CLOSING GENERAL SESSION

Light Rail Without Wires
A Dream Come True?

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Since the dawn of electrification over a century ago, overhead wires have been used to convey electrical power and communications to offices, factories, and homes. Transportation, too, in the form of streetcars, and 0more recently, light rail vehicles, has commonly used overhead wires to transfer power to vehicles. Many people consider these wires to be unsightly and undesirable, but reluctantly accept them as a necessary evil because of a lack of practical alternatives. Only a few cities have managed to run significant streetcar systems without overhead wires for any length of time and all such systems are now defunct. In recent years, new technological developments in hybrid vehicles and ground level switched contact systems are at last showing signs of offering some practical alternative solutions. For light rail applications, the most promising development is the INNORAIL ground level switched contact system now being applied to the new light rail system in Bordeaux, France, which will be examined in detail. Based on the significant progress being made there, it seems likely the dream of having a practical alternative to overhead wires will be coming true in the very near future.

WHY HAVE OVERHEAD WIRES?

Dislike of overhead wires in the urban environment is not a new phenomenon. From the introduction of electrically powered apparatus over a century ago, people have protested against the erection of overhead wires, especially in the more affluent sectors of the city. As far back as the 1890s, major established, affluent cities such New York City, Washington, D.C., London, and Paris garnered enough political support to enact city ordinances prohibiting the erection of any type of overhead wires in specifically designated areas. For most cities, however, financial and practical considerations usually ended up winning the argument and as a result, overhead wires were erected.

During the development of the fledgling streetcars, a wild flurry of new and often impractical electric power supply approaches were tried, from the first experimental battery powered passenger carrying cars of 1847, to the first successful electric streetcar system, built by Frank J. Sprague in 1888 for Richmond, Virginia. Sprague's system, which was the first to use both an overhead contact wire and trolley poles, demonstrated such a clear superiority over other approaches of the time that it soon became the industry standard for supplying power.

Later developments have mostly focused on refining this relatively simple, economical, and reliable direct electrical contact technology, known today as the overhead contact system (OCS). These systems have operated efficiently and mostly unchallenged until today, with the biggest design change being a gradual transition from using trolley poles on the streetcars to pantographs on the more modern version, the light rail vehicle. As a result, almost every streetcar/light rail system in operation or being planned today uses an overhead wire to supply power.

CHANGING URBAN LANDSCAPES

In recent years, with cost-effective improvements in cable insulation and burial techniques, there has been a renewed interest in improving the quality of the urban cityscape. New housing additions have sought to create attractive neighborhoods by burying all cables and concealing transformers. Cities have undertaken expensive area improvement programs to eliminate garish billboards and signs, and to place local power feeders and communications cables underground, greatly improving the appearance of the area and generating public pride.

As those who have undertaken the task of trying to add a new light rail system to an established neighborhood know well, the concept of erecting overhead wires for a new system is unpopular with the public. This is what happens to the urban landscape when overhead contact wire is erected (Figure 1).

Even with attempts to minimize the visual intrusion of the OCS system, the impact is still significant. However, the elimination of these wires and their supporting structures is a problem for light rail systems because up to now, there has been no practical alternative to OCS. The next section examines some ways in which this problem might be resolved.

ALTERNATIVE SOLUTIONS

There are a number of potential alternatives available, but most either pose extreme technological challenges or are fatally flawed in some basic characteristic. Over the years, through the process of development and elimination, three potential solutions stand out as being the most promising:

(a) **(b)**

FIGURE 1 Urban landscape (a) with OCS wires; and (b) without OCS wres.

- Conduit power (old, but proven technology);
- Hybrid vehicles (combination of power sources including fuel cells, super capacitors, flywheels, microturbines, batteries, and internal combustion engines); and
- Ground level switched contact systems (center running 'third rail').

To address these adequately would be beyond the scope of a single paper, although an attempt has been made to provide an overview in a earlier paper entitled *At Last, Light Rail Systems Without Overhead Wires* published in the proceedings of the APTA 2003 Rail Transit Conference. Since the publication of that paper, it has become clear that resurrection of the old conduit system remains impractical from both a cost and operational standpoint, while the hybrid vehicle development program appears to be stalled indefinitely. Therefore we will concentrate on the ground level switched contact systems, and in particular on the INNORAIL system currently being commissioned in Bordeaux, France.

GROUND LEVEL SWITCHED CONTACT SYSTEMS

Based on proven third rail power transfer systems, a promising approach might be to place the power supply rails directly between the running rails and pick up the power using third rail type shoegear. The basic concept will remind many of Lionel and Marklin model trains. The problem with this approach is, of course, the danger inherent in having ground level power rails energized at 750V/dc when the rails are accessible to the public. This problem can be solved by making the power rails a series of separate sections—the system can switch each section on or off individually so that a power rail section is energized only when the vehicle is directly over it.

There have been a number of recent attempts at making this approach work. These include the E-Tran bus system developed for Minnesota by Nick Musachio, (1986–1992), the STREAM bus system for Trieste, Italy developed by AnsaldoBreda, (1994–present), the ALISS Light Rail Vehicle (LRV) system for Bordeaux, France developed by Alstom, (1999–2002) and the INNORAIL LRV power system developed by Spie Rail, a subsidiary of Spie Entertrans (1999–present), also for Bordeaux, France. Only the ALISS and the INNORAIL systems were specifically designed with sufficient power capacity for application to a light rail system.

Out of all these, the INNORAIL system is currently the most advanced and well on its way to a significant LRV system application in Bordeaux.

Bordeaux's Light Rail Transit System as a Driver for New Technology

When the new Bordeaux light rail transit (LRT) system vehicle specification was released for tender to potential suppliers in 1999, it included a requirement to provide a power supply system that did not use overhead contact wires through an architecturally important and aesthetically sensitive section of the city adjacent to the Cathedral, some 1.8 mi (3 km) of the system route. Historically, it is important to note that even in their earlier streetcar days, Bordeaux never had overhead contact wire in the town center, as a conduit power system provided vehicle power until the system was dismantled. Potential suppliers experimented with various options to meet these requirements, including flywheel energy storage. Upon close evaluation, all existing technological solutions had significant drawbacks, including weight, cost, space requirements, and performance between stations when stopping was required.

Eventually, it was determined that a completely new development, the ground level switched contact system, known in France as the APS system, short for Alimentation par Sol, was required to provide the reliable system needed. Two competing versions of this system were subsequently developed and evaluated, the Alstom ALISS system and the Spie Rail INNORAIL system. In the summer of 2002, the INNORAIL system emerged as the final choice for implementation in Bordeaux.

More importantly, the requirement for INNORAIL equipped sections of the Bordeaux system is now to be increased to 6.3 mi (10.5 km), nearly half the total 15.5 mi (25 km) Phase 1 system length. This is more than twice the initial requirement, clearly a vote of confidence by the city of Bordeaux in the viability of the technology.

An important lesson to learn from this is that strong and unwavering political support for a new technological development required to meet a perceived public need, will produce the motivation needed to develop and adopt it.

INNORAIL Basics

As is common with all the earlier ground level contact system approaches, the INNORAIL system uses a series of switched contact rails installed between the running rails, separated by insulated rail sections to ensure complete electrical isolation of each section. Each individual section is only energized when its local power rail contactor receives and verifies a low power, specially coded signal coming from the vehicle transponder that can only be detected when the vehicle is directly over the section. At all other times, the power rail segment is automatically grounded.

Two sets of pickup shoes are provided on the vehicle to provide continuity of power as the vehicle crosses insulated sections. The basic elements of the system are illustrated in the following two diagrams (Figures 2 and 3).

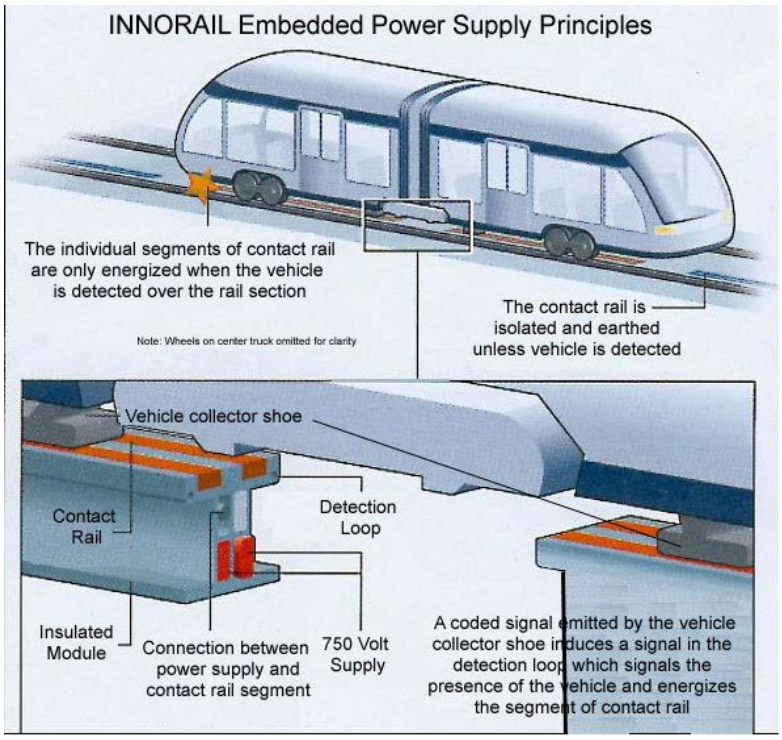


FIGURE 2

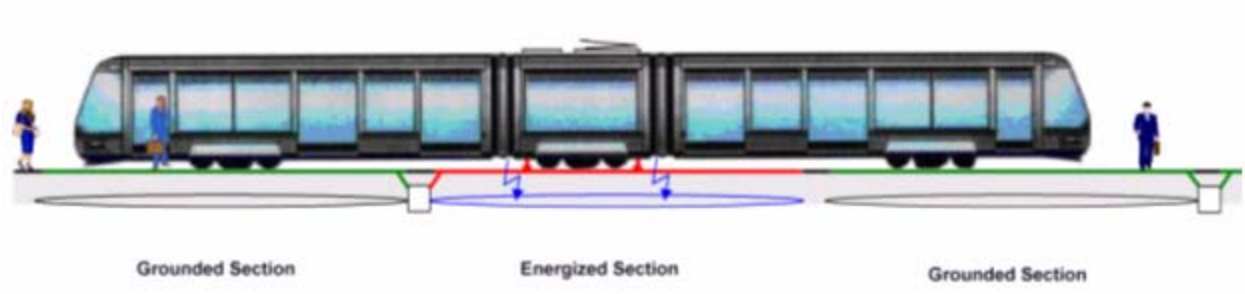


FIGURE 3 INNORAIL ground level switched contact system.

The INNORAIL power rail sections are designed with a very low profile, standing only 6.7 in. (17 cm) high. This allows them to be easily accommodated in virtually every type of track installation, including ballasted track. The INNORAIL system may also be retrofitted to many existing LRT systems (Figures 4 and 5).

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 (Figure 6).

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

In Bordeaux, transitions from INNORAIL to conventional OCS (and vice versa) are manually initiated by the vehicle operator with the vehicle stopped at a passenger platform. This transition is completed within normal station dwell times. According to the manufacturer, it is also possible for this process to be automated, allowing the transition to be accomplished with the vehicle moving.

The crossing of special track work such as turnouts and crossovers is made using special insulated sections, which allow the pick-up shoes to cross the running rails (Figure 7).

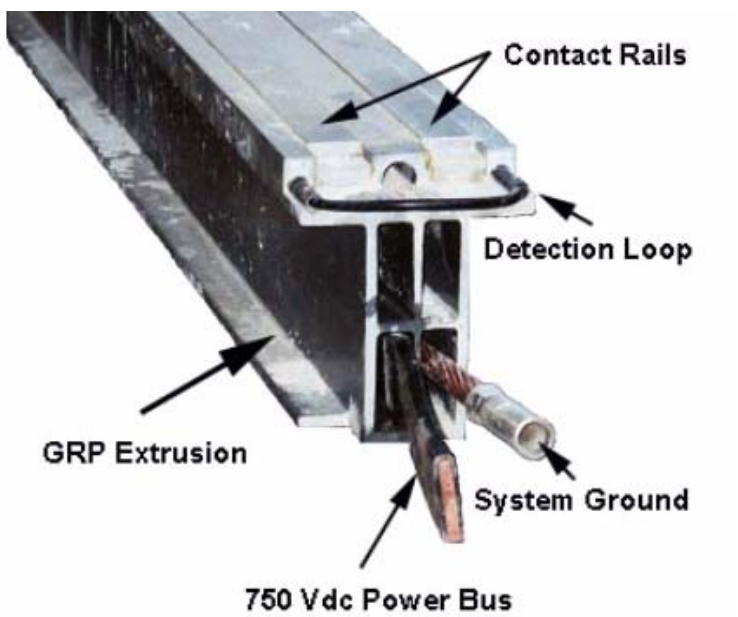


FIGURE 4 INNORAIL power rail cross section.

Ballasted Track

Paved Track

Embedded Track

Grass Track

FIGURE 5

FIGURE 6 Station transition point.

FIGURE 7 Crossing special trackwork.

INNORAIL System Development

Development of INNORAIL began in the Spie Rail works in Vitrolles in the south of France in early 1999. Full size system component mockups were installed on streetcar Line 68 in nearby Marseille by December 1999, with fully functional prototype components installed by May 2001. This allowed the operation of a limited proof of concept installation using a modified 600V/dc high-floor vehicle and 1,968.5 ft (600 m) of sectional power rails, of which 492 ft (150 m) were in installed in city streets (Figure 8).

Meanwhile, in the north at Ollainville, track components in a variety of installation configurations were being subjected to a simulated 30 years of street traffic by the RATP Test Laboratories, being repeatedly crossed by 11 ton rubber tired vehicle loads (Figure 9).

By 2002, INNORAIL early production components had been installed on 2,296.6 ft (700 m) of LRV test track at the Alstom La Rochelle factory where the new Citadis LRVs for Bordeaux are being constructed. Extensive testing followed, using a state-of-the-art 100% low-floor Citadis vehicle operating at 750V/dc (Figure 10). To date, over 2,100 mi (3,500 km) of endurance running tests have been performed, including crossing special trackwork and automatic transition to emergency battery power.

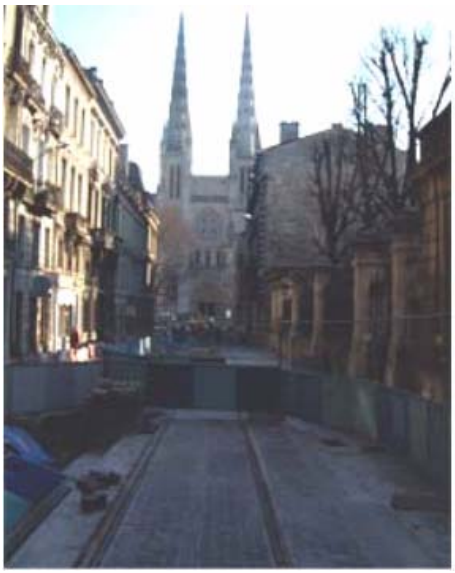
Bordeaux's LRT System

As was noted earlier, the Phase 1 Bordeaux system length (Lines A and B) totals 15.5 mi (25 km), of which 6.3 mi (10.5 km) or nearly half the system is INNORAIL equipped. The INNORAIL equipped sections are located in the old city center, on the historic stone bridge crossing the Garrone River, on Line B as far as Talence, and two short sections in Lormont and Cenon (Figure 11). The entire Phase 1 system is scheduled to be in revenue service by the end of 2003.

FIGURE 8 Proof of concept.

FIGURE 9 Endurance testing.

FIGURE 10 System testing.



(a)

(b)

FIGURE 11 (a) Old City Center; and (b) Garonne River Bridge.

Phase 2 of the development (Line C) will add another 11.6 mi (18.7 km) to the system. The percentage to be equipped with INNORAIL has yet to be finalized, but at least 3.1 mi (5 km) are expected.

The Bordeaux LRT system development produced one of the largest LRV orders in Europe, a total of 70 X 100% low-floor, air conditioned vehicles (Figure 12). The order breakdown is as follows:

- 6 X 107.93 ft (32.9 m) long, 213 passenger Citadis 302 and 38 X 144.36 ft (44 m) long, 300 passenger Citadis 402 100% low-floor vehicles in Phase 1.

FIGURE 12 Citadis LRV.

- 12 X 107.93 ft (32.9 m) long Citadis 302 and 14 X 144.36 ft (44 m) long Citadis 402 100% low-floor vehicles in Phase 2.

As is the norm for European LRV operations, they run only single car trains, adding more vehicles to the system as demand requires. The system typically runs trains at 4 min intervals (2 min at peak).

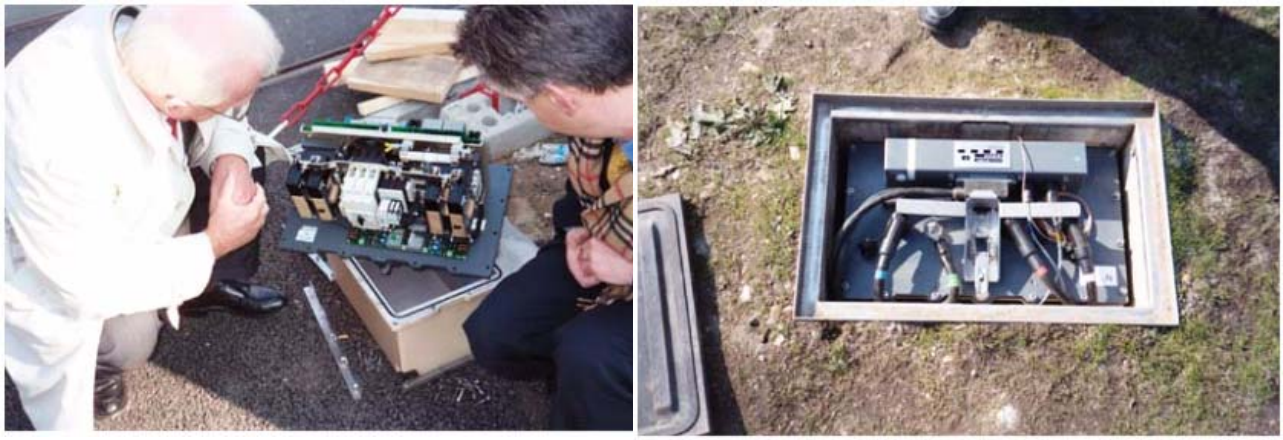
INNORAIL System Components

Fixed Installation

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

Sectional Power Rails (as mentioned earlier) These low profile sections are typically in 36 ft (11 m) lengths fitted with 26.25 ft (8 m) of conductor rail and 9.84 ft (3 m) of insulating rail. These FRP pultrusions contain integral duct banks that carry all power, ground and control cabling., as well as the vehicle detection loop for that section. These assemblies also have a spare cable duct that could potentially be leased to local fiber optic or coax cable service providers. The ratio of conducting rail to insulating rail is based on the vehicle operating speed, which in the case of Bordeaux, is 44.7 mph (20m/sec or 72 km/h).

Power Rail Control Contactor Units One is located every 72.2 ft (22 m), and controls two segments of power rail (Figure 13). These units are modular and can be replaced in less than 5 min. Although a solid state switching unit would logically be utilized, traditional contactor units were chosen for this application because the short duty cycles caused difficulties in semiconductor heat rejection at these current levels. It is still very likely that a solid state solution will eventually be applied.



(a) (b)

FIGURE 13 (a) Interior of power rail control unit; and (b) Installed power rail control unit.

Insulating Junction Boxes An insulating joint box is located every 72.2 ft (22 m) to mechanically and electrically join the ends of the power rails at all locations. These boxes are silicone sealed after all connections are made to keep out moisture (Figure 14).

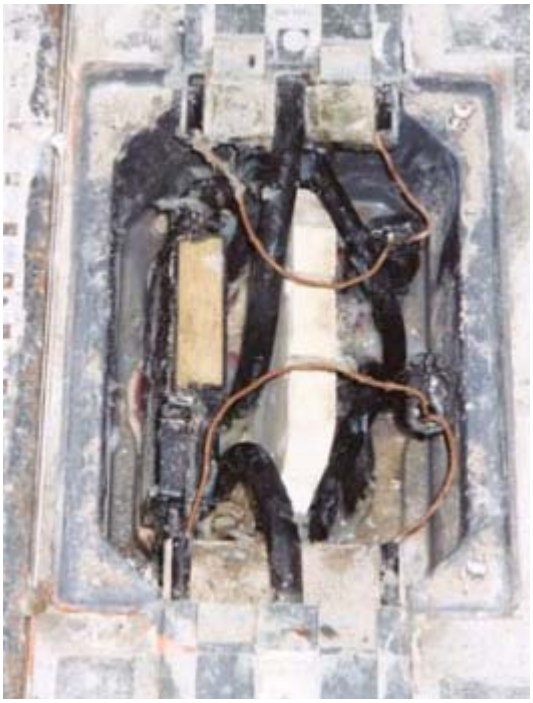
Grounding Contactor and System Monitoring Equipment For safety purposes, a cabinet containing a grounding contactor and system monitoring equipment is installed in each substation (Figure 15). The condition monitoring system is designed to detect faults in any power rail segment within 200 milliseconds, disconnect and ground the main 750 V/dc power feeder to all segments fed by that substation, automatically isolate the faulty segment and restore the system power to the remainder of the system in less than 2 seconds. These faults include, most importantly, a segment remaining live after the vehicle signal is lost and of course, short circuit or similar faults.

On the Vehicles

The INNORAIL system is capable of being installed on almost any type of light rail vehicle, including 100% low-floor vehicles. The following additional equipment is required to operate on an INNORAIL equipped system:

Emergency Battery Set One roof mounted unit is required on each vehicle to allow it to transition through any dead power segments (Figure 16). To save space, this unit is mounted under the pantograph frame on the vehicle center section. This battery set contains 63 x 12 volt sealed, aircraft certified, lead acid batteries and can provide approximately 1 min of vehicle movement at reduced speed [1.8 mph (3 km/h)]. This will move the vehicle a minimum of two failed power rail segments, although 500 ft (152 m) is routinely achieved.

Retractable Power Pickup Shoes Two sets of center truck mounted pickup shoes are necessary for current collection, mounted at the ends of the truck (Figure 17). The shoegear uses graphite shoes to keep the fixed installation wear to a minimum, although in the initial stages, soft iron shoes have been used to clean and polish all the contact surfaces.



(a)

(b)

(c)

FIGURE 14 Junction box (a) interior; (b) installed; and (c) with control unit.

FIGURE 15 System monitoring.

FIGURE 16 Battery box.

FIGURE 17 Shoegear installation.

Pickup Shoe Control Box Extra control components required to activate the pickup shoes and interlock with the pantograph controls.

Power Control Box This roof mounted box contains the additional contactors and controls needed to for switching 750V/dc power coming from the pickup shoes or the emergency battery set (Figure 18).

Cab Controls and Monitoring equipment Additional controls required to operate and monitor the vehicle's INNORAIL related equipment.

Safety Grounds Extra ground points installed under the low-floor section of the vehicle to suppress any possible fault conditions. These are shown in Figure 17.

Safety and Certification

With a readily accessible ground level power system, safety is clearly a key concern. A variety of safeguards are designed into the system to prevent any single point failure from causing a hazardous condition. Independent safety certification insures that the designs perform as expected.

The safety certification process has been and continues to be addressed by various well known and respected French certification authorities and independent assessors including CERTIFER and RATP. The process so far has been as follows:

- Independent system assessment in accordance with **EN 50126** – Railway Applications – The Specification and Demonstration of Availability, Maintainability and Safety (RAMS) and **ENV50129** – Safety Related Electronic Systems for Signaling .
- Approval of the Preliminary Safety Case – this was completed in January 2000.
- Approval of the Final System Safety Case – is currently more than 90% complete and with the current progress in energizing the Bordeaux system, it is expected to be fully completed and approved by the time of this conference.

As mentioned earlier, each section of INNORAIL power rail is solidly grounded unless a signal is received by its local power control unit, and separate substation monitoring circuits double check this by looking for voltage on the rail without a vehicle signal. This is to prevent any section from being inadvertently energized when not safely covered by an LRV.

FIGURE 18 Power control box.

Another major consideration is leakage from an energized power rail section when conditions are wet. Being on the Atlantic coast, Bordeaux is always humid and subject to frequent rain. Further, the streets are washed using salt water taken from the harbor, creating a very conductive and corrosive environment. Energized rail tests under standing salt water conditions have measured less than 5 volts leakage outside of the running rails which is considered acceptable.

Unfortunately copies of the Hazard Analysis used in the certification process and detailed design approach used to respond to these concerns are not yet readily available.

Adapting INNORAIL Technology to U.S. LRT Systems

A number of U.S.-specific issues must first be addressed before the INNORAIL system can be applied to a U.S. LRT system,. Following a technical assessment visit to Bordeaux in February of this year, the following observations were made regarding the suitability of the INNORAIL ground level contact system for U.S. applications:

- The INNORAIL ground level contact system is well developed and has applied sound engineering principles in its design and construction. All equipment is solidly constructed and is likely to survive in its operating environment.
- The system appears to mitigate all reasonable identifiable safety hazards, thus Safety Certification in the United States should be achievable. Such certification will require considerable preparation and documentation to be presented to U.S. local certifying authorities, but can build on the experience of the Bordeaux in its safety certification process.
- Adapting to multi-car operation may be achieved by increasing the size of the main power bus with no change to the basic INNORAIL installation as the ducts can accommodate a larger cross section power bus. Substation size and spacing should remain as is normal for typical U.S. OCS operation.
- Adapting for higher operating speeds is also said to be possible by the supplier. This would require relatively minor changes in the relative lengths of the conducting and insulating rail inserts to achieve the desired power rail switching.
- Sole sourcing is also a consideration. The INNORAIL system technology is proprietary and only available from one source, thus sole source procurement will currently be required. Fortunately, this may be allowable under Section 9.h.of FTA Circular C4220.1E *Third Party Contracting Requirements.*
- "Buy America" requirements are also an issue in U.S. procurements. However most, if not all, of the INNORAIL system components could be manufactured using 60% or more U.S.-manufactured components or possibly completely manufactured under license in the U.S.
- Adapting for higher gradient operation under section failure conditions has a higher impact as the Bordeaux LRT system profile is relatively flat. Should the U.S. LRT system being designed have any significant gradients involving INNORAIL operation, a larger set of batteries will be required for the Emergency Battery Set, adding to the vehicle cost and weight.
- Adapting the vehicle system components to U.S.-manufactured LRVs should be fairly straightforward due to the universal nature of the additional vehicle equipment required The biggest challenges would be the fitting of the retractable shoegear in the very confined area surrounding the center trailer truck and the space and weight distribution impacts on the vehicle roof area.
- Cost is always a critical issue. Currently the system is only operating in France and has yet to be "Americanized," thus any cost projections are somewhat speculative. However, based on the

supplier's current estimates, the fixed installation should be within 5% of traditional OCS system costs, plus approximately 5% per LRV for the additional INNORAIL related vehicle mounted equipment. With series production, this could become no increase in cost over OCS.

- Operation in ice and snow conditions is currently not addressed. With its fully exposed conductor rails, icing is certain to occur. There are some potential solutions, such as electrical trace heating, but they will add cost, both in initial installation and energy wise.

Adapting INNORAIL for use on US LRT systems looks possible from a cost, safety, and engineering point of view as long as snow and ice are not a major factor. The author is aware of several U.S. cities that are actively considering this technology and the number is likely to grow as the system becomes fully operational at the end of this year.

The biggest single hurdle today is availability of the system. In March of this year, the Spie Rail INNORAIL technology was sold to Alstom who are currently showing no interest in the U.S. market for this very promising technology. It is hoped that if sufficient interest is shown here, we too may have the capability to operate without wires.

CONCLUSIONS

For the first time in many decades, the dream of having quiet, non-polluting, electric light rail vehicles running without any overhead wires is on the verge of becoming a reality.

The INNORAIL ground level switched contact system in Bordeaux is about to become a significant operational system, although more day-to-day operational experience is needed to fully prove system reliability over time. Nonetheless, this system is sufficiently developed enough that the author believes this to be a viable system and worthy of consideration for many new light rail systems.

One thing is certain, public opinion is very supportive of "wireless" systems and as this technology becomes more mature and available, widespread adoption is inevitable.