LINEAR MOTOR PROPULSION FOR URBAN TRANSIT

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Abstract

Modern urban transit systems must provide a high level of service with short headways. The design of the route alignment must be flexible and permit steep grades to reduce system cost. Reliable precision stopping at stations under all weather conditions is essential. Linear Induction Motor (LIM) propulsion ideally meets the operating requirements, providing adhesion-independent transmission of acceleration and brake forces. The topology used is a short vehicle mounted primary and a long track mounted secondary. The effects of the LIM topology must be considered in order to design a viable transit system. Issues are the air gap, changes in reaction rail configuration, the vertical forces and the operation as a direct drive. Two generations of LIM propulsion have been developed and are described in this paper. LIM propulsion has been successfully deployed in five advanced transit systems.

1 Introduction

Bombardier Transportation is a world leader in applying Linear Induction Motor (LIM) technology to urban transit systems. The development of the technology started in 1975 and resulted in the implementation of five transit systems with the LIM on board with a total system length of more than 100 km. In addition, LIM-in-track systems were implemented for passenger and material transport.

Linear motor propulsion is the optimum solution to achieve the operational requirements for automated urban transit systems; in particular Bombardier's Advanced Rapid Transit (ART), as it provides independence from adhesion. The ART was developed to provide a total transit solution for urban communities that did not need or could not afford a conventional subway system. Twenty-five years later, the selection of LIM Propulsion remains the first choice.

In 1975 the government of the province of Ontario in Canada started a development program for an Intermediate Capacity Transit System (ICTS). The development occurred in five phases by UTDC (Bombardier acquired UTDC's assets in 1992):

Phases 1 and 2	Program definition and trade studies, 1976
Phase 3	Prototype development, 1980
Phase 4	Pre-production vehicle, 1983
Phase 5	Commercial deployment, 1984

These first generation (MKI) vehicles are in operation on:

- The Scarborough Rapid Transit system in Toronto, Canada
- The SkyTrain in Vancouver, Canada
- The Detroit People Mover system in Detroit, USA

The success of these systems and the market demand for a higher-capacity vehicle led to the development of a second-generation (MKII) vehicle. This program was undertaken from 1987 to 1991. This vehicle is used on new systems as well as existing systems. Second generation vehicles are in operation on:

- Kuala Lumpur LRT System 2 in Malaysia,
- SkyTrain in Vancouver,
- JFK International Airport in New York City, USA.

Bombardier Transportation also has extensive experience in the development and application of LIM-in-track systems. A people mover was installed at Houston's International Airport in 1981 with an extension in 1990. Bombardier Transportation is the licensee of the Walt Disney Corporation for the WEDway people mover technology used for this project. An advanced version of this technology was used for the United States Senate subway in Washington, DC. LIM-in-track systems are also used for material transport; an example is the baggage transfer between terminals at the Changi airport in Singapore, commissioned in 1990.

An integrated transit system consists of many elements. This paper describes the LIM propulsion system as part of the ART vehicles. It addresses the rationale for the selection of the LIM technology, specific issues of LIM propulsion for transit applications, the propulsion design and urban transit systems using LIM propulsion.

2 LIM Propulsion Rationale

2.1 Operational Requirements

LIM propulsion is an integral part of the Advanced Rapid Transit system solution to the operational requirements for a total transit system. The requirements were established with input from municipal planning authorities and transit authorities as well as from studies of North American cities [1]. These requirements demand a high and flexible service level. The system must operate under all weather conditions, including snow and ice. The system must be environmentally acceptable and have minimum land use, noise and visual impact. It must integrate well in an urban environment. Reduced system and operating costs are also part of the requirements.

2.2 ART System Characteristics

A development program was undertaken from 1976 to 1984 to develop the technology to fulfill the operational requirements. Trade studies were performed for all elements of the ART system. Steel wheel on steel rail, rubber tire and MAGLEV were considered for the suspension and guidance. The selection of steel wheel on steel rail provides all-weather capability, ease of switching and proven, easily available guideway elements. Steerable bogies allow for low-radius curves, increasing the flexibility of the guideway alignment. LIM propulsion was selected to provide high operational availability due to its independence from adhesion, high grade capability (6% or higher) and low maintenance. Driverless operation with a moving block system provides short headways and flexibility to adapt the system capacity to the actual demand. The short headway allows achievement of the throughput with short, light vehicles, reducing the cost of stations and the guideway.

2.3 LIM Propulsion Advantages

Adhesion-independent service braking is the most important feature of LIM propulsion for the ART system. The importance of achieving the required brake deceleration under all weather conditions is described in detail in [2]. An operating case in the referenced paper is summarized here to highlight the adhesion issue. A transit system with short headway operation brakes with a conservative deceleration rate of 1 m/s^2. The required adhesion is 0.1, axle unloading not considered. The slide probability is 0.1% based on tests by British Rail [3]. A typical ART system, with 24-hour operation and headways from 1.5 minutes during 6 hours, 3 minutes during 12 hours and 6 minutes during 6 hours, will perform approximately 10 000 precision stops per day. Even with the low probability of 0.1% there will be 10 slide events per day. The vehicle must follow a trajectory that brings it to a precise stop at the platform, particularly when platform doors are used. A slide moves the vehicle outside the trajectory and a higher brake rate is required from the non-sliding axles to regain the trajectory. Algorithm A in figure 2.3-1 attempts to regain the trajectory by commanding maximum braking. Algorithm B recalculates a new trajectory reducing the adhesion demand in comparison with algorithm B. The adhesion demand on the non-sliding axles is increased and they could also slide, particularly on a 4-axle vehicle. If this occurs, the station stop is missed.

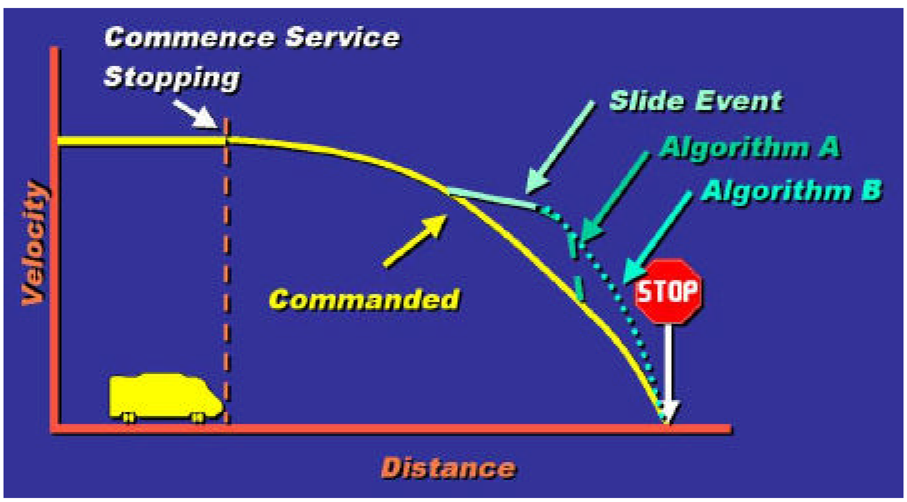

Figure 2.3-1 Consequences of Sliding

Several mitigation approaches can be used to correct the situation. The vehicle can be jogged back to position. This may not be possible under short headway operation as the next train is too close. In this case the train must skip the stop and proceed to the next station. Both of these methods are an inconvenience to the passengers and disturb the operation as the following trains are delayed. Anti-slide protection prevents wheel flats but still does not allow the train to follow the required trajectory, since it reduces the deceleration rate. Another approach is reduced brake rate, which also decreases the throughput.

LIM propulsion transmits tractive and brake efforts directly to the guideway, eliminating the slide problem. Reliable and accurate station stops under all weather conditions are assured. The independence of adhesions allows steep grades in the alignment, reducing system construction cost. Existing systems have grades up to 6.5%; higher grades are possible. The elimination of all rotating parts, gears and coupling reduces rolling resistance, equivalent rotating mass, maintenance costs and noise. Long wheel life is achieved because the wheels are not transmitting any force except for final stopping.

3 LIM Issues in Transit Applications

Any drive technology must be robust enough to withstand the harsh transit environment and round-the-clock operation in many ART applications. The particularities of a LIM drive must be considered in the design of the system and its operation.

3.1 Topology Effect

The LIM used for the ART is a short stator (primary), long rotor (secondary) arrangement. The primary (called LIM) is installed on the vehicle. The passive secondary (called reaction rail) is installed between the rails on the guideway (Figure 3.1-1)

Figure 3.1-1 LIM Topology

The air gap is most important for the behaviour and performance of the LIM. Reaction rail installation tolerances and LIM adjustment tolerances must be selected so that they are achievable in practice. A mechanical analysis determines the gap, which must be set so that no mechanical contact occurs under worst-case load conditions; tolerances and wheel wear between LIM height adjustments. The gap is 10–11 mm under nominal load and tolerances. The magnetic gap (entrefer) is longer by the thickness of the aluminium top cap (see Figure 4.1-2). A magnetic gap analysis is performed to determine the magnetic gap to be used for performance calculations of the LIM, assuming worst-case conditions for electrical performance (for example new wheels). The magnetic gap is 15.5-16.5 mm under load and with new wheels. Experience shows that the gap can be achieved in construction and can be maintained in operation. The reaction rail is inspected twice a year. Infrequent adju stment would be required to compensate for rail wear. The LIM height is adjusted after wheel profiling.

Figure 3.1-2 Vehicle guideway interface

A single-sided LIM topology generates significant vertical force between the LIM and the reaction rail as a result of the attractive magnetic forces and the repelling electromagnetic forces. This force has equal or higher magnitude than the longitudinal thrust and can be much higher under fault and zero slip condition. The LIM structure, the bogie and the attachment of the reaction rail to the guideway have to be designed for these forces. The short stator topology produces end and edge effects. The end effect reduces thrust as the speed increases. It also leads to LIM current unbalance that needs to be considered in the inverter design.

3.2 LIM Operation

LIM propulsion is a direct drive. The magnetic active surface is limited in length and width by the bogie. The LIM is operated at peak thrust to achieve the required force. The operating point for peak thrust varies significantly due to changes in the magnetizing inductance. The gap changes due to installation tolerances, load variations, deflections and wheel wear. The magnetic design of the reaction rail changes as a different design is used for high and low thrust zones. Furthermore, no reaction rail is installed through switches. The temperature of the reaction rail top cap changes due to the ambient temperature and the losses when the LIMs move along the reaction rail. The first generation controls were set for nominal conditions. The thrust envelope used for operation was de-rated from the maximum achievable to account for deviation from nominal conditions. Second generation controls are adaptive and track the peak thrust operating point under varying operating conditions. The thrust envelope used for operation is the peak thrust of the LIM. The four operating areas of constant current motoring, constant voltage motoring, constant current braking and constant voltage braking must be carefully coordinated and optimized as an improvement in one area could have a negative effect in another area.

3.3 Efficiency

The LIM is less efficient than an equivalent rotary machine. For a transit operator, the issue is not the efficiency but the operating cost or more accurately the energy cost per passenger km. Major factors determining the energy consumption of a system are vehicle mass, rolling resistance, auxiliary systems, speed profile, alignment and guideway heating (if required). A vehicle with LIM propulsion must be compared with a vehicle of different technology providing the same passenger throughput and service availability. For example a rail vehicle with rotary drive may need more axles to achieve the same service level and availability under adverse adhesion conditions; its higher weight results in higher energy consumption. A rubber-tired system has a higher rolling resistance and may need guideway heating under wet or snow conditions, increasing the energy consumption. Comparison for the SkyTrain in Vancouver show that the LIM technology is competitive in regards to energy cost on the basis of service provided.

4 LIM Propulsion for ART Vehicles

4.1 First Generation (MKI) LIM Propulsion

The first-generation vehicles and LIM propulsion systems entered revenue service in 1985. The vehicle is 12.7 m long over couplers and has a tare mass of 14 370 kg. The vehicle is propelled by two LIMs. Each LIM is installed in a steerable bogie. The MKI LIM consists of a linear stack of laminations with a conventional two layer; three-phase winding insulated with class H materials. The mechanical structure is designed to hold and compress the lamination stack and to transmit the longitudinal and vertical forces to the bogie yoke. The yoke acts as the steering mechanism and transmits the vertical forces to the axles and wheel trough a stiff primary suspension that minimizes the effects of the vertical forces and vehicle loading on the air gap. Ten fans located above the windings cool the LIM. Unfiltered air is pushed down through the windings and exhausted towards the bottom of the LIM. The LIM is provided with sensors for over-temperature detection. Early insulation problems under freeze-thaw cycles were corrected by changes in the insulation materials and manufacturing process. The maintenance requirements are very low as the only moving parts are the cooling fans. Maintenance consists mainly of blowing out the windings.

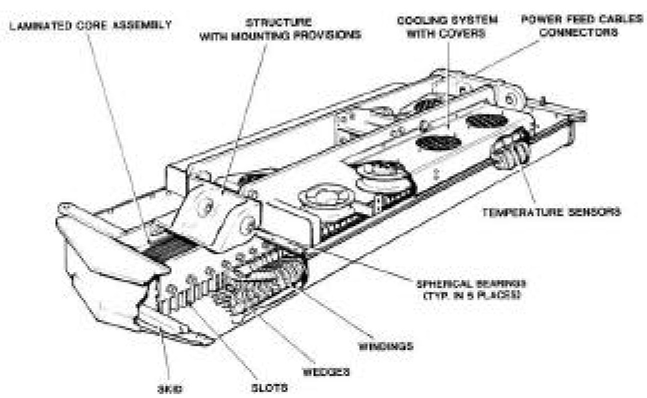

Figure 4.1-1 MKI Linear Induction Motor

Number of Poles	6
Number of Phases	3
Rated Voltage	450 V
Peak Thrust	12 kN
Vertical Force	25 kN
Peak Current	485 A
Rated Power	120 kW
Total Mass	640 kg
Length	2.2 m
Width	0.62 m

Table 4.1-1 MKI LIM Characteristics

The reaction rail consists of a laminated back iron of 10 soft steel bars. The number of laminations is a trade-off between thrust reduction and reaction rail cost. Laminated back iron is used in high thrust areas. Low thrust areas such as yards have a reaction rail with solid back iron. No reaction rail is installed in switches. An aluminium top cap (6063-T3 with a resistivity of 3.5 micro-ohms per meter) is the secondary winding. A mechanical assembly allows transmission of the forces to the guideway. The MKI and MKII vehicles use the same reaction rail.

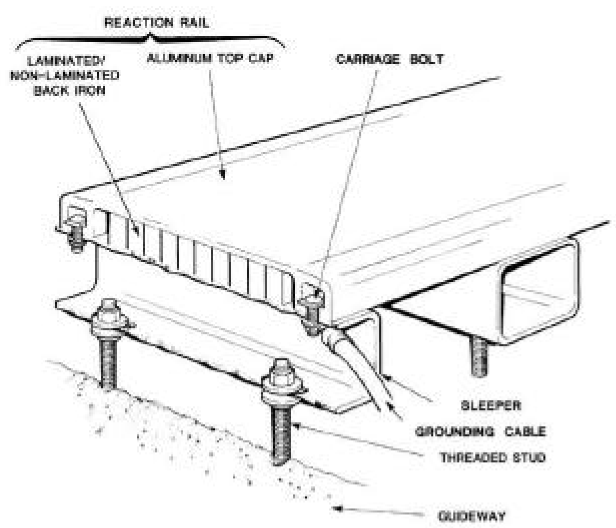

Figure 4.1-2 Reaction Rail

A power conversion unit (PCU) consisting of an input breaker, an input filter and a three-phase, variable voltage, variable frequency inverter supply each LIM. The first units use power transistors for the inverter while units that are more recent use GTOs; the transistor and GTO modules are interchangeable. The PCUs are naturally cooled and required tight packaging to fit in the space available. The thrust is controlled by regulating the LIM current. The slip frequency is set according a fixed slip frequency vs. speed function to operate the LIM at peak thrust under nominal conditions. The controls are a discrete technology; the electronics racks are installed under the seats inside the vehicle. Regenerative braking is used with controlled resistors on the wayside to assure receptivity at all times. Installation of the brake resistor on the wayside reduces vehicle weight and on board equipment size.

4.2 MKII LIM Propulsion

The ART MKII vehicle has increased passenger capacity with a length of 16.3-17.6m and a tare mass of 22 000 - 24 000 kg depending on the application. The larger MKII vehicle requires higher thrust from the propulsion system. The MKII LIM is an evolution of the MKI LIM. The magnetic circuit was optimized for higher performance and ease of manufacture. The primary width was increased and the coil pitch changed. The cooling airflow in the LIM was optimized to increase the thermal rating. Two fans blow the cooling air in a plenum lengthwise over the top of the primary stack. Openings in the side frame allow the air to flow over the coil heads, and the air is exhausted to the side. The bottom of the LIM is completely enclosed to prevent foreign object damage. The insulation is rated class H. The LIM is designed for a supply voltage of 750 V DC at the collector shoes, increased from 600 V DC.

Figure 4.2-1 MKII Linear Induction Motor

Number of Poles	6
Number of Phases	3
Rated Voltage	570 V
Peak Thrust	20 kN
Vertical Force	25 kN
Peak Current	550 A
Rated Power	160 kW
Total Mass	640 kg
Length	2.23 m
Width	0.67 m

Table 4.2-1 MKII LIM Characteristics

The PCUs supplying the MKII LIMs are based on IGBT technology. Similar to the MKI PCU they consist of a high-speed circuit breaker, input filter and inverter. Forced-air cooling is used to reduce the weight. The PCUs for the Vancouver SkyTrain vehicles use an input step-up/down chopper to convert the nominal 600 V DC supply to 750 V DC intermediate circuit voltage for the inverter to achieve the required thrust envelope.

An adaptive control adjusts the slip frequency so that the LIM always operates at the peak thrust point under all operating conditions for thrust demands between 80% and 100%. The standard vector control for a rotary machine was adapted for this purpose. The controls are microprocessor based and include built-in diagnostics. They are installed in the PCU itself, which is linked through a network to the onboard health monitoring system.

5 Urban Transit System with LIM Propulsion

5.1 The ART Transit System

The ART system is designed for a capacity of 10 000 – 40 000 passenger per hour per direction. The guideway is usually elevated with some sections at grade or underground. The Automatic Train Control (ATC) system utilizes Alcatel Canada's communication based SELTRAC moving block. Operation is driverless including in the storage yard. The power supply is by third or fourth rail depending on the system. Other features are extensive communication, closed circuit TV and platform intrusion detection.

5.2 ART Vehicles

The MKI vehicle entered revenue service in 1984. The vehicle structure is aluminium with two passenger doors per side. Each vehicle has two LIM propulsion systems with steerable bogies. Automatic couplers allow the formation of trains.

Length Width	12.7 m 2.5 m
Typical Passenger Capacity (Standees @ 6/m^2)	90
Total Mass	14 370 kg

Table 5.1-1 ART MKI Main Data

The MKII vehicle has an increased passenger capacity. The vehicle structure is aluminium on a steel underframe. The width at floor level is the same as MKI, so that MKII vehicles can operate on the same track as MKI vehicles. There are 3 passenger doors per side. Two vehicles are semi-permanently coupled and the passenger compartments are connected with a gangway. A derived design with wider car body and two wide passenger doors per side is used at the JFK International Airport in New York City, USA. Reference [4,5] provides a detailed description of the MKII vehicle.

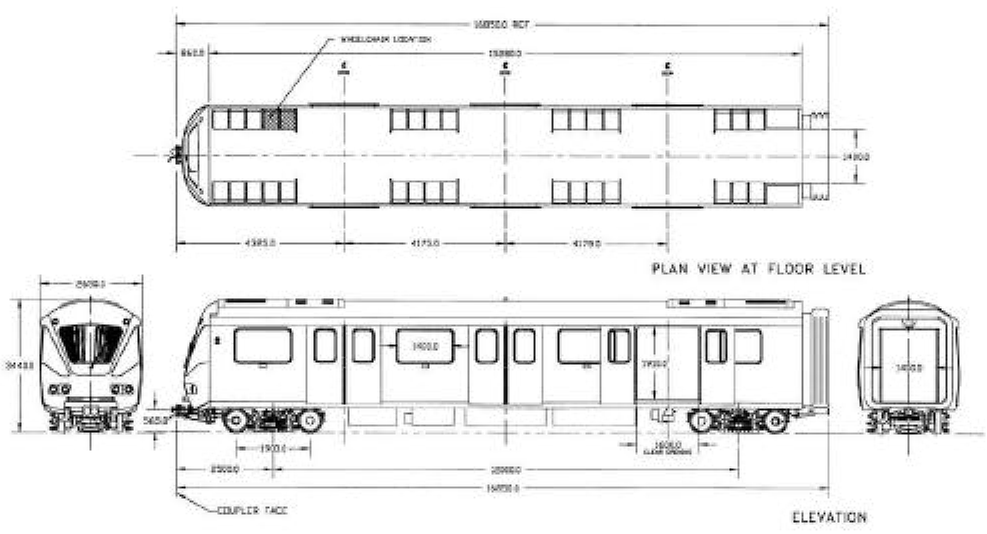

Figure 5.1-2 ART MKII General Arrangement.

	Kuala Lumpur	SkyTrain	JFK
Length	16.35 m	17.35 m	17.6 m
Width	2.6 5m	2.65 m	3.2 m
Typical Passenger Capacity (Standees @ 6/m^2, 5.4/m^2 for JFK)	171	185	295
Total Mass	22 000 kg	22 300 kg	24 000 kg

Table 5.2-2 ART MKII Main Data

5.3 Scarborough Rapid Transit, Toronto Canada

The Scarborough Rapid Transit system in Toronto was the first deployment of the ART MKI technology. The system length is 6.8 km and has 28 MKI vehicles configured as married pairs that can be coupled to form a 4-car train. The vehicles have a cab, which allows for cab-signalling or automatic control.

5.4 SkyTrain, Vancouver, Canada

The SkyTrain system in Vancouver started revenue service in 1986 with a length of 21.5 km. Three extensions increased the length to 28.9 km with grades up to 6.5%. A total of 150 MKI vehicles were delivered in several series. They operate as married pairs in 2-, 4- or 6-car trains. Operation is driverless with automatic coupling. The system has carried over 400 million passengers safely, reliably and cost effectively.

Figure 5.3-1 ART MKI Train on an inclined section at SkyTrain in Vancouver, Canada

The system is presently being extended with the new 20.3 km Millennium Line, increasing the total system length to 49.2 km. The maximum grade of the extension is 6%. Its first segment went into operation in 2002. 60 ART MKII vehicles were added to the fleet. MKI and MKII vehicles can operate on both the base system and the new Millennium Line. The MKII vehicles are configured as semi-permanently coupled married pairs with a gangway between the vehicles. The vehicles can be automatically coupled to 4-car trains. Yard movement and storage is automatic.

5.5 Detroit Downtown People Mover, Detroit, USA

The Detroit Downtown People Mover went into revenue service in 1987. It is a single-track loop connecting the business core in Detroit. The system is 4.7 km long with 13 stations. The guideway passes through buildings. 12 MKI vehicles are operated driverless as singles or coupled to trains. Yard movement and storage is automatic.

5.6 Kuala Lumpur LRT System 2, Kuala Lumpur, Malaysia

The Kuala Lumpur LRT System 2 [6] is the first deployment of ART MKII vehicles. The first phase was completed in time for the Commonwealth Games in 1998. The system length is 29 km with 19 above ground and 5 underground stations. The maximum grade is 6.25%. The underground stations are equipped with platform doors. 70 ART MKII vehicles are in service. They are configured as semi-permanently coupled pairs connected with a gangway. Operation is driverless, including in storage.

Figure 5.5-1 ART MKII Train in on an elevated section at Kuala Lumpur, Malaysia

5.7 AIRTRAIN, JFK International Airport, New York City USA

The AIRTRAIN system will connect ten fully enclosed stations using an elevated dual track guideway to link all terminals in JFK's terminal area with two branches that interface with New York's regional transit system. The system length is 13 km with a maximum grade of 5.4%. 32 ART MKII vehicles with wide bodies are being supplied. The vehicles feature extra-wide doors and onboard luggage racks to accommodate airline passenger luggage. The vehicles are designed to operate driverless as single units or in trains of up to four vehicles. Yard movement and storage is automatic. Revenue service starts in 2002.

Figure 5.6-1 ART MKII wide body vehicle for AIRTRAIN at JFK International Airport, New York, USA.

6 Operating Experience

Bombardier Transportation's experience with over 700 LIM propulsion systems in operation confirms that the linear induction motor is ideally suited for automated urban transit systems. Adhesion is no longer a factor as motoring and braking forces are directly transmitted between the vehicle and the guideway. This is of crucial importance for automatic operation as slide can lead to emergency brake application or position uncertainty. Bombardier Transportation can appreciate these issues as supplier of both LIM propulsion and rotary propulsion (Ankara subway and London's Dockland Light Railway) for automated systems.

7 Conclusion

LIM propulsion provides the operator with reliable all-weather performance at a minimal maintenance cost. After 25 years LIM propulsion remains the ideal choice for automated urban transit systems, operated at short headways and difficult alignments. Bombardier continues to develop the ART technology to provide transit system operators with optimum, cost effective solutions to their transportation needs.

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