedded between the rails at station stop locations. The level of charging at station stops is dependent upon the dwell time at each station (time required for passenger are boarding and alighting). The charging station (power box) is supplied by the German company, Wampfler, which is actively promoting this technology for transit. Wampfler has also supplied an inductive power supply for a people mover at Mexico City's airport and for buses in Genoa, Italy. Electric buses using inductive charging at stations are also being prototyped by Hino in Japan and the University of Auckland, New Zealand.

Fig. 17 - Streetcar at the Grove

Bombardier, one of the world's largest suppliers of rail vehicles, is developing their 'Primove' system for continuously powering a rail car via inductive power transfer from under the street. They have recently completed a demonstration project in Bautzen, Germany, reaching speeds up to 24 mph (40 km/h) and operating on grades up to 6%, on a 0.6 mile (1 km) test track. Bombardier has recently announced receipt of an order for installation of the system on a 0.5 mile (0.85 km) line in Augsburg, Germany.

The Primove application uses a 'Flexity' model tram equipped with a 'Mitrac' ultra-capacitor energy storage system on the vehicle. The in-ground system does not utilize direct contact of the collector on the car with the rail in the street. A cable loop is installed under the pavement and energy is transferred through a magnetic field to a receiver mounted on the vehicle's truck. Transfer of energy is restricted by the distance between the vehicle-mounted collector and in-ground conductor and supplemented by the on-board ultra-capacitor system when needed. Charging of the ultra-capacitor can occur during regenerative braking or during period of light power demand such as when coasting. The in-ground conductor is switched such that it is only energized when a vehicle occupies the segment underneath the vehicle and is non-powered at all other times similar to the surface contact rail systems. An illustrative graphic from a recent Bombardier brochure is shown in Figure 18.

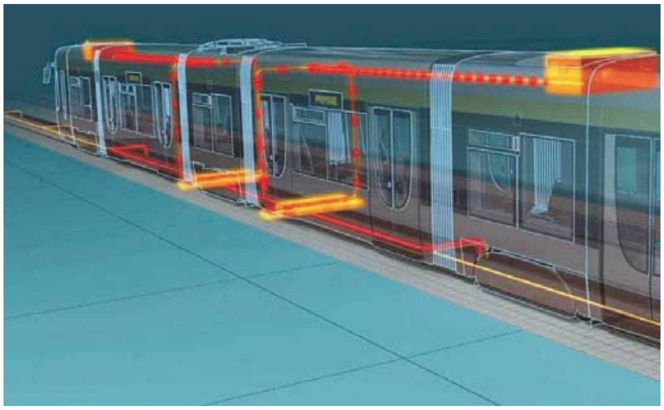

Fig. 18 - Bombardier Primove Graphic

On-Board Energy Storage

A disadvantage of the wayside power system alternatives is the need for the installation of a fixed infrastructure, to produce the same results as an overhead catenary system, but at a greater cost. A variety of different technologies used to store energy onboard vehicles to propel them without the fixed infrastructures described above, have been developed. These technologies differ in the amount of energy that can be stored and the distance the vehicles can travel before needing to replenish that energy. The energy source is either some external power supply or kinetic energy captured by the vehicle in motion and converted to electrical energy. The storage medium is either batteries or ultra-capacitors. The kinetic energy can also be stored by some mechanical device, such as a flywheel.

Batteries

The use of high-voltage battery-banks to power transit vehicles is a proven technology. The composition of batteries has evolved from the original lead-acid type to nickel-cadmium (NiCad), to nickel-metal-hydride (NiMH) and currently moving toward lithium ion (LiB) batteries. Each advancement in battery technology has resulted in a reduction of the battery weight required to store the same amount of energy. Another improvement is that the NiMH and LiB batteries do not contain either lead or cadmium.

Batteries provide the highest energy density of the electrical storage options, allowing the longest operating distance per installed weight. The most significant downside is the relatively slow charge/discharge capability and tight monitoring required. The battery charging current must be controlled so that permanent damage to the batteries does not occur. Avoiding this situation requires a separate micro-processor-controlled battery charger and cooling of the battery compartment. It also results in slower vehicle acceleration rates and top speed when operating on battery power. Newer LiB models are beginning to allow faster charge/discharge rates without a significant reduction in service life.

Batteries also need to be oversized for their intended application. To prolong battery life, it is best to keep the operating range between 20% and 80% of the total capacity. For an installed capacity of 25 kWh, this means 5 kWh must be reserved at both the lower end and the higher end, resulting in a useable capacity of 15 kWh. Additional capacity during operation could be realized using regenerative energy from braking.

Since the 1990s, San Francisco MUNI has been using NiCad batteries to power an Emergency Propulsion Unit (EPU) used to move electric trolleybuses off-wire around road obstacles and also to maneuver the trolleybuses in their parking and maintenance facility. The EPU is a high voltage battery pack consisting of 163 cells mounted on the roof of the vehicle.

The District’s existing Inekon streetcars have a similar emergency power supply application using the standard on-board battery as a back-up power supply. This system only provides power at 24 Vdc and is therefore severely limited in speed and distance. Under battery power the streetcar can move at only about 2 miles per hour for 500 feet on level track. This capability is intended to allow a streetcar to clear an intersection in case of loss of overhead power on the line, and for short movements in the storage yard and maintenance facility. The NiCad batteries are installed under the car, whereas high voltage battery sets are typically installed on the roof.

Rail vehicles with longer distance operability using NiMH batteries were placed into service in Nice, France, in 2007. Nice has two historic town squares, Place Massena and Place Garibaldi, each about 0.3 miles long and where the use of overhead wire was strongly discouraged. The town squares are near the center of the 5.5-mile (8.7 km) line. Vehicles are powered by overhead wire everywhere but these two locations, where they rely on on-board battery power. Travel over the remainder of the system allows sufficient time to fully charge the batteries from the overhead wire. Figure 19 provides a photograph of one of the Nice vehicles, manufactured by Alstom, operating on an overhead wire portion of the line.

Fig. 19 - Alstom Nice Streetcar

High voltage NiMH battery sets with lesser capacity than provided for the Nice vehicle are also installed on the streetcars manufactured by Alstom that operate on the APS surface-mounted contact rail system. The batteries are required to move the vehicle over a dead section of contact rail if such is encountered. The battery systems in these vehicles are very similar to those installed on the Nice vehicles.

In 2007, the Japanese railcar supplier, Kawasaki, introduced its hybrid SWIMO ‘Smooth WIn MOver’ or SWIMO that can run on overhead wire or on-board batteries (see Figure 20). The SWIMO vehicle is shorter and narrower than many other examples of modern streetcars, measuring only 50 feet (15 m) long and 7.3 feet (2.23 m) wide. It has 28 seats and a maximum capacity of 62 passengers. Media reports claim this vehicle can travel up to 6 miles (10 km) at a top speed of 12 mph (20 km/h) on battery power alone. It has been reported that the SWIMO has been operated up to 23 miles (37 km) without recharging under test conditions. The vehicles are equipped with NiMH batteries stored under passenger seats.

Fig. 20 - Kawasaki SWIMO streetcar

This year Kinki Sharyo unveiled their American version of the Japanese J-tram, named AmeriTram. The AmeriTram uses LiB technology and has located the batteries under the seats. The batteries are accessible for maintenance from the exterior of the car through access panels on the exterior sides of the vehicle. Because of the battery location, the car design is limited to one double-width door per side. The AmeriTram has been estimated to be capable of operating up to 3 miles (4.8 km) in revenue service during off wire operation.

Fig. 21 – Kinki Sharyo AmeriTram

Ultra-capacitors

New technological advances have made ultra-capacitors a viable alternative for on-board energy storage, and several manufacturers are pursuing implementation on streetcars. The attraction for propulsion suppliers is the relative ease of charging and discharging compared to the tight control of current required for batteries. The downside is the lower energy density compared to batteries, which limits the travel range without intermediate recharging.

One feature of ultra-capacitor operation is that there are no chemical processes associated with the charging and discharging of the unit. This makes it effective for very rapid transfer of power such as when starting a vehicle or recovering regenerative braking energy. Without a chemical reaction, degradation of the materials is much less of a concern than with batteries. The typical construction materials are aluminum, carbon, paper, and an organic electrolyte, making it environmentally friendly.

The downside to ultra-capacitors is their low energy density and higher cost when compared to batteries. Typically, an ultracapacitor can only store 10 to 20% of the energy storable in a battery for the same unit weight. This limits the amount of energy that can be reasonably stored on a vehicle and, therefore, the distance the vehicle can travel. However, continuing advances in this technology, including the introduction of carbon nanotubes, are increasing the energy density and lowering the price of these components.

Bombardier developed a prototype on a light rail vehicle and placed it into revenue service in Mannheim, Germany. This vehicle was tested over a four-year test period ending in 2007. This vehicle uses the ultra-capacitors primarily for the recovery and storage of excess regenerative braking energy and not operation off-wire. Nonetheless, off-wire operation for the vehicle was demonstrated for a distance of up to 0.3 miles (500 m) with one start and stop. The system, known as ‘MITRAC’, is a main component of Bombardier’s environmentally-friendly initiative, EC04, announced last year. Testing of the MITRAC system is ongoing at their test track in Bautzen, Germany. Meanwhile, the transport agency in Mannheim has ordered 19 ultracapacitor-equipped light rail vehicles from Bombardier. Figure 22 illustrates the placement of the ultracapacitor assembly on the roof of the vehicle.

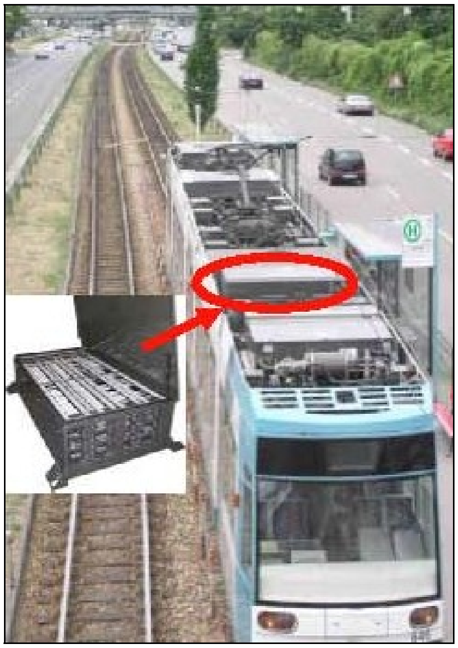

Fig. 22 - Bombardier Mannheim LRV with Ultracapacitor Bank

Ultra-capacitors are also used by the Spanish carbuilder, CAF, to move trams between stations without the need for an overhead wire. Similar to the Bombardier system discussed above, the ultra-capacitors are contained in a unitized compartment, the ACR, and mounted on the roof of the vehicle. The Urbos III streetcar with the ACR option is in service in Seville, Spain. The application permits the Urbos III to run without wayside power between stops and recharges the ultra-capacitor energy storage at stations within 30 seconds. Off wire operational range is reported to be 0.75 miles (1.2 km). In Seville the trams operate off-wire over a distance of 0.3 miles (0.5 km) at speeds of 9 mph (15 km/h) with all auxiliary systems including full air conditioning.

Fig. 23 – CAF Urbos 3

Hybrid Battery/Ultra-capacitor

The combination of both batteries and ultra-capacitors into one system combines advantages of the large storage capacities of batteries and the quick charge/discharge time of ultra-capacitors. The result is a system that can absorb all regenerated braking energy, provide quicker accelerations, and travel off-wire for long distances.

Siemens, a major supplier of rail vehicles, has developed the HES system consisting of both NiMH batteries and ultra-capacitors. The modified Combino streetcar has been operating in revenue service in Lisbon, Portugal since 2008. It can travel off-wire for distances up to 1.5 miles (2.4 km) with grades up to 2.8% and speeds of 20 mph (33 km/h) under normal operating conditions. Recharge time at stations has been reported as short as 20 seconds.

Flywheels

Flywheels, a concept of energy storage that has long been studied, has been given a second look with the development of new composites and integrated control electronics. They serve as a mechanical means of storing energy from braking. They are typically housed in a reinforced vacuum chamber installed on the roof of the vehicle, and rotate at speeds of 20,000 rpm and higher. Energy density is better than for ultracapacitors, though less than batteries. It should be possible to use this technology for short distances or for longer distances if there is a means of intermediate recharging from an overhead supply at passenger stations.

The main drawbacks to flywheel storage is the considerably higher capital cost compared to batteries or ultra-capacitors and the complexity of maintenance over the long term.

Alstom demonstrated a prototype of a flywheel system on a Citadis Tram in Rotterdam, Netherlands, in 2005. The demonstration project used the flywheel for recovery and storage of excess regenerative braking energy. Off-wire operation was tested and vehicles were reported to run at a “reasonable” speed with good acceleration. Data on the distance operated was not available.

CAF also tested a flywheel system in tandem with the original Urbos 2 testing on ultra-capacitors. After testing of both systems on the Seville line, CAF decided to pursue ultra-capacitors instead.

On-Board Power Source Technologies

Several technologies are being investigated that eliminate the need for an external power source altogether. They are typically combined with some type of on-board energy storage technology to power the rail vehicle. These include engine-generator packages (’gen sets’) and fuel cells.

Fuel/Electric Hybrids

This technology employs an engine-generator to produce electricity that is used to power electric motors, eliminating the need for overhead wire. The engine may be fueled by diesel, gasoline, compressed natural gas, or some other combustive product that is stored on the vehicle. This solution is well-known and in widespread use for vehicles such as diesel-electric locomotives. In a hybrid application, the generated power is used in areas without an overhead catenary system and traditional pantographs are used where an overhead wire is present.

An example is the Kassel ‘tram/train’ shown in Figure 24 where the tram operates solely by diesel engine in non-electrified suburban territory and solely by overhead wire within the urban area. There are two diesel-generator sets mounted on the roof of the vehicle. These Alstom Citadis vehicles are 130 feet (40 m) long and 8.7 feet (2.65 m) wide and require 82 foot (25 m) radius curves, which are difficult to fit on urban streets.

Fig. 24 - Alstom Regio Citadis in Kassel

Another example is the Siemens Combino Dualis used in Nordhausen, Germany. The Nordhausen cars are a modified version of the Siemens ‘Combino’ streetcar platform, and dubbed the ‘Duo’ for their dual-mode capability, they are about the same length as the District’s Inekon streetcars and can turn tighter 50 foot (15 m) curves. The Duo’s are equipped with a single 3.9 liter engine and 180kW generator placed in a compartment inside the passenger area of the car. The engine/generator is housed in the compartment between the two sets of doors, and the fuel compartment is located between one set of doors and the articulation unit as shown in Figure 25 below.

Fig. 25 - Engine/Generator (Siemens)

Fuel Cells

The development of fuel cells for use in the transit industry is still in the very preliminary stages with no known applications to streetcars. There are several demonstration projects with electric buses, and 10 prototypes are currently in revenue service at AC Transit in Oakland, CA. The prototypes are using proton exchange membrane (PEM) cells powered by hydrogen or methanol, with hydrogen getting the most interest. The buses use the fuel cells to drive electric motors as well as to charge batteries which then can assist the electric drives. The fuel cells essentially replace the engine-generators described in the preceding section of this report.

The FTA has funded research in fuel cell-powered buses since the late 1990s at Georgetown University and in 2007 began the National Fuel Cell Bus Program to push further development. Concurrent with this effort, the California Air Resource Board has instituted a similar development program. In the diagram shown in Figure 26, the fuel cell generates electricity which is routed through propulsion control equipment to operate electric motors connected to the bus axle. The electricity is also used to charge batteries which can supplement vehicle movement.

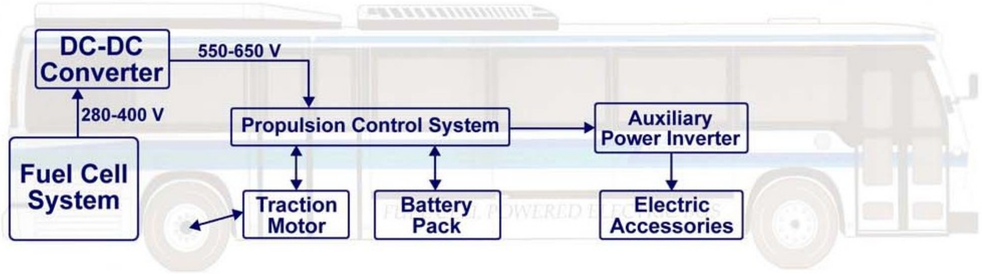

Fig. 26 - Functional Diagram of a Fuel Cell Bus

IMPLEMENTATION ISSUES

Modern alternatives for off-wire operation of rail vehicles are feasible, and vehicles using the many of these technologies have been in revenue service since 2003, as described in the sections above. However, the modern alternatives are still in their infancy with limited applications, to date. Each method brings unique issues to the construction and operation of the system. This section presents a basic listing of the anticipated issues for each technology.

Wayside Technologies

The sub-surface contact rail previously used in the District is no longer considered viable for the following reasons:

- The construction costs and utility relocations, and automotive traffic disruptions required for the installation of the underground contact rail (Figure 5) would be onerous.
- Operation of the systems requires underground chambers staffed by two maintainers at each entry and exit to the wireless area to install or remove the high voltage collector shoe.

- The in-street slot would leave high voltage rail exposed and susceptible to damage from items that may be dropped or intentionally inserted into the slot.
- Weather and drainage impacts on the alignment have been previously documented as shown in Figure 8.

The surface-mounted contact rails have been in revenue service in France on segments with reserved right-of-way for streetcar operation. The systems will also require in-ground distribution and switching networks that will substantially increase construction costs and equipment costs. Some specific issues that will need to be addressed prior to implementation of this type of system in the District are:

- The resiliency of the copper bars to repeated impacts from automobile and truck traffic. Mechanical damage will result in the need for accelerated replacement of the conductor rail.
- The ability to maintain a clean surface on the rail for continuous current transfer. Operation with intermittent contact due to dirt or rubber tire residue will result in pitting on the rail and shoe precipitating the need for accelerated replacement.
- The effects of corrosive chemicals such as road salt on the exposed surfaces of the conductor rails.
- Inclement winter weather where ice or snow can prevent contact with the rail surface will need to be addressed.
- The pre-formed rail assemblies will be considered proprietary or patentable and available from a sole supplier.
- The supplier of the wayside system may dictate the vehicle supplier if the technology is considered proprietary or patentable and is subject to licensing requirements.
- The ability of the pre-formed rail assemblies to be shaped around tight curves or to form crossovers with the grounded running rail for multiple line operation.

- The ability to maintain contact on tight vertical curves such as underpasses is unknown.
- Installation and protection of in-street high voltage contactor boxes at frequent intervals.
- Theft of the exposed copper conductor rails.

The non-contact surface rail system transferring power by induction eliminates several issues seen with the contact surface rails, primarily by replacing the copper conductor with an insulator. The following specific issues for the non-contact system have been identified:

- The systems are very new and the experience with them is limited to controlled demonstration lines on dedicated right-of-way only.
- The resiliency of the insulated covers to repeated impacts from automobile and truck traffic needs to be evaluated. Mechanical damage will result in the need for accelerated replacement of the conductor rail.
- The transference of energy from the wayside to the vehicle depends on maintaining a small gap between the vehicle's collector and the supply rail which may restrict the vertical curve capabilities in areas such as underpasses.
- The pre-formed rail assemblies will be considered proprietary or patentable and available from a sole supplier.
- Installation and protection of in-street high voltage contactor boxes at frequent intervals is required.

On Board Energy Storage Technologies

On-board energy storage is a service proven technology dating back to the early 1900's. The main reason for the prevalence of overhead wire distribution systems has been the much lower cost and reduced operating weight of the vehicles. However, recent advances in battery and ultra-capacitor are decreasing these advantages.

One of the main issues with deployment of these technologies has been cost with the historical price for battery storage at $1000/kWh. Recent advances, driven by the electric automobile market, have resulted in decreasing costs and increasing service life. Reports on the declining costs indicate that the $650/kWh price in 2010 will decrease to $250/kWh by 2020. Nissan is currently claiming the cost of the lithium battery pack in the Leaf electric model is $375/kWh.

Another important issue is the weight of the energy storage devices and the impact on the vehicle structure. Historically, streetcars have used Lead-acid or Nickel Cadmium batteries for on-board storage of back-up control power. These batteries typically store only 40 Watt hours per kilogram of weight. The development of NiMH batteries increased the available energy to about 95 Wh per kilogram. Newer LIBs are reaching up to 130 Wh per kilogram. These densities are permitting the storage of over four times the energy for the same weight. (Ultra-capacitors are primarily used for quick discharge/recharge times and have energy densities of only 5 Wh per kilogram.)

All on-board energy storage technologies have limitations with the amount of energy that can be stored on the vehicle versus the amount of energy required to operate across a wireless area. Operation in mixed traffic lanes is particularly difficult to estimate as unpredictable, but normal, events such as an unusually high traffic volume, traffic accident or diplomatic motorcade can extend the time off wire and exhaust the stored energy, before it returns to powered track, thereby stranding the vehicle. When addressing the reserve capacity for contingencies, and whether to make the system redundant to avoid a single point failure resulting in a stranded a vehicle, it is possible to have more reserve capacity than actual capacity required for operation. The lower capacity of ultra-capacitors may also impact operation outside of a reserved right-of-way due to shorter discharge times and less tolerance to traffic delays. Would all streetcars be provided with the capacity required for the greatest off-wire demand or would specific vehicles be restricted to specific lines?

The requirements for recharging of the onboard systems also need to be considered with the intended line operations. Batteries will sustain longer operation off wire, but will subsequently require a longer time under wire for re-charging. For instance, a battery installation providing a 5 mile (8.3 km) range of off-wire operation may need to be under wire for 30 minutes to fully recharge. Ultra-capacitors, which may only attain 0.6 miles (1 km) off wire, are capable of being recharged in as little as 30 seconds, but in this scenario, each passenger station would require a high-reliability high voltage recharge station which will impact the construction budget.

On Board Energy Generation Technologies

Fuel cells are a nascent technology as it relates to streetcar development and is not ready for a revenue service deployment at this time. The use of a diesel-generator to provide power off wire is a well-proven concept. The issue with a diesel power generation is its incorporation into a small streetcar. Some of the issues to be anticipated are:

- The installation and maintenance of the diesel-generator set and fuel tank in the streetcar's passenger compartment as was done in Nordhausen is problematic as shown in Figure 25.
- Installing the diesel-generator and fuel tank set on the roof will require a longer streetcar such as the 130 ft (40 m) streetcar used in Kassel. The roof structure would need to be strengthened in a typical streetcar to support the weight.
- Fueling services for the vehicles at the maintenance facility similar to a bus fueling station will be required.
- The noise and exhaust run counter to the "green" image being promoted.

OPERATIONAL ISSUES

Streetcars are normally operated as single units. Therefore, redundancy of the on-board systems becomes an important consideration. The goal is to have no single failure which renders the streetcar unable to move, thereby requiring towing to remove the car from the line and restoring revenue service. For example, streetcars in Bordeaux have on-board batteries to move the car if the APS system fails, and Bombardier's vehicles will have on-board ultra-capacitors to accommodate failures of the IPT system. The CAF streetcars using ultra-capacitors would need to be capable of traveling to two passenger stations in the event one station's charging system is not functional.

With the on-board energy storage technology, redundancy can be achieved by installing two housings for the batteries or ultra-capacitors. One unit could be associated with each end of the vehicle and be capable of powering the vehicle across the off-wire section on its own. Similarly, accommodating the redundancy requirement with the fuel/electric hybrid would require the installation of two small engines. Each engine would still need the ability to move the streetcar across the off-wire section on its own, though at a degraded level of performance.

The issue of how to move a vehicle with an exhausted power supply should be considered prior to utilizing the on-board storage technologies. The stranding of one vehicle on a streetcar line can shut down the entire alignment as there will be no method for passing a stranded vehicle and blocking a traffic lane in rush hour may result in bad publicity if it occurs with any frequency. The estimation of transit times to ensure a successful crossing while operating without a reserved right-of-way will be difficult.

PROCUREMENT ISSUES

The procurement of a small order of streetcars can be a challenge. Some suppliers, particularly if they have a backlog of booked work, may not be interested in contracting for small quantities of vehicles as it is very difficult to distribute the engineering and other one-time costs among the small order and keep the price affordable, and especially so if they incorporate new technologies and deviate from the suppliers' standard off-the-shelf vehicle platforms. From this perspective, the District must consider the modifications that need to be made to a supplier's existing streetcar. Alternatively, the District may wish to consider a larger order of streetcars for multiple lines to amortize the engineering and development costs.

The carbuilder's experience and staffing will be very important to a successful procurement. The District does not have a large or experienced streetcar maintenance staff to assist with the start-up problems experienced with new systems. It should be noted that Bordeaux's first installation of the Alstom APS required two years of operation to achieve acceptable reliability levels.

An alternative to the traditional method of procuring vehicles to fit the wayside being installed is the "turn-key" approach. In this approach both the vehicle and wayside are procured as one package from a single supplier. The District would accept delivery of the completed operating system. One of the major benefits of this approach is allowing the wayside power systems to be competitively bid against the on-board storage or generation systems.

The table below provides a list of suppliers and their experience as related to the supply of streetcars. The supplier list includes those suppliers known to have expressed an interest in providing streetcars in the United States. It is not intended to preclude other potential suppliers who may not be currently known.

Supplier	Streetcars in Service	Wireless Operation Experience	Turnkey Systems Experience
Alstom	Yes	Yes	Yes
AnsaldoBreda	Yes	On Order (2010)	Yes
Bombardier	Yes	Yes	Yes
Brookville Mining	Yes	Switch locomotives & mining trams	No
CAF	Yes	Yes	Yes
Gomaco	Yes	Yes	No
Inekon	Yes	On Order (2011)	No
Kawasaki	Yes	Yes	Yes
Kinki Sharyo	Yes	Yes	Yes
Siemens	Yes	Yes	Yes
Stadler	Yes	No	No
United Streetcar	On Order (2007)	No	No

Figure 27. Suppliers Interested in North American Streetcar Market

EXISTING VEHICLES

The District currently owns three streetcars manufactured by Inekon and commissioned in the Czech Republic in 2007. The vehicles are currently configured to run only under wire with a minimal off-wire capability designed primarily to facilitate emergency movements to clear traffic in the event of a loss of the overhead wire. The vehicles are currently being stored at the WMATA Greenbelt Facility.

In late 2007 Inekon responded to a WMATA request to look at the possibility of operating off-wire for limited distances at specific intersections where the District's view corridors might be crossed. In December of 2007 Inekon submitted a study indicating a NiMH battery set could be installed on the vehicle to provide off-wire distances of up to ½ mile (0.8 km) at speeds up to 10 mph with currently available batteries. The primary limitations were the short length of the vehicles and the weight of the batteries. In the last four years LiB batteries have been advanced to the level that it should be possible to increase the calculated range significantly while remaining within design limitations. Inekon has also recently announced receipt of award for a Seattle Streetcar order incorporating LiB technology designed to run up to 2-1/2 miles off-wire with a very similar carbody.

If a wayside power supply option is selected, the mounting a new power collector to the underframe or truck of the Inekon vehicles may be possible. However, supplier cooperation and installation of a compatible energy storage device would need further investigation.

SUMMARY

For a small-to-medium order of vehicles, the right technology will be highly dependent on supplier interest and the status of the design. A new start-up operation should concentrate on technologies that have an established service record and require minimal refinements for their intended use in the project at hand. The table in Figure 28 offers a subjective comparison of the readiness of these alternatives for application on the wayside or on-board rail vehicles.

Option	Proof of Application	Supplier Interest	Procurement Risk
Alstom APS Surface Contact Rail	Revenue	Moderate	Sole Supplier
AnsaldoBreda TramWave Surface	Demonstration	Moderate	Sole Supplier

Option	Proof of Application	Supplier Interest	Procurement Risk
Contact Rail			
Bombardier PriMove Non-Contact Rail	Demonstration	High	Sole Supplier
Batteries	Revenue	High	Low
Ultra-Capacitors	Revenue	High	Low
Fuel/Electric Hybrids	Revenue	Moderate	Low

Fig. 28 - Readiness of Alternatives for Further Examination

Another primary concern is the cost of constructing and maintaining both the wayside infrastructure and the vehicles themselves. These costs are dependent on the option selected and are summarized in relative terms in Figure 29 below.

Option	Infrastructure Costs	Vehicle Costs	O&M Costs
Alstom APS Surface Contact Rail	Increase	Moderate	High
AnsaldoBreda TramWave Surface Contact Rail	Increase	Moderate	High
Bombardier PriMove Non-Contact Rail	Increase	Moderate	Slight
Batteries	Reduction	Moderate - High	Moderate
Ultracapacitors	Reduction	Moderate - High	Slight
Fuel/Electric Hybrids	Reduction	High	Moderate

Fig. 29 - Relative Anticipated Costs

With the current state of the technology and the small quantity of vehicles envisioned, it is our opinion that the best option would be a procurement approach open to either the wayside in-ground supply or the battery/ultracapacitor storage on-board the vehicle. The most significant differences between the two is that a battery solution has the lower risk due to the maturity of the technology while the wayside solutions can simplify the construction and operation of the entire network by providing an unlimited distance at a higher cost than the overhead distribution system. An open competitive procurement between the technologies should result in the Best Value for the District of Columbia.

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