Aerial Ropeway Transportation Systems in the Urban Environment: State of the Art

B. Alshalalfah[1]; A. Shalaby[2]; S. Dale[3]; and F. M. Y. Othman[4]

Abstract: The evolution of public transit modes has been remarkable, fueled by the need for different transit modes to handle different demand levels, urban environment patterns, and natural constraints and barriers. One of these needs is the desire to overcome geographical and topographical barriers such as mountains, valleys, and bodies of water, which cannot be conquered by conventional transit modes without very large investments and changes made to the natural topography. Aerial ropeway transit (ART), a type of aerial transportation mode in which passengers are transported in a cabin that is suspended and pulled by cables, is one of the solutions to such cases. ART has its origins in aerial lifts that have been used for decades in Alpine ski resorts to transport skiers and tourists in cable-suspended cabins. The use of aerial transportation in the urban environment, which was once considered an unlikely possibility, has gained more attention worldwide, and it is now used as a public transit mode in several terrain-constrained urban areas around the world. This article describes the origins of aerial transportation and its advantages, components, service characteristics, available technologies, and applications around the world. The paper concludes with a fair assessment of the existing ART technologies. **DOI: 10.1061/(ASCE)TE.1943-5436.0000330.** © *2012 American Society of Civil Engineers.*

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Introduction

Conventional public transportation systems offer a wide range of transit modes to serve people in urban areas. Bus and streetcar routes are usually aligned along corridors of low to medium passenger demand, whereas rapid transit systems (i.e., subways) are typically built where passenger demand is the highest in dense urban areas. Semirapid transit, such as light rail transit (LRT) and bus rapid transit (BRT), is more appropriate for corridors with medium passenger demand and population density. However, real-world applications of these technologies in urban areas might not always be feasible because of several factors that are not necessarily attributed to passenger demand. In many urban contexts, geographical and topographical barriers such as mountains, valleys and bodies of water, and the very large infrastructure costs associated with overcoming these barriers, may not permit the consideration and/or the implementation of conventional public transportation systems for such areas. In such cases, transit agencies may look to unconventional modes of travel to serve the needs of the residents of geographically constrained areas.

Several unconventional transit technologies and modes that are designed to deal with specific functions have found significant applications in many areas around the world (Vuchic 2007). One of these technologies that are increasingly used in areas with geographical and topographical barriers is aerial ropeway transit (ART). The term "aerial ropeway transit" was coined for the purpose of this paper to describe any form of aerial ropeway systems that are implemented in the urban environment as a public transit mode.

This paper begins with an overview of ART, its origins, system components, and system characteristics. The overview is on the basis of information gathered from the limited available literature on the subject and other resources such as ART vendors and applications around the world. Following that, a detailed review of available ART technologies is presented. The service and system characteristics of this technology are then compared with those of conventional transit modes. A discussion of the existing ART applications around the world is then presented, including applications in Portland (USA), Roosevelt Island (USA), Medellin (Colombia), Caracas (Venezuela), Hong Kong, and Constantine (Algeria). The last section of this paper presents an assessment of the present ART technologies, their benefits and limitations, and the advancements needed for ART to be a fully recognized transit member.

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Introduction: What is ART?

ART is an aerial public transit technology in which cabins (also called carriers, vehicles, or cars) are suspended and propelled from above by cables. The underlying technology of ART has been around for more than a century, where it has been applied mostly in terrain-challenged recreational contexts (e.g., gondolas/telepherique in ski resorts) to transport skiers and tourists

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to-and-from mountain tops. In recent years, however, the same technologies that have been used in these resorts have been adopted and implemented as a mode of transit in non-Alpine but geographically constrained urban regions, where conventional transit service was deemed very difficult or unfeasible to implement. ART can be thought of as a member of the broader cable-propelled transit technology (CPT), which also includes rail-supported cable cars. CPT can be defined as a transit technology that moves people in motor-less, engine-less vehicles that are propelled by a steel cable (Dale 2011).

The literature and industrial community use the term "ropeway" to describe a system that is used for transporting materials and/or passengers in carriers suspended from or controlled by ropes or cables. The Colorado School of Mines (2010) states that the term "aerial ropeway" is used to refer to any ropeway system that is suspended in the air (2010). On the other hand, aerial ropeway transit describes any type of aerial transportation mode in which passengers are transported in a cabin that is suspended and pulled by cables. The literature on aerial ropeways as a transit mode in the urban environment is very scarce. The main research on the subject was done by Neumann (1992), who provided a detailed discussion of the performance, cost, and application potential of some cable-propelled technologies. The study included a discussion of some aerial ropeway systems in the urban environment and other types of cable-propelled systems such as funiculars and people movers in airports. Neumann (1999) later provided a thorough review of cable-propelled people movers and their future potential. The study included a review of the history of cable-propelled movers from the 1800's through the 1990's, and a description of the characteristics of some individual systems around the world.

During the past decade, ART has gained increasing attention worldwide as a cost effective and attractive transit mode for terrain-constrained urban areas. An ART system can use one of the following aerial technologies: Aerial Tramways, Dual-Haul Aerial Tramways, Monocable Detachable Gondolas (MDG), Bicable Detachable Gondolas (BDG) and Tricable Detachable Gondolas (TDG). These technologies and their characteristics will be discussed later in this article. The next section discusses the components of an ART system.

ART System Components

In the United States, state governments and agencies use the Passenger Ropeways Standard [American National Standards Institute (ANSI) 2006] as the governing standard for passenger ropeway systems. This establishes a standard for the manufacture, construction, operation, and maintenance of passenger transportation systems that use cables, ropes, or other flexible elements for power transmission in the system. The systems mentioned in the standard include aerial tramways, detachable and fixed-grip aerial lifts, surface lifts, tows, and conveyors. Almost all ART systems have the same basic components, irrespective of the technology used. The basic components of any ART system include carriers (cabins), terminals, towers, ropes, and evacuation and rescue systems. The following is a discussion of each component.

Carriers (Cabins)

Carriers are defined as the structural and mechanical assemblage in or on which the passenger(s) of a ropeway system are transported. The carrier includes the carriage or grip, hanger, and the passenger cabin (ANSI 2006). The carriers can consist of large cabins as in the case of aerial tramways, or small and medium cabins as in the case of gondolas. The carriers are usually described by capacity (e.g., two 80-passenger cabins on an aerial tramway system, 15-passenger gondola cabins). The cabins are always totally enclosed and have standing room to reach full capacity (Colorado School of Mines 2010).

Terminals (Stations)

Virtually all ART systems have two terminals: a drive terminal and a return (idle) terminal. If a vertical change takes place, the terminals are called the upper and lower terminals. The bull-wheel in the drive terminal can operate as the drive wheel, and the bull-wheel at the return terminal acts as a fixed return mechanism. For detached-grip gondola operations, a separate area for slow down and loading is needed in the terminals and is often electronically monitored for safety. Some systems that use gondolas might have a few intermediate stations to pick up and drop off passengers between the drive and return terminals (Dwyer 1975).

Towers

Towers are intermediate structures that support the track and haulage ropes between terminals. They are often steel framed, and are sometimes pylon-shaped. The tower's primary function is to hold and allow the haulage rope movement through wheels. Towers must also have guides to keep carriages from hitting them for safety. Towers might not always be necessary depending on the length of the system. For long systems, intermediate towers are necessary to provide support to the system and therefore eliminate the need for long spans.

Ropes

The rope (cable) is the heart of any aerial ropeway transit system. The rope is formed by intertwining individual wires to form a strand and then the strands to form a rope (cable). There are many processes for manufacturing ropes and choosing the appropriate rope for any given application. One critical point is to specify whether the rope is a haulage rope or a track rope (aerial tramways) or if one rope supports both functions (MDG gondolas). Ropes are generally described by their outside diameter in inches. Common usage is a $1\,1/8$ inch (2.85 cm) haul rope and a $1\,7/8$ inch (4.76 cm) track rope for a bicable system (discussed subsequently), or a $1\,3/8$ inch (3.49 cm) rope for a gondola system (Colorado School of Mines 2010).

Evacuation and Rescue System

All aerial ropeway systems have provisions for an auxiliary drive in the event of electric power failure, usually gasoline or diesel driven. Once this drive, called the evacuation power unit, is engaged, passenger loading ceases and the ropeway operation is shutdown after the ropeway has been unloaded. According to the ANSI (2006), the evacuation power unit should not depend on the mechanical integrity of any other power unit to drive the ropeway. At a minimum, the evacuation power unit should be capable of starting and moving a line with all carriers loaded to 110% of weight capacity in a forward direction at not less than 0.51 m/s.

Most aerial systems have provisions for evacuation of stranded carriers by using harness and rope to lower individual passengers to the ground below (Colorado School of Mines 2010). Large reversible aerial tramways have a rescue system that sends an independently powered, small cabin out to remove passengers from a stranded carrier. In the more advanced dual-haul aerial tramway systems (that will be discussed later), the drives of the two passenger cabins are not interconnected, which allows for evacuations to occur by means of a bridge connected between the two adjacent cabins. For gondola systems, the abseil technique (the controlled descent of the cabin down the rope) is used for monocable gondola evacuation on normal terrain with low ground clearance. For

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Fig. 1. An aerial tramway:(a) cable configuration; (b) a cabin; (The Doppelmayr Group 2011)

difficult terrain and higher ground clearance, the bicable and tricable gondola systems incorporate an evacuation car that runs along the track ropes (Leitner Technologies 2011).

Available ART Technologies

ART technologies that have been used as mass transit modes in urban areas include five technologies: aerial tramways, dual-haul aerial tramways, monocable detachable gondolas (generally called gondolas), bicable detachable gondolas, and tricable detachable gondolas. The following is a discussion of these technologies.

Aerial Tramways

An aerial tramway (also called reversible ropeway or jig-back ropeway) is a type of aerial lift in which two passenger cabins (vehicles) are suspended from one or more fixed cables (called track cables) and are pulled by another cable (called a haulage rope). The fixed cables provide the support for the cabins, whereas the haulage rope is solidly connected to the truck (the wheel set that rolls on the track cables) by means of a grip [see Fig. 1(a)]. The haulage rope is usually driven by an electric motor, moving the cabins from one end to the other (Dwyer 1975). The tramway is sometimes called jig-back because the power source and electric engine at the bottom of the line effectively pull one carrier down by using the weight to push the other carrier up. The two passenger cabins are situated at opposite ends of the cable loops. Thus, while one is coming up, the other is going down the mountain, and they pass each other midway on the cable span (see Fig. 2).

Aerial tramways usually have large cabins [see Fig. 1(b)] that can carry between 20 and 200 people at speeds of up to 43.2 km/h (refer to Table 1 for a summary of the service characteristics of aerial tramways) (The Doppelmayr/Garaventa Group 2011). Depending on the size of the car, line speed, and line length, transport capacities vary between 500 and 2,800 persons per h per direction (pphpd). Some aerial trams have only one cabin, which lends itself better to systems with small elevation changes along the cable run. On the basis of the available information, there are two aerial tramway systems that are used as a mass transit mode, both of them in the United Sates: the Portland aerial tram and the Roosevelt Island tramway.

Dual-Haul Aerial Tramways

Dual-haul aerial tramways are relatively new ropeway technologies that are built to improve some of the characteristics of aerial

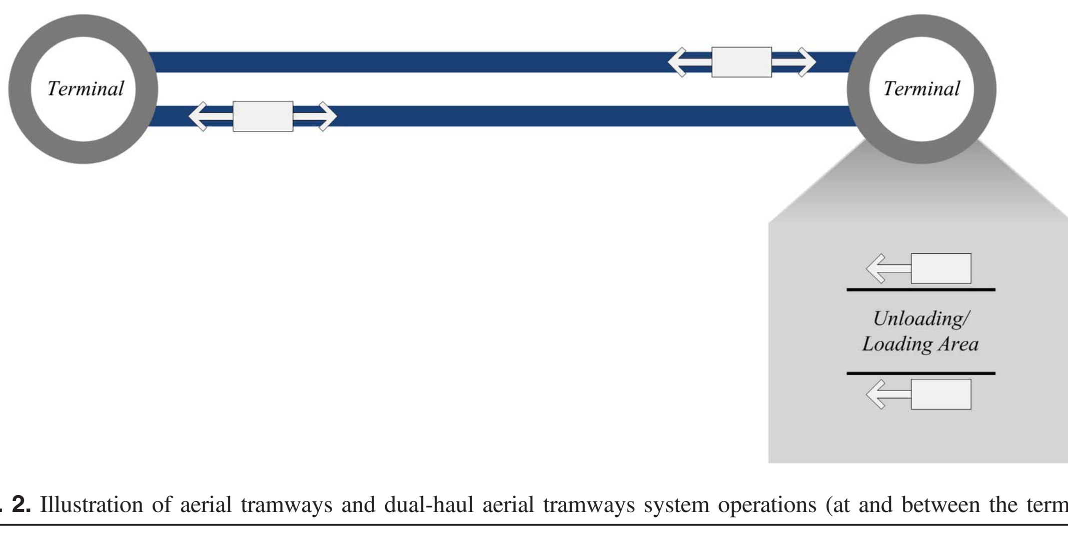

Fig. 2. Illustration of aerial tramways and dual-haul aerial tramways system operations (at and between the terminals)

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tramways. Similar to aerial tramways, this system consists of two reversible cabins that run on parallel tracks. However, unlike aerial tramways that have fixed ropes and a haulage rope loop for the two cabins, the dual-haul system has two guide ropes and a haul rope loop per cabin (see Fig. 3). At the top of each track, the haul rope for that track loops back to the bottom instead of looping over to serve the other track as occurs with a normal aerial tramway. This feature allows for single-cabin operation when demand warrants. The independent drive also allows for evacuations to occur by means of a bridge connected between the two adjacent cabins. Another advantage of the dual-haul system is its stability in high wind conditions owing to the horizontal distance between the two guide ropes comprising each track. Table 1 presents a summary of the service characteristics of dual-haul aerial tramways.

Monocable Detachable Gondolas

A gondola lift, or as it technically known as monocable detachable gondola, is a type of aerial lift in which the cabin is suspended from a moving loop of steel cable that is strung between two terminals, sometimes over intermediate supporting towers [see Fig. 4(a)]. The cable is driven by a bull-wheel in the terminal, which is connected to an engine or electric motor. Gondolas have small cabins, set at regularly spaced close intervals. The systems are continuously circulating with cabins passing around the terminal bull-wheels. As shown in Fig. 5, cabins detach from the hauling rope at terminals,

Fig. 3. Cable and cabin configuration of a dual-haul aerial tramway; sourced with permission from the Roosevelt Island Operating Corporation (RIOC 2011)

Table 1. Service Characteristics of ART and Conventional Public Transit Systems

Mode category	Mode	ROW category	Support	Guidance	Propulsion	TU control
	Conventional transit service characteristics					
Street transit	Bus	C	Road	Steered	ICE	Driver/visual
	Tram	C	Rail	Guided	Electric	Driver/signal
Semirapid transit	BRT	B	Road	Steered	ICE	Driver/visual
	LRT	B	Rail	Guided	Electric	Driver/signal
Rapid transit	Metro	A	Rail	Guided	Electric	Signal/ATO
	Regional	A	Rail	Guided	Electric/Diesel	Signal
	Aerial Ropeway Transit Service Characteristics					
Aerial ropeway transit	Aerial trams	A	Cable	Guided	Electric	Automated
	Dual-haul Aerial trams	A	Cable	Guided	Electric	Automated
	MDG	A	Cable	Guided	Electric	Automated
	BDG	A	Cable	Guided	Electric	Automated
	TDG	A	Cable	Guided	Electric	Automated

Mode category	Mode	Operating speed (km/h)	Cars per TU	Vehicle capacity	Investment cost/km (US$ million)[a]	Line capacity (ppdph)
	Conventional transit service characteristics					
Street transit	Bus	15–25	1	80–125	0.5–0.6	3,000–6,000
	Tram	12–20	1–3	100–300	5–10	10,000–20,000
Semirapid transit	BRT	20–40	1	80–180	5–40	6,000–24,000
	LRT	20–45	1–4	100–720	10–50	10,000–24,000
Rapid transit	Metro	25–80	4–10	720–2,500	40–100	40,000–70,000
	Regional	40–80	1–10 (14)	150–1,800	50–120	25,000–40,000
	Aerial ropeway transit service characteristics					
Aerial ropeway transit	Aerial trams	Up to 43.2	1	20–200	15–25[a]	500–2,800
	Dual-haul Aerial trams	Up to 27	1	Up to 100	20–25[a]	Up to 2,000
	MDG	Up to 21.6	1	4–15	5–10[a]	Up to 3,600
	BDG	Up to 21.6	1	4–15	10–20[a]	Up to 3,600
	TDG	Up to 30.6	1	Up to 35	15–25[a]	Up to 6,000

[a]Capital cost estimates are extrapolated from existing and proposed ART systems, and data gathered from other resources such as (The Doppelmayr/Garaventa Group 2011; Dale 2011).

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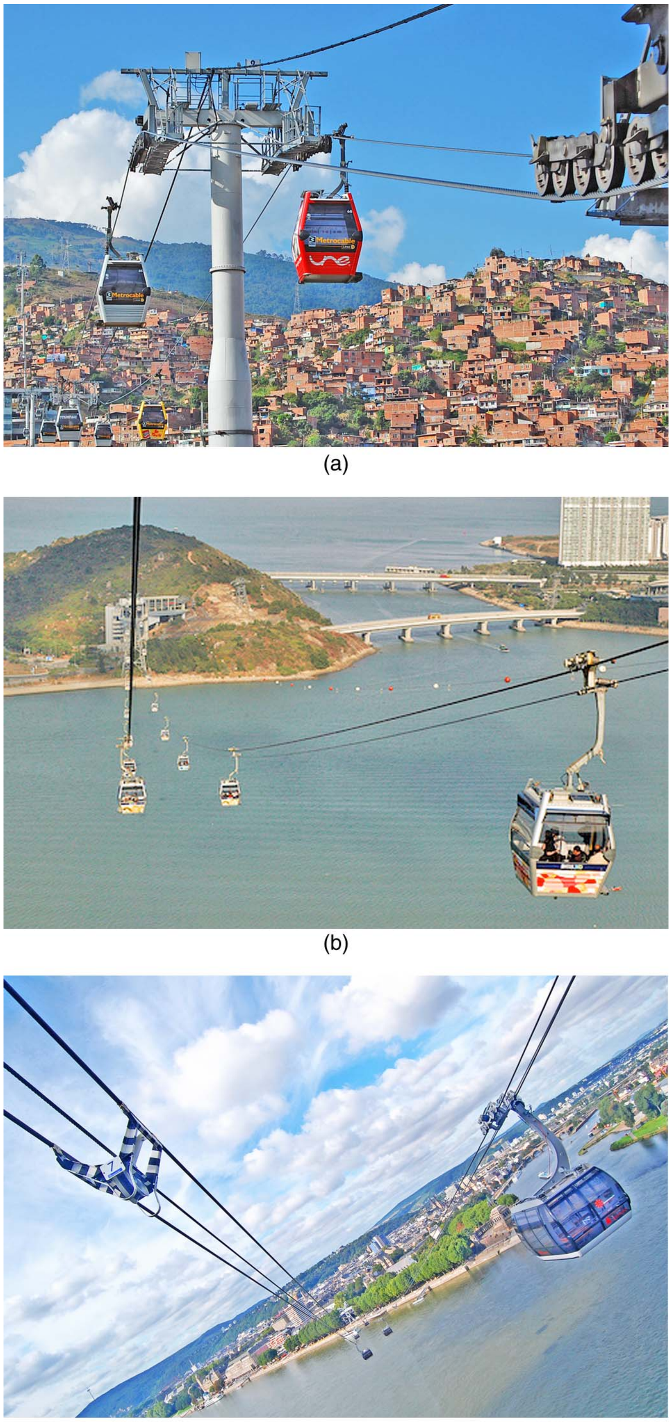

(a)

(b)

(c)

Fig. 4. Cable and cabin configuration of: (a) monocable detachable gondola; (b) bicable detachable gondola [source (Dale 2011); original image by James Wheare, licenced under a Creative Commons cc-by-licence]; and (c) tricable detachable gondola-bicable detachable gondola.

are decelerated, and carried through the unloading and reloading areas at a very slow speed, then accelerated for reattaching to the haulage rope for high speed travel on the line between terminals (Colorado School of Mines 2010). Cabin, capacity of MDG systems varies from 4 to 15 persons per cabin, and system capacity can be as much as 3,600 pphpd (The Doppelmayr/Garaventa Group 2011). Table 1 provides a summary of the service characteristics of MDG systems.

MDG technology was originally developed to be used in ski resorts, where it has seen wide success and popularity in the Alpine regions and tourist areas. It attracted attention from some transit agencies, especially in terrain-constrained areas, where conventional transit service is problematic, and sometimes impossible, to implement. Among the most successful implementations of gondolas as transit modes are two systems in South America, in the cities of Medellin (Colombia) and Caracas (Venezuela). These two systems will be discussed in more detail later in this paper.

Bicable Detachable Gondolas

BDG systems combine features of both gondola and reversible ropeway systems. They use reversible ropeway technology in their operation (i.e., separate ropes serve the two functions of static support ropes, or track cables, and a moving haul rope), which allows the system to have long spans, and therefore overcome difficult terrain conditions [see Fig. 4(b)]. The system is detachable (like gondolas), which allows the system to have a high capacity similar to the capacity of detachable circulating systems and similar operations at the terminals (see Fig. 5).

The difference between BDG and MDG systems is that unlike MDG systems, which are both propelled and suspended by the same cable, BDG systems have two separate cables for the two functions. Cabin and transport capacities of BDG systems are similar to those of MDG systems, with cabin capacities ranging from 4 to 15 persons per cabin and transport capacity of up to 3,600 pphpd (The Doppelmayr/Garaventa Group 2011). Table 1 provides a summary of the service characteristics of BDG systems. Successful implementations of BDG technology as a transit mode exist in Hong Kong and Singapore. The BDG system in Singapore was originally an MDG system but was rebuilt in 2010 and converted to a BDG system.

Tricable Detachable Gondolas

Similar to BDG systems, TDG systems (sometimes referred to as 3S technology) combine features of both gondola and reversible ropeway systems (i.e., separate ropes serve the two functions of static support ropes, or track cables, and a moving haul rope) and detachable gondolas. However, unlike BDG systems, TDG systems have two stationary cables that support the cabins instead of one as in BDG systems [see Fig. 4(c)]. Although TDG systems are more expensive than both MDG and BDG systems, this added cost is more than offset by their advantages, as these detachable circulating ropeways can carry more passengers with higher speeds. In fact, TDG systems operate with carrier capacities of up to 35 passengers for a maximum system capacity of 6,000 pphpd. Table 1 provides a summary of the service characteristics of aerial tramways. ART vendors think that TDG technology can theoretically achieve a capacity of 9,000 pphpd if needed, although systems with such capacity do not exist yet to prove this claim.

Other advantages of TDG systems include their outstanding wind stability, low power consumption, and the use of very long spans of up to 3,000 m (Leitner Technologies 2011). Successful implementation of TDG technology in the urban environment exists in the city of Koblenz (Germany), as discussed later in this paper. The system is primarily a tourist-based system, but its implementation within the city of Koblenz provides evidence of the ability to use TDG technologies in urban areas.

ART Service Performance

Table 1 provides a summary of the technological, service, and performance characteristics of the main ART technologies. The Table

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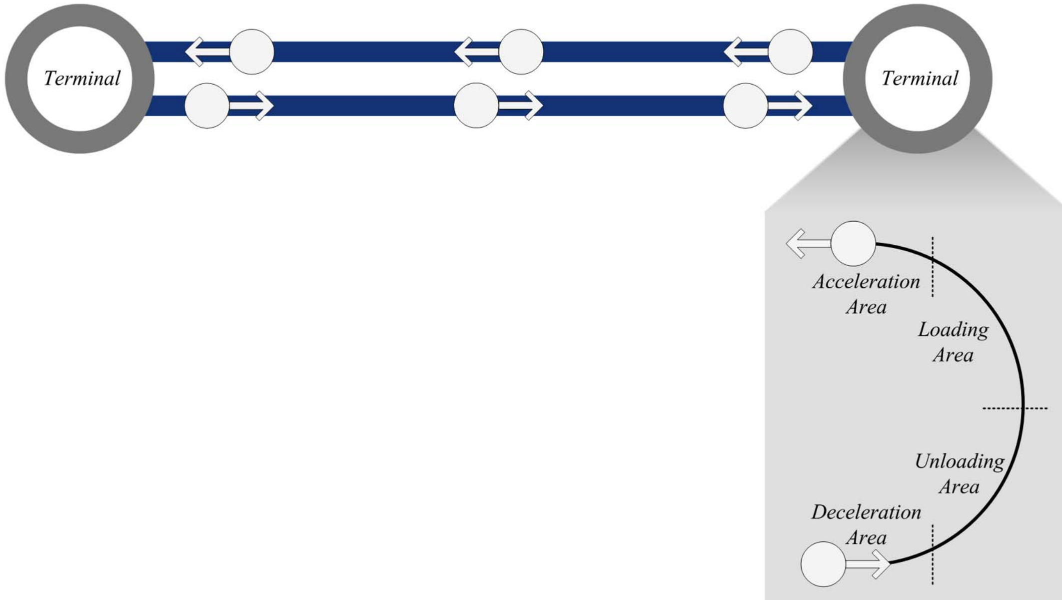

Fig. 5. Illustration of gondola systems operation (at and between the terminals)

includes quantitative service and performance measures such as capacity, speed, cost, and technological characteristics such as right of way, propulsion, and guidance. For comparison, the Table also includes the corresponding characteristics of conventional street transit modes.

As shown in the Table, the service and performance characteristics of individual technologies vary from one ART technology to another. In fact, some individual ART system performance characteristics can be deceiving, as they do not necessarily reflect the overall performance of the system. This feature is attributable to the fact that ART system performance relies heavily on the type of technology, its limitations, and type of operation. For example, although aerial trams have large cabin capacities that can reach 200 passengers/cabin and can achieve very high operating speeds of up to 43 km/h, they fail to achieve high transport capacities (maximum of 2,800 pphpd) because of limitations related to the number of cabins (maximum of two cabins on any system) and the synchronized operation of the two cabins (that restricts the independent operation of cabins). On the other hand, although MDG and BDG systems have small cabin capacities (maximum of 15 passengers/cabin) and lower operating speeds compared to aerial tramways (21.6 km/h), they achieve higher transport capacities of up to 3,600 pphpd because of their detachability and ability to operate with very high-frequency (12 s headway). ART vendors tried to overcome this dilemma by introducing the TDG system, which is the most advanced ART technology. TDG systems try to improve upon the capacities achieved by the other technologies (i.e., MDG, BDG, and aerial tramways) by having larger cabins and higher speeds than MDG and BDG technologies. At the present time, and given the necessary terminal size, TDG systems can achieve transport capacities of up to 6,000 pphpd by having higher cabin capacities (up to 35 passengers/cabin) and higher operating speeds (up to 30.6 km/h). A successful implementation of a TDG system exists in Koblenz, Germany, with a transport capacity of 3,700 pphpd.

In terms of comparing ART systems to conventional transit modes, ART systems in general have similar performance to that of street transit (buses and trams) and even low-performing BRT systems. Aerial trams, MDG, and BDG systems have capacities close to (or more than) the average capacities achieved by street transit such as buses and trams, as reported by Vuchic (2007). TDG systems, on the other hand, can achieve capacities relatively similar to those of low-performing semirapid transit services (6,000 pphpd).

In terms of investment cost, ART systems have low investment cost in terms of the cable technology and towers needed to operate an ART line. The most expensive ART technology (TDG) requires an investment of US$15–25 million to build one kilometer of the system, which is less than what is required for a similar-length semirapid transit line. However, the main cost component for an ART system is the cost of building the two ART terminals, which is the case in most ART applications. MDG systems, on the other hand, require a modest investment of US$5–10 million to build one kilometer of the system (including the two terminals). However, one of the two terminals also is used as a maintenance and storage facility for the system cabins, therefore eliminating the need for separate storage and maintenance facilities (and all the costs associated with these facilities) that characterize conventional transit modes.

Current Status of ART Implementation

The available information on aerial ropeway transit in the literature is very limited, even though ART systems now operate in several cities around the world. The construction (capital) cost numbers provided in the following case studies sometimes include costs that are not associated with the systems themselves but are specific for some systems, such as the cost of building huge terminals/stations and other services/amenities that add to the cost of the system, but cannot be separated from the total cost of the system. This might show capital costs that are not consistent with the capital cost estimates of the different technologies provided in Table 1.

Portland Aerial Tramway, US

In 1999, the Oregon Health & Science University (OHSU) identified South Waterfront as the best expansion site for its campus, assuming a rapid and reliable transit connection between the campus and the waterfront could be established. A study was commissioned and it concluded that an aerial tram was the best solution. Accordingly, construction of Portland Aerial Tramway began in

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Table 2. Service Characteristics of Some ART Applications around the World

ART system		Country	ART type	Opening year	Line length (m)	Line speed (km/h)	Cabin capacity	Peak headway (s)	Offered line capacity (ppdph)	Number of cabins in service
Portland Aerial Tramway		US	Aerial tram	2007	1,005	35.4	78	5 min	936	2
Roosevelt Island Tramway[a]		US	Aerial tram/Dual-Haul[a]	1976[a]	940	26	126	7.5 min	1,000	2
Medellin Metrocable	Line K	Columbia	MDG	2006	2,789	18	10	12	3,000	93
	Line J			2008	2,072	18	10	12	3,000	119
	Line L			2010	4,595	22	10	65	550	27
Caracas Metrocable		Venezuela	MDG	2010	1,800	18	10	12	3,000	70
Cable constantine		Algeria	MDG	2008	1,516	21.6	15	22.5	2,400	35
Complexo Do Alemao		Brazil	MDG	2011	3,400	21.6	10	12	3,000	152
Maokong gondola		Taiwan	MDG	2007	4,030	21.6	8	12	2,400	144
Ngong ping cable car		Hong Kong	BDG	2006	5,700	27	17	18	3,500	112
Singapore cable car		Singapore	BDG	1974	1,650	14.4	6	15	1,400	81
Koblenz cable car		Germany	TDG	2010	890	19.8	35	34	3,700	18

[a]The system was modernized in 2010 and was converted to a dual-haul aerial tram instead of an aerial tram.

August 2005, and the tram opened to the public on January 27, 2007, with a total cost of US$57 million.

The tram consists of two stations (terminals) and a single intermediate tower. Table 2 shows the service characteristics of the Portland Aerial Tramway. The tram is part of Portland's public transportation network that includes the Portland Streetcar, MAX Light Rail, and TriMet buses. The lower terminal is located in the South Waterfront neighborhood, adjacent to a stop on the Portland Streetcar line, which connects the South Waterfront neighborhood with downtown Portland. The tram's route goes over a state highway, two frontage/service roads, an interstate highway, and several neighborhoods. The alternative to riding the tram is via public roadways through a 1.9 mile (3.1 km) route with numerous traffic lights and intersections (see Fig. 6).

Earlier studies by transportation officials originally estimated the tram would carry over 1,500 people a day, a figure that was expected to rise to 5,500 by 2030. Those initial estimates proved to be modest, as the tram actually attracted one million riders in its first 10½ months of operation, an average of 3,700 riders per day (City of Portland 2007).

Roosevelt Island Tramway, US

The Roosevelt Island Tramway, which also uses aerial tramway technology, was built in 1976 as a temporary transportation solution for Roosevelt Island. However, the tram became too popular to discontinue and was converted into a permanent facility in 1989. Similar to the Portland system, the tram has two terminals and two cabins. Since 2005, the tram service has been integrated with the New York Metropolitan Transit Authority (MTA) MetroCard system, allowing tram riders to transfer to other MTA services such as the bus and subway systems without paying an extra fare.

On March 1, 2010, the Roosevelt Island Tramway was closed as part of a US$25 million project to upgrade and modernize the system. Among the improvements, the new tram cables and cars are allowed to operate independently of each other in a dual-haul system. The new dual-haul system allows for greater scheduling flexibility as the cabins run independently of each other, which will permit maintenance of one cabin while the other remains operational (RIOC 2011). Table 2 shows the service characteristics of the Roosevelt Island Tramway.

Medellin Metrocable, Colombia

Medellin is located in the Aburra Valley and therefore is surrounded by hills that are home to underdeveloped neighborhoods (or barrios) that cannot be reached by mass transit services such as the Medellin Metro system. In some cases, these areas cannot even be served by street transit services. One of these barrios is the Santo Domingo barrio, where the only form of public transit was a private bus company that infrequently served the area. At the time, the residents of Santo Domingo could expect to spend 2–2.5 h for a

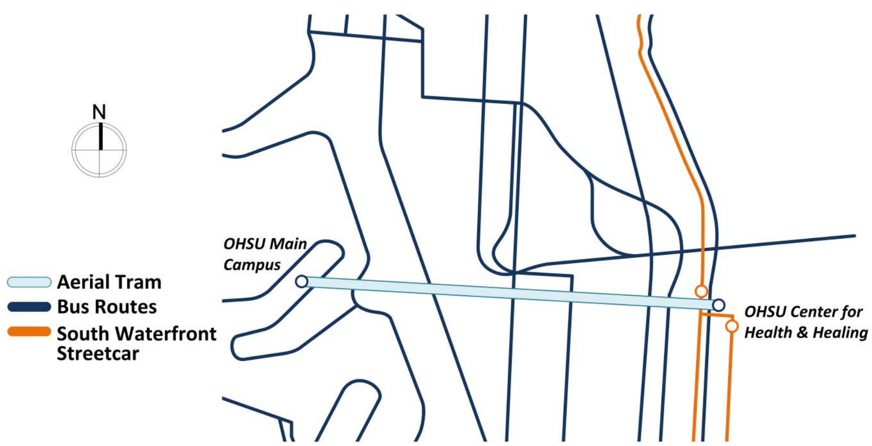

Fig. 6. Map of Portland transit system showing the Portland Aerial Tramway route

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one-way commute to work in the Medellin core (Dale 2011). These topographical constraints led to the conclusion that other (unconventional) types of transit modes should be explored to serve the residents of the neighborhood.

In the early 2000's, Metro Medellin considered connecting Santo Domingo to the metro system via an MDG gondola system. In 2006, Medellin opened its first gondola line (Line K) with the purpose of providing a complementary transportation service to that of the Medellin Metro (The Portal of Medellin 2011). The line cost US$26 million with a length of 2.8 km and 4 stations, and it was an enormous success. The commute time for residents of the neighborhood to the Medellin core was cut by almost a half (to 1–1.5 h). Since then, two other Metrocable lines have been built: Line J (cost US$50 million) and Line L (cost US$25 million). The system is managed by Metro Medellin. Table 2 shows Medellin Metrocable service characteristics. Fig. 7 shows the map of all the Metrocable lines and the Medellin Metro system.

Caracas Metrocable, Venezuela

The city of Caracas, Venezuela, is located in a narrow mountain valley and, similar to Medellin, has impoverished and poorly connected hillside barrios. One MDG line, called the Caracas Metrocable, was built to address pressing mobility needs. The line consists of five stations, including two terminals and three intermediary stations, and cost US$18 million. Currently, the line has full-fare integration with the local transit network, even though the line is built for the purpose of serving tourists to the area, not local commuters. Table 2 shows Caracas Metrocable service characteristics.

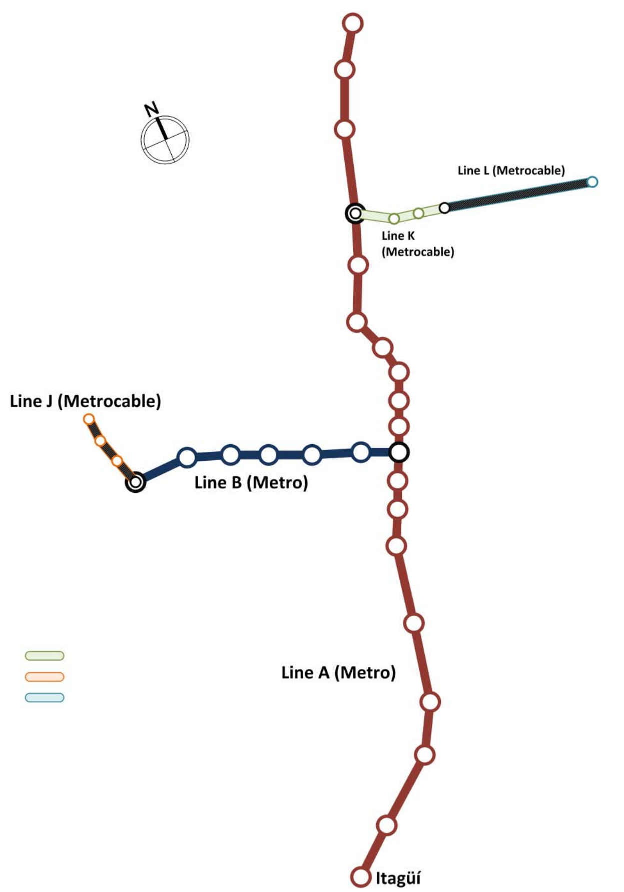

Fig. 7. The combined metro and metrocable map of the city of Medellin, Colombia

The success of the Caracas Metrocable has encouraged the local authorities to expand the current ART system to include other areas of the city. In addition to the current construction of a 4.8 km second ART line (Palo Verde), there are other studies underway to build more new lines in Caracas. Fig. 8 shows both the existing ART line (starting at Parque Central Metro station) and the new line under construction (gray line starting at Palo Verde Metro station) as a part of the Caracas Transit System.

Cable of Constantine, Algeria

The Cable of Constantine was opened in 2008 to connect the east and west banks of the city of Constantine, Algeria. The system runs daily from 6:00 am to 11:00 pm. The system has three stations, including two terminals and one intermediate station. The first section of the line is 425 m long and the second section is 1,091 m long, resulting in a total line length of 1,516 m. The system serves 100,000 residents of the northern sector of the city. Table 2 presents the system characteristics of the Cable of Constantine.

The system is popular among the residents, as it carries more than 10,000 passengers per day. In fact, the success of the first ART line in Constantine seems to have encouraged the local authorities to repeat the experience by offering the government to create no fewer than four new lines to relieve transportation problems in Constantine, which is known for its particularly rugged topography. One of the proposed lines will link the downtown Bekira, and the other will connect the city center to Daks, two locations known for their high density urban development and high traffic congestion. The first line will extend over a distance of 5 km and serve a population of over 120,000 residents. The second will cover a distance of 3 km and should greatly help relieve the region's traffic problems (The Constantine d'hier 2010).

Ngong Ping Cable Car 360, Hong Kong

Ngong Ping Cable Car is a bicable gondola system (referred to by its operators as a cable car) linking Tung Chung Town Center (where it connects with Hong Kong's Mass Transit Railway—MRT- Tung Chung station) with Ngong Ping on Lantau Island, with eight towers including the stations. The idea of the system came to life in 2000 when, following a feasibility study, the Hong Kong government issued an invitation for a 30-year franchise on a build-operate-transfer basis for the operation, management, and maintenance of a gondola system [Hong Kong Mass Transit Railway (MRT) 2011].

Construction of the Cable Car Project started at the beginning of 2004 and the system opened in November 2006. The system is owned by the MTR Corporation, the operator of Hong Kong's rail system, with a length of 5.7 km, which provides a 25 min aerial alternative to the current one-hour journey by road. Table 2 shows the service characteristics of Ngong Ping Cable Car.

Rhine Ropeway, Koblenz, Germany

The Rheinseilbahn is a TDG (3S) gondola system in the city of Koblenz. The system is used to shuttle locals and tourists from downtown Koblenz to the location of the annual Bundesgartenschau (BUGA) horticultural show located 1 km across the Rheine River. The BUGA is projected to open in the summer of 2011, but almost a year before the show's opening (i.e., 2010), the Rheinseilbahn is already in service.

The system operates at a line speed of 19.8 km/h, a speed lower than the 30.6 km/h that can be achieved by TDG systems. The system has a capacity of 3,700 ppdph with a cabin capacity of 35 persons per cabin. The system characteristics (speed and capacity) are much lower that what can be achived by TDG systems because of the tourist-based nature of the system, where tourists

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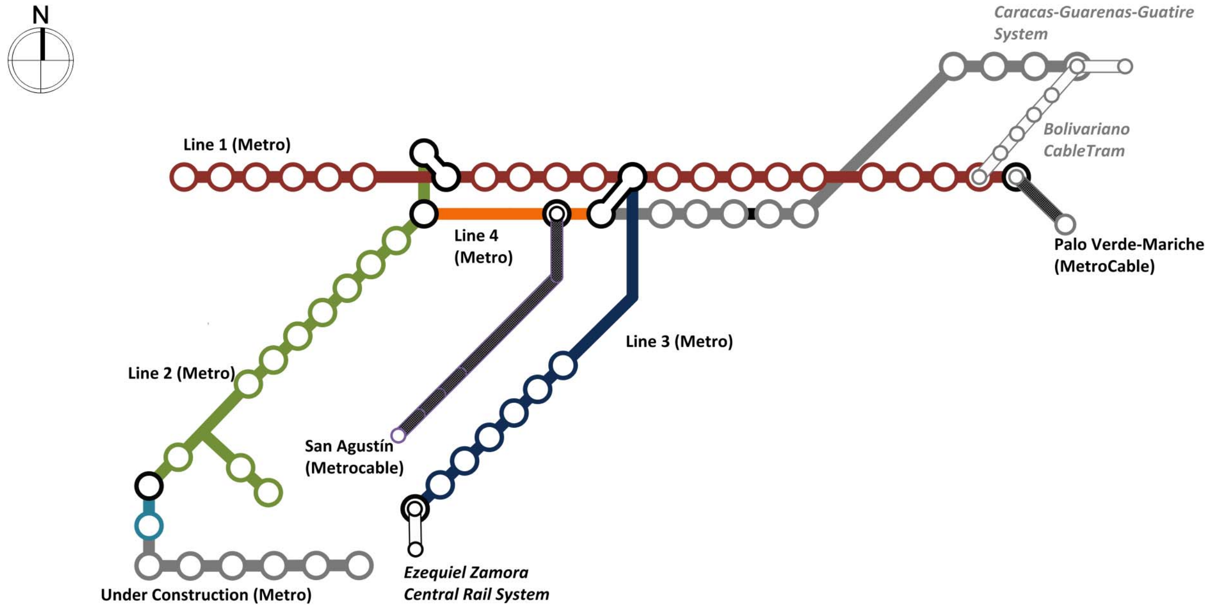

Fig. 8. The combined metro and metrocable map of the city of Caracas, Venezuela

prefer lower speeds to enjoy the scenery, and the low ridership expected on the system. Table 2 shows the service characteristics of the Rhine Ropeway.

Summary of Case Studies

As explained in the preceding discussion, each case has its own characteristics and system design depending on the technology used. However, it is clear that in all cases, ART was implemented because it was deemed a more effective transit mode than conventional transit modes in these terrain-constrained urban areas. The fact that most of these applications came to life during the past decade and have been very successful proves that ART is gaining more attention from transit agencies around the world, because ART is a viable and feasible transit mode especially in geographically constrained urban areas. In fact, some of the existing urban ART applications reviewed in this paper are planned for expansion (e.g., Caracas, Medellin, and Constantine systems) or revamping (e.g., Roosevelt Island Tramway). Moreover, the success of the existing ART applications in the urban environment has led to plans for the introduction of new ART applications all over the world. A strong example of this would be the Simon Fraser University Gondola in British Columbia, Canada, which has already conducted a preliminary feasibility study and—at the time of writing—was in the advanced stages of public consultation and business case analysis.

Assessment of ART Technology

Although it is not a panacea for all transportation problems and challenges, ART possesses unique advantages that can be of critical benefit to cities with natural barriers, some of which can only be solved by technologies like ART. However, ART still has several challenges that limit its effectiveness and hinder its path to be a fully recognized transit mode. The following can be thought of as the main advantages (benefits) of ART technologies compared to conventional transit modes:

1. It is a terrain-specialized transit mode that is suitable for negotiating natural barriers such as mountains, valleys, and bodies of water. ART could effectively help connect distant locations at similar or different elevations, which facilitates the development of mountains with residential and commercial land uses without the need for changing the mountainous topography of cities.
2. ART has a limited footprint (with the exception of terminal stations in some cases), as towers usually require minimal space and intermediate stations could be integrated into commercial buildings similar to the Ngong Ping Cable Car in Hong Kong and the Caracas Metrocable in Venezuela.
3. It is a relatively inexpensive technology and has fast implementation times.
4. Because of its aerial medium, ART does not need to follow the street topology, allowing for flexible network design that is not restricted to existing street alignments, and therefore reducing the total travel time of passengers by eliminating the need to travel on congested, long roads. For example, the travel time on the ART systems of Portland, Medellin, and Hong Kong is substantially lower than the comparable travel time by using the street network, which saves the passengers in these cities extra travel times.
5. Its operation is automated, which allows for customizing capacity to demand and for relying less on the driver workforce.
6. Owing to its automated operations, certain ART technologies such as the dual-haul aerial tramway can provide high-frequency service with high reliability rates, and this service can be available "24/7".
7. It is energy efficient because it relies partly on gravity and counterbalancing methods for propulsion.
8. Its emission rates are low, as the ART cabins have no onboard engines/motors. ART technologies usually have one electric engine in one of the terminals to support the operations of the system.
9. It provides a smooth, quite ride, offering riders a very pleasant travel experience.

Despite its many attractive benefits, ART is still a relatively new transit technology in the urban environment. Therefore, the technology is still in its early stages, which means that there is still large room for improvement, and this can be noticed in the advancements that the ART manufacturers have made in the past few years.

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However, some of the issues that ART manufacturers might need to consider include the following:

1. The integration of multiple ART lines into a network may be a challenge as the technology presently is not amenable to line branching, and the design of transfer stations where different ART lines can intersect is not straightforward and has not been done before. Almost all world implementations have been in the form of single lines.
2. Similarly, the integration of ART lines with conventional transit systems (subway, bus, LR and T) poses some design challenges, although recent attempts seem to find some solutions (e.g., Medellin, Colombia).
3. The maximum capacity achievable with this mode is unlikely to match that of semirapid transit (LRT and BRT). Increasing line capacity is dependent on a number of factors including cabin capacity, headway, wait time, and speed. In some contexts, ART line capacity also is dependent on the longest unsupported cable span achievable and the heaviest weight such cables can carry.
4. The design and locations of ART stations need careful consideration. Terminal stations seem to have larger footprints than terminals of other transit modes. This is primarily attributable to the fact that ART terminal stations house maintenance bays and car yards that add to the space requirement. In the absence of new innovative solutions to reduce the terminal station footprint, their locations have to be carefully selected in areas with low space constraints. For intermediate ART stations, it would be desirable to design those stations to allow leapfrogging of cabins. The integration of ART stations with urban land use and with other transit modes is of prime importance. Finally, access to ART stations should be carefully designed to minimize disutility associated with access.
5. Other issues of ART include privacy (flying above private properties) and safety in case of emergencies such as power failure. The latter issue has been addressed by modern gondola and ART installations through the use of a backup diesel engine.

Recognizing the above issues, manufacturers and designers of ART systems are continually making efforts to find new innovative solutions, and new implementations of ART systems are benefiting from such solutions.

Concluding Remarks

The introduction of new transit systems and modes into the family of urban transit systems has been an area of great interest to transit agencies, inventors, manufacturers, and governments. The need for transit modes for specific functions/conditions has led to the introduction of entirely new and unconventional modes such as ART. However, categorizing these new modes as transit modes has to be technically sound and defensible. Vuchic (2007) identifies the following two conditions that any new mode must fulfill to become a full member of the family of transit modes

- They must be technologically and operationally sound, and
- They must have a performance/cost package at least equal to that of an existing (conventional) mode.

The first condition is easily met by ART because the technology and operation of ART has proven its worth, as evidenced by the success of several ART applications around the world and the noticeable ART technological improvements over a short period of time. However, given that most of the existing ART applications are found in terrain-constrained areas, the real challenge/opportunity for ART will be the technology's ability to expand and prove its worth in nonmountainous and space-constrained urban areas such as downtown areas, thus enriching the set of technological options available to transit planners. In fact, some applications of the technology have been in flat terrain, such as the case of the biannual federal horticulture convention in Germany. In 2003, an MDG system was built for the convention that was held in Rostock, and at the end of the convention the system was disassembled and reassembled in Munich for the 2005 convention.

Currently, the second condition is yet to be fully addressed because the research into ART systems and technologies has been limited to ART manufacturers, with limited contributions from the scientific community. The need to address this condition presents researchers with an opportunity to start developing a performance/cost package that gives ART a boost to become a fully recognized transit mode.

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References

American National Standards Institute (ANSI). (2006). "Passenger ropeways-Aerial Tramways, Aerial Lifts, Surface Lifts, Tows and Conveyors-Safety Requirements." *ANSI B77.1*, New York.

City of Portland. (2007). "Portland aerial tram 2007 annual report." City of Portland, Portland, OR.

Colorado School of Mines. (2010). "About ropeways." ⟨http://library.mines.edu/About_Ropeways⟩ (Jan 25, 2011).

Dale, S. (2011). "The gondola project." ⟨http://www.gondolaproject.com⟩ (Jun 3, 2011).

Dwyer, C. (1975). *Aerial tramways, ski lifts, and tows: Description and terminology*, U.S. Department of Agriculture, Forest Service, USDA, Washington, DC.

Hong Kong Mass Transit Railway (MRT). (2011). "Ngong Ping 360." ⟨http://www.np360.com.hk⟩ (Jan 22, 2010).

Leitner Technologies. (2011). "Leitner products." ⟨http://www.leitner-lifts.com⟩ (Jan 13, 2011).

Neumann, E. (1992). "Cable propelled people movers in urban environments." *Transp. Res. Rec. 1349*, 125–132.

Neumann, E. (1999). "The past, present, and future of urban cable-propelled people movers." *J. Adv. Transp.*, 33(1), 51–82.

Roosevelt Island Operating Corporation. (2011). "Tramway service." ⟨http://www.rioc.com⟩ (Feb 20, 2011).

The Doppelmayr/Garaventa Group. (2011). "Doppelmayr/Garaventa products." ⟨http://www.doppelmayr.com⟩ (Jan 7, 2011).

The Portal of Medellin. (2011). "Medellin metrocable." ⟨http://www.medellininfo.com⟩ (Jan 9, 2011).

The Constantine d'hier. (2010). "Constantine cable car." ⟨http://www.constantine-hier-aujourdhui.fr/LaVille/travaux_telepheriques.htm⟩ (Dec 29, 2010).

Vuchic, V. (2007). *Urban transit systems and technology*, Wiley, Hoboken, NJ.