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Accelerating Moving Walkway: A review of the characteristics and potential application

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Abstract

Moving walkways have been used for people transport for more than a century. One of the latest innovations in this field is the Accelerating Moving Walkway (AMW), which provides higher transport speed. However, the application of moving walkways is still limited to short-distance travel up to 300 m. This paper summarizes and analyses the findings of a literature review on (accelerating) moving walkways, which aims to compare the characteristics of AMWs with other public transport systems, namely buses, light rails, Automated People Movers (APMs), and Personal Rapid Transits (PRTs). Based on the comparative evaluation, we conclude that AMWs can be competitive to the other transport modes. Hence, we propose the potential application of AMWs for the transport of people, i.e. pedestrians, over longer distances. Subsequently, issues related to the concept of long-distance AMWs are briefly introduced as topics for further research.

Keywords: Accelerating Moving Walkway; Public transport system; Comparative evaluation; Characteristic; Pedestrian; Long distance

1. Introduction

Moving walkways are a mode of people transport that fall into the category of continuous people movers, as they continuously provide transport capacity during operation. There is no waiting time for passengers who wish to use them. Moving walkways can be found in sporting arenas, shopping centres, exhibition auditoriums, and, most significantly, major transportation facilities such as airports and train/metro stations. Other people transport systems may also exist in these public areas. Nevertheless, moving walkways have found their own niche within the transport market (Young, 1995).

The conventional moving walkways have a constant transport speed of approximately half of the maximum pedestrian walking speed. Their speed-range of 0.5–0.83 m/s is considered low, sometimes resulting in a low level-of-service and passengers' impatience. Hence, many passengers choose to walk on the moving walkway, or simply bypass it and walk on the adjacent floor instead. Nowadays growth in the scale of public facilities

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results in the increase of walking distances. In airports and stations, for instance, people must walk farther in order to change from one plane or train to another, or to go from a terminal to a parking area. This requires improvements of the conventional moving walkways to cope with the demand for short travel time. Since a few years ago, some manufacturers have developed new designs of moving walkways. These systems maintain the same entry and exit speeds as those of the conventional moving walkways to accommodate safe boarding and alighting, but provide higher speed in the mid-section. Such moving walkways are known as Accelerating Moving Walkways (AMWs).

AMWs are proposed to be suitable to accommodate a heavy traffic of pedestrians for a relatively short distance up to 1 km (Gonzalez-Alemany and Cuello, 2003; Saeki, 1996; Shirakihara, 1997). Furthermore, Abe et al. (2001) stated that AMWs are expected to meet the increasing demand for a people mover arising from the so-called transportation gap ranging around 100 m to 2 km. Yet, moving walkways currently only serve distances up to 300 m. It is thus interesting to study the possibility to extend the travel distance up to the proposed figure above, or even longer.

This paper presents the findings of a literature study on (accelerating) moving walkways. The objective is to compare the characteristics of AMWs to those of various discontinuous transport systems, namely buses, light rails, Automated People Movers (APMs), and Personal Rapid Transits (PRTs). This paper provides a clear comparative evaluation, by which the competitiveness of AMWs can be judged.

The remainder of this paper is arranged as follows. Section 2 introduces the history and development of (accelerating) moving walkways. Section 3 discusses the research methods used in this study. Section 4 comprises the characteristics of the various transport modes, which are then compared and evaluated in Section 5. In Section 6, we propose the potential application of AMWs and discuss the issues that need to be studied further. Section 7 contains our conclusions.

2. An overview of moving walkways

In the NEN-EN 115:1998 (CEN, 1998), a moving walkway is known as a passenger conveyor. It is defined as a 'power-driven installation with endless moving walkway (e.g. pallets, belt) for the conveyance of passengers, either on the same or between different traffic levels'. Other names used for the moving walkway are, for instance, the moving walk, moving sidewalk, pedestrian conveyor, or travolator. Moving walkways that convey passengers between different levels are also called moving ramps. A close family of the moving ramps are the escalators, which consist of steps or stairs.

Numerous concepts of moving walkways for people transport have been proposed for over a century (Tough and O'Flaherty, 1971). The first working system was the moving walkway in the 1893 World's Colombian Fair in Chicago. This system had two platforms running at 1.3 and 2.6 m/s, the slow platform being used solely for access to the faster one. This installation was about 1310 m long and was laid in a great ellipse on the exposition site. The capacity of the system was 31,680 passengers/hour.

The most ambitious installation in history was the moving walkway at the Paris Exposition in 1900. It ran in a one-way elevated loop, covering a distance of 3360 m. The system had two platforms moving at 1 and 2 m/s. The fast platform had a maximum capacity of 57,600 passengers/hour, although during operation it only carried a daily average of 31,000 passengers/hour. A number of stations provided ticket offices and entry stairs to the system.

After the demonstration of the moving walkway in 1900, despite many developments in concepts and proposals, there were no further installations for the next 50 years. In the late 1950s, constant-speed moving walkways began to be installed and since then they have become more common.

Conventional moving walkways are based on either the pallet or the rubber-belt system. The pallet type moving walkways use the standard escalator components and techniques, seeing that this type closely resembles a flat escalator. The passenger-carrying rubber belt evolved from their industrial counterparts, putting more importance to the ride quality, i.e. comfort, smoothness, safety, and stability. Compared to the pallet system, the rubber-belt system requires less maintenance due to a reduction in the number of mechanical components. Passenger belts are fabric- or steelcord-reinforced rubber belts, the latter being mostly used. AMWs are also based on the pallet or rubber-belt systems. To achieve acceleration, AMWs implement various innovative designs such as in-line accelerating belts (Fujitec, 2002; Loder, 1998), sliding pallets (Abe et al., 2001;

Gonzalez-Alemany and Cuello, 2003; Ikizawa et al., 2001), parallelogram pallets (Saeki, 1996; Shirakihara, 1997), and accelerating rollers (Cote and Gempp, 1997).

3. Research methods

3.1. Scope of study

This paper confines the discussion of people transport systems to buses (consisting of buses in mixed traffic, bus lanes, busways, and guided buses), light rails, Automated People Movers (APMs), Personal Rapid Transits (PRTs), and Accelerating Moving Walkways (AMWs). The first four modes are categorized as discontinuous people movers, while the last mode is a continuous people mover. These transport systems were chosen based on the consideration that they have the potential to provide a low-cost, high-speed, high-capacity mass transit. A number of characteristics were selected as the criteria for evaluation. The advantages and disadvantages of each transport systems were reviewed.

The performance of a transport system is usually measured by its passenger capacity and speed (Fouracre et al., 2003). These technical characteristics are important criteria in this study. Transport planners and operators always look at passenger capacity in detail to determine whether the transport system can fulfil the demand. Speed is considered since it is one of the factors that determine the total travel time. The financial characteristics, comprising of capital cost and operational cost, also become key criteria for evaluation. Clearly, costs are always a major concern in any transport system development and operation.

Additional characteristics to be considered include the required corridor width for a two-way system, headway, stop spacing, safety, and environmental impacts (including energy use). The required corridor width is determined by the width of the vehicle and the track gauge. It is related to land-use, which eventually relates also to the capital cost. Furthermore, it is especially of interest if the transport system needs to be installed in a limited space or in an already built-up environment. Headway represents the frequency-of-service of the systems, which has influence on the passengers' waiting time. Stop spacing determines the accessibility of the transport system and the passengers' walking time. It also influences the average speed of the transport system. Safety is considered by both operators and users when choosing which transport mode to develop, operate, or use. It usually translates into the number of accidents which involve passengers and non-users. Meanwhile, the environmental impacts and energy use of transport are becoming a greater concern than ever before. People are now more aware of these issues due to the increase of pollution and congestion, and the scarcity of non-renewable energy resources.

3.2. Search strategy

To obtain the required literatures, we firstly conducted a computerized search through databases. Another computerized search was carried out directly in the websites of journals and scientific magazines that were not covered by the databases. We also used Google and Google Scholar to locate articles that were not published in journals or scientific magazines. These include reports and working papers from transport research units, consultants, and manufacturers. A physical search of the collection in the library of Delft University of Technology was also done. Additionally, we obtained data from statistics, reports, and databases provided by national transportation associations, for instance the American Public Transportation Association (APTA) and the National Transit Database (NTDB). Finally, we found more publications using the ancestry approach, tracking the research cited in the literatures that we had already obtained. While many publications were found for buses, light rails, APMs, and PRTs, publications that discussed moving walkways and Accelerating Moving Walkways were limited.

3.3. Selection of data

Travel time is determined by the travel distance and the transport speed. The transport speed used for the analysis in this paper is the average speed of the transport system. It is mainly influenced by the number of stops and the distance between stops, and not so much by the maximum speed. Because of the intermediate stops, discontinuous transport systems seldom operate at their maximum speed. Therefore, comparing the maximum speed would not give a proper representation of their actual operation. However, for the analysis of the AMWs, we use the speed at the high-speed section. This exception is taken considering that the high-speed section forms the longest part of the AMW system. Thus, passengers will be transported at this speed for most of the travel time.

The capacity discussed in this paper is the maximum system capacity, unless stated otherwise. The maximum system capacity is calculated based on the assumption that the system is fully loaded and running at the minimum headway. This is difficult to achieve in practice since a transport system is seldom able to operate in this manner. Many factors contribute to the lower practical capacity such as uneven passenger demand during the peak hour, day-to-day fluctuation in demand (e.g. workdays and weekends, or due to seasons, weather, and special events), varying standing densities of the passengers, dwell time at stops, junction capacities, junction priorities, grades and curves in the route, maintenance, unplanned events (e.g. propulsion failure, track failure, equipment failure, accidents), and, as in the case of light rails and APMs, uneven loading of cars within a train and signalling restrictions (CfIT, 2005; Parkinson and Fisher, 1996). The data of practical capacity are, however, not always available in the literatures. If so, CfIT (2005) suggests that 75% of the theoretical capacity should be assumed for analysis. For a moving walkway, a reasonable estimate of practical capacity would be about 50% of the theoretical capacity (Turner, 1998).

The capital cost analysis focuses on capital cost per kilometre, which is derived by dividing the total cost for completing the system by the number of kilometres. We used cost per kilometres as our measure because it presents comparable information on a common basis. The capital cost in this paper covers the cost of land and utilities, infrastructures, and vehicles. For the operational cost, we included the cost per passenger-km and the cost per vehicle-km. The cost per passenger-km is a suitable measure to represent the operational cost of an AMW system because the passenger-km of an AMW, which is the sum of the trip distances travelled by all passengers, can be easily calculated. The cost per vehicle-km of an AMW system is more difficult to determine since, firstly, AMWs do not consist of vehicles (although it is possible to assume an AMW as one) and, secondly, it is more complicated to determine the total distance that has been 'travelled' by the treadway of the AMW when it is in service. However, it has the advantage that it avoids uncertainty inherent in average load factors. Due to this reason, we decided to also look into the cost per vehicle-km. The operational cost generally covers staff-related costs, vehicle operational costs, and vehicle and infrastructure maintenance costs (Brand and Preston, 2003b).

The data on capital cost and operational cost were taken from different years. To maintain consistency in the comparative analysis, the capital and operational costs were then projected into 2005 US dollars using the appropriate Consumer Price Index (CPI). It must be noted, though, that there is a difficulty regarding cost comparison between existing systems and new systems. Existing systems such as buses, light rails, and APMs could benefit from some economies of scale and a learning effect. They have experienced a longer period of development and operation, which may lead to falling unit costs. PRTs and AMWs, being almost totally new systems, are more prototype-like. Hence, they will normally yield higher unit costs. On the other hand, there is a risk that some forms of operational costs might be underestimated due to the lack of a long period of operating experiences. Thus, there is a certain degree of uncertainty with regards to the true long term costs for PRT and AMW systems. However, this problem is almost impossible to overcome without a true real-world test period (Tegner, 2003).

Understanding that the characteristics of each type of transport system vary widely due to the diverse conditions and features of every installation, we used the data obtained from the reviewed literatures to determine the range of values of the systems' characteristics. The data from the literatures were noted and compiled, and then the range of values for each characteristic was approximated.

4. The characteristics of various high-speed transport systems

The characteristics of the observed transport systems are described in this section. The sources of these characteristics are clustered according to the type of transport systems and the criteria of evaluation, as presented in Table 1.

Table 1
Sources of information on the characteristics of each transport systems

	Bus	Light rail	APM	PRT	MW	AMW
Speed	Brand and Preston (2003a,b), Fouracre et al. (2003), GAO (2001), Gossop (2005), Kittelson & Associates et al. (2003), Lowson (2003), Parsons Brinckerhoff et al. (2001), Reconnect (1999), Young (1995)	Brand and Preston (2003a,b), Fouracre et al. (2003), GAO (2001), Kittelson & Associates et al. (2003), Kuhn (2001), Lowson (2003), Parsons Brinckerhoff et al. (2001)	Henderson (1992), Kuhn (2001), Leder (1991), Lowson (2003), Muller and Allee (2005), Reconnect (1999), Richardson (2005), Shen et al. (1996), Warren and Kunczynski (2000), Young (1995)	ATRA (2003), Brand and Preston (2003a,b), Henderson (1992), Lowson (2003, 2005), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001), Reconnect (1999), Tegner (1999), Warren and Kunczynski (2000)	CEN (1998), Donoghue (1981), Fruin (1992), Kittelson & Associates et al. (2003), Leder (1991), Tough and O'Flaherty (1971), Turner (1998), Young (1995)	Abe et al. (2001), Browning (1974), Cote and Gempp (1997), Donoghue (1981), Fujitec (2002), Gonzalez-Alemany and Cuello (2003), Henderson (1992), Ikizawa et al. (2001), Loder (1998), Reconnect (1999), Saeki (1996), Shirakihara (1997), Turner (1998)
Capacity	Brand and Preston (2003a,b), CfIT (2005), Fouracre et al. (2003), Leder (1991), Parsons Brinckerhoff et al. (2001), Young (1995)	Brand and Preston (2003a,b), CfIT (2005), Fouracre et al. (2003), Kuhn (2001), Parsons Brinckerhoff et al. (2001)	Henderson (1992), Kuhn (2001), Leder (1991), Muller and Allee (2005), Richardson (2005), Shen et al. (1996), Warren and Kunczynski (2000), Young (1995)	Anderson (2000), ATRA (2003), Brand and Preston (2003a,b), Henderson (1992), Lowson (2002, 2005), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001)	CEN (1998), Fruin (1992), Kittelson & Associates et al. (2003), Leder (1991), Turner (1998), Young (1995)	Abe et al. (2001), Browning (1974), Ikizawa et al. (2001), Loder (1998), Saeki (1996), Shirakihara (1997), Turner (1998)
Capital cost	APTA (2004a), Brand and Preston (2003a,b), CfIT (2005), GAO (2001), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001), Tegner (2003), Venter (1997)	APTA (2004b), Brand and Preston (2003a,b), CfIT (2005), GAO (2001), Parsons Brinckerhoff et al. (2001), Shen et al. (1996), Tegner (2003), Venter (1997)	Kuhn (2001), Muller and Allee (2005), Richardson (2005), Shen et al. (1996), Venter (1997), Warren and Kunczynski (2000)	ATRA (2003), Lowson (2002, 2005), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001), Tegner (2003), Yoder et al. (2000)	Jakes (2002), Muller and Allee (2005), Venter (1997)	Fujitec (2002), Loder (1998), Saeki (1996), Shirakihara (1997)
Operational cost	APTA (2004a), CfIT (2005), GAO (2001), Muller and Allee (2005), NTDB (2004), Parsons Brinckerhoff et al. (2001), Tegner (2003)	APTA (2004b), CfIT (2005), GAO (2001), NTDB (2004), Parsons Brinckerhoff et al. (2001), Tegner (2003)	Kuhn (2001), Muller and Allee (2005), NTDB (2004)	ATRA (2003), Anderson (1999, 2000), Tegner (1999, 2003), Lowson (2005), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001)	Muller and Allee (2005)	Saeki (1996)
Corridor width	Brand and Preston (2003b)	Brand and Preston (2003b)	Kuhn (2001)	ATRA (2003), Brand and Preston (2003b)	Turner (1998)	Turner (1998)

(*continued on next page*)

Table 1 (*continued*)

	Bus	Light rail	APM	PRT	MW	AMW
Headway	Fouracre et al. (2003), Parsons Brinckerhoff et al. (2001), Young (1995)	Fouracre et al. (2003), Parsons Brinckerhoff et al. (2001)	Henderson (1992), Leder (1991), Muller and Allee (2005), Shen et al. (1996), Warren and Kunczynski (2000), Young (1995)	Anderson (2000), ATRA (2003), Henderson (1992), Lowson (2002, 2005), Muller and Allee (2005), Parsons Brinckerhoff et al. (2001)	–	–
Stop spacing	Fouracre et al. (2003), Lowson (2003)	Fouracre et al. (2003), Lowson (2003)	Kuhn (2001), Lowson (2003), Warren and Kunczynski (2000)	Lowson (2002, 2003)	–	–
Safety	Brand and Preston (2003a,b), Gossop (2005), Parsons Brinckerhoff et al. (2001)	Brand and Preston (2003a,b), Parsons Brinckerhoff et al. (2001)	Kuhn (2001), Shen et al. (1996)	Anderson (1999, 2000), ATRA (2003), Parsons Brinckerhoff et al. (2001)	CEN (1998), Donoghue (1981),	Donoghue (1981), Ikizawa et al. (2001), Loder (1998), Saeki (1996), Shirakihara (1997)
Environment al impact (including energy use)	Brand and Preston (2003a,b), Gossop (2005), NTDB (2004), Parsons Brinckerhoff et al. (2001), Reconnect (1999)	Brand and Preston (2003a,b), NTDB (2004), Parsons Brinckerhoff et al. (2001)	Kuhn (2001), NTDB (2004), Reconnect (1999)	Anderson (2000), ATRA (2003), Lowson (2002, 2005), Parsons Brinckerhoff et al. (2001), Reconnect (1999), Tegner (1999)	ThyssenKrupp (2004)	Reconnect (1999), ThyssenKrupp (2004)

4.1. Bus

Buses are rubber-tired vehicles with drivers, which operate mostly on roads, either in mixed traffic, bus lanes, or busways. Buses in mixed traffic contribute to congestion, which in turn may cause delays for the buses themselves. Bus lanes and busways give the buses right-of-way. However, bus lanes are usually built as part of the public road space and are only marked by road signs or traffic signs. They do not have built-in protection that separates them from other traffic, so they are susceptible to illegal use such as parking. Busways, on the other hand, do not allow other vehicle to share the space. Another bus-based transport system is the guided bus, which is a form of dual-mode system designed to enable a conventional bus to operate on both ordinary roads and special guideways. Guided buses operate in their own corridor, thus not affected by traffic congestion or illegal parking (Brand and Preston, 2003b). Since other traffic cannot interfere, busways and guided buses lead to a higher level-of-service.

The system capacity of a bus lane is around 4500–7500 passengers per hour per direction (p/h/d). Busways can have a system capacity reaching up to 25,000 p/h/d. This high system capacity is, however, only possible with multiple vehicle stopping bays and more than one busway lane per direction (Brand and Preston, 2003b). The system capacity of guided buses also ranges between 4500 and 25,000 p/h/d. In mixed traffic, the system capacity is around 1000–4500 p/h/d. At airports, buses usually operate on terminal frontage and circulation roadways on a non-exclusive basis. Depending on the headway, the system capacity of airport buses can reach 1500 p/h/d (Leder, 1991).

Bus stops in mixed traffic and bus lanes are usually built with spacing between 200 and 600 m. Lowson (2003) used a model to calculate the optimum stop spacing for buses, which yield to a value of 500 m. This resembles the average stop spacing used by buses in city operations, although a typically closer stop separation will occur in the city centre. The short separations between stops are useful to minimize walking times of passengers, but they lead to a significant reduction in the average speed (Lowson, 2003; Warren and Kunczynski, 2000). The average bus speed in mixed traffic is around 15–20 km/h, while in bus lanes and busways it is around 15–25 km/h and 22–50 km/h, respectively (Brand and Preston, 2003a,b). For guided buses, the average speed is between 30 and 50 km/h. The higher speed for busways and guided buses is achieved because of the lower stop densities. For busways and guided buses, the stop spacing is usually around 500–1000 m. However, the average speed of all bus-based systems is far below the maximum speed, which, depending on the local regulation, can reach up to 100 km/h. Buses can have a minimum headway of 60 s, although 2–30 min is more practical.

The capital cost for a bus-based system intended for mixed traffic is low, mainly because it makes use of existing roads. The capital cost for such a system can be between $0.14 and 6.75 million/km (GAO, 2001). On the other hand, the construction of dedicated bus lanes or exclusive right-of-ways involves high capital costs and displaces valuable roadway space. Interpolation of data from existing sites gives an estimate that the capital cost of a bus lane and busway system is around $1.14–26.41 million/km and $4.38–38.65 million/km, respectively (CfIT, 2005; GAO, 2001). For the guided bus, the capital cost ranges between $2 and 7 million/km, which is somewhat lower than for bus lanes and busways. This is due to the limited number of guided bus systems in the world, constituting only 25 km of guided bus tracks. Hence, the data of capital cost for guided buses are only based on these existing systems. The operational cost for buses is between $0.09–0.95/passenger-km and $1.22–14.75/vehicle-km (APTA, 2004a; GAO, 2001). Distinctive data of the operational costs of each type of bus-based system was not available. One of the factors that contribute to the operational cost for buses is the high requirements for personnel, consisting of drivers, administrative staffs, and maintenance workers. Each vehicle may require five or more drivers plus other support staff to provide the necessary full day service every day of the year (Lowson, 2005; Warren and Kunczynski, 2000).

The energy use of buses varies between 0.3 and 1.56 MJ/passenger-km (Brand and Preston, 2003b; Lowson, 2002). Until today, most buses are still operated by diesel engines, which cause relatively high pollution. With ultra low sulphur diesel (ULSD) and exhaust treatment technology, the emissions from diesel engines can be reduced. Bus-based systems produce a noise level around 70–84 dB(A) (Brand and Preston, 2003a; Parsons Brinckerhoff et al., 2001). For guided buses, noise levels are perceptibly lower on the guideway than on normal roads, at around 56–59 dB(A) (Gossop, 2005).

Buses are considered quite flexible because they can fit in any demanding space constraints, can respond to differences in service needs, and can be easily reconfigured. The required corridor width for a two-way bus system in mixed traffic is around 6–8.5 m, which refers to a minimum road width. For buses in bus lanes, busways, and guided buses, the corridor width is 6–8 m, 8–13 m, and 5.8–6.2 m, respectively (Brand and Preston, 2003b). Buses are considered relatively safe. However, the passenger safety of conventional bus systems is said to be lower when compared to bus lanes and segregated bus systems on their own right-of-way. Unfortunately, buses generally have poor public image. They are often considered uncomfortable, especially when they operate at or near their nominal capacity. Sometimes passengers have to stand in a crowded space during the trip. In airport applications, it is tedious to enter and exit a bus while carrying luggage. Buses are also not very suitable for accommodating indeterminate passenger arrivals. In such situations, the frequency of the bus must be high in order to provide an adequate level-of-service, resulting in buses running with very small loads. Another drawback is the long waiting time, which sometimes causes the total trip time to be not much quicker than walking.

4.2. Light rail

A light rail is a rail-based system that can operate in mixed traffic on tracks on ordinary roads, or on segregated tracks with either a longitudinal right-of-way or a full right-of-way. The application of light rails in mixed traffic may face interference from other road users, which can deteriorate the rapidity and reliability of the service. Thus, light rail operates best when fully segregated from other traffic, but this will significantly increase the cost.

The distance between stops in a light rail network can be between 250 and 1000 m, with an average of about 500 m. A stop spacing of 250 m is considered exceptional. Based on his model, Lowson (2003) suggested that the optimum spacing should be 750 m. A light rail has a maximum speed of 80–90 km/h. This maximum speed is seldom achieved due to the short stop spacing. The average speed is around 15–25 km/h for light rails operating in mixed traffic and around 21–45 km/h in segregated tracks (Brand and Preston, 2003b). The design capacity varies according to the system's arrangements (i.e. the number of trains, the number of cars per train, and the headway), ranging from 1000 to 30,000 p/h/d (Brand and Preston, 2003a; Fouracre et al., 2003). Light rails have a minimum headway of 60 s, although a 2–30-min headway is more typical in practice.

The cost of a light rail system can differ a lot due to the great variety of features that the system may offer. In general, the capital cost can be between $8.5 and 83.5 million/km (GAO, 2001). High capital costs arise in systems that include tunnel sections. The required corridor width for a two-way light rail system is 5–6.5 m. The construction of a light rail system is difficult to modify once it has been fixed in place. Therefore, careful planning, including for future expansion, is important. The operational cost of light rails is around $0.15–5.42/passenger-km and $2.95–22.44/vehicle-km (APTA, 2004b; GAO, 2001).

The energy use of light rails is estimated to be between 0.7 and 2.5 MJ/passenger-km (Brand and Preston, 2003b; Lowson, 2002). Light rails are powered by electric propulsion and, therefore, are environmentally friendly. Noise levels for light rail are relatively low at about 60–74 dB(A) (Brand and Preston, 2003b; Parsons Brinckerhoff et al., 2001). However, ground vibration due to the operation of light rails may affect the surroundings.

Light rails are considered a reliable and safe mode of transport that can handle high capacity of people. Its capacity can be increased with a lower increase in operational cost because each light rail train, no matter what number of cars, can be operated by just one person. Light rails give maximum advantage for high volumes of passengers. For smaller number of passengers, their advantage relative to buses is minimal. The odds of travelling in a crowded vehicle while standing and the difficulties of entering and exiting with luggage, just as in buses, may also happen when using light rails. Nevertheless, they are considered more comfortable than buses.

4.3. Automated People Mover

An Automated People Mover (APM) is a mode of public transport, which consists of discrete vehicles that have automatic (driverless) control, use specialized guideways, and operate on exclusive right-of-way. APMs are usually in the form of trains consisting of one or more cars. Each train operates on a single route that can have intermediate stations. The system capacity ranges from 1000 to 30,000 p/h/d.

The maximum speed of APMs can reach up to 90 km/h. However, if an APM has to stop at a number of intermediate stations that are separated only in short distance, or if the track incorporates many curves, the maximum speed is hardly achieved. The distance between stops can be between 500 and 1500 m, with an optimum spacing of around 750 m (Lowson, 2003; Warren and Kunczynski, 2000). This leads to an average speed of around 15–50 km/h. APMs typically use headways between 60 and 180 s.

When constructing an APM system, attention should be given to their integration with other elements, especially if they are to be installed in a built-up environment. The required corridor width for a two-way APM system is around 4.4–6.5 m (Kuhn, 2001). Most APMs are located on elevated structures or underground, so vertical transport facilities such as elevator, escalator, or moving ramps are required. Furthermore, they need stations, equipment rooms, a central control area, and maintenance facilities. Hence, the capital costs for APMs are high. They also require high level of maintenance. The capital cost of existing APM systems vary between $12.5 and 147.9 million/km (Jakes, 2002; Richardson, 2005; Shen et al., 1996). However, over the years, the cost for a new APM system steadily increased, both in terms of capital cost and continuing operational and maintenance costs (Jakes, 2002; Venter, 1997; Warren and Kunczynski, 2000). As a result, many new projects cannot afford to include APMs in their transportation plans. The operational cost of an APM can be around $0.15–11.77/passenger-km (NTDB, 2004; Tegner, 2003). In terms of cost per vehicle-km, it is around $10.1–45.6/vehicle-km (NTDB, 2004).

Due to its electric propulsion, APM operations can be regarded as locally pollution-free. Noise emission of APMs is perceived to be around 54–72 dB(A) (Kuhn, 2001; Reconnect, 1999). However, ground vibrations can occur due to APM operations. Data on APM energy use are very limited. Based on three systems, it is found that the energy consumption of APMs range between 1.62 and 12.78 MJ/passenger-km (NTDB, 2004). The higher value of energy use is exceptional, which happened due to relatively low passenger-km in the corresponding corridor. The average energy use was found to be around 2.66 MJ/passenger-km.

APMs in general have high passenger acceptance due to their high safety and service record. APM systems are also quite flexible to modify. Many APM projects are designed for future expansion. If no guideway is added in the expansion, the system capacity can be changed by modifying the number of trains, the number of cars per train, or the headway.

4.4. Personal Rapid Transit

A Personal Rapid Transit (PRT) is another type of automatic (driverless) control vehicle, aimed for public transport. It takes the form of a small vehicle, available for the use of an individual or a small group of people travelling together by choice. PRTs typically have four seats, but other systems with 6–10 seats also exist. They run on small, separated guideways that are usually elevated, although at grade and underground guideways are possible. The required corridor width for a two-way PRT track is 4–5 m. It is claimed, however, that PRTs likely require only one lane (Brand and Preston, 2003b). The guideways form a fully connected PRT network, with offline stations located along the guideway at a spacing of 250–500 m (Lowson, 2003). Unlike APMs, PRTs serve origin-to-destination transport without intermediate stopping. The service is available on demand rather than on fixed schedules.

PRTs can have a maximum speed of 30–50 km/h, but the average speed of the vehicles is usually around 20–25 km/h (Brand and Preston, 2003b; Lowson, 2002, 2003). The headway can be between 0.5 and 30 s, although a 2-s headway is claimed to be practical (Andréasson, 2001; Henderson, 1992; Lowson, 2002; Muller and Allee, 2005). With the 2-s headway, the capacity of a PRT system can reach 1800 vehicles per hour per direction. If each PRT vehicle can carry up to four passengers, the maximum system capacity will be 7200 p/h/d. In practice, the daily average occupancy factor of automobiles is about 1.2–1.6 (Anderson, 2000; Henderson, 1992; Lowson, 2002). If a PRT is assumed to be comparable to a car, then most trips in a PRT vehicle will be taken by one person. On the other hand, two or more passengers at a station in peak periods are likely to discuss their destinations and share rides rather than wait for the next vehicle, making it reasonable to apply an occupancy factor of 2.0 (Muller and Allee, 2005). Hence, a practical system capacity of 1800–3600 p/h/d can be achieved.

The capital cost for a PRT system is estimated to be around \$4.21–15.99 million/km (ATRA, 2003; Tegner, 2003). In fact, a higher capital cost of \$25.99 million/km was estimated for the Raytheon system, but this figure is considered exceptional (Yoder et al., 2000). The operational cost of a PRT ranges from \$0.07 to 0.28/passenger-km (Tegner, 1999, 2003). In terms of cost per vehicle-km, Anderson (1999) estimated that the operational cost is around \$0.11/vehicle-km. Due to lack of data, a range of value for the operational cost per vehicle-km cannot be given.

PRTs are electrically powered, so there is no emission of pollutant during operation. The average energy use is 0.55 MJ/passenger-km (Lowson, 2002). Again, lack of data prevents us from estimating the range of value for energy use. Studies show that the noise emission level of PRTs is around 35–65 dB(A) (ATRA, 2003; Lowson, 2002). The safety of PRTs is considered high due to the segregated tracks. Furthermore, it benefits from personal security since it is likely that all trips are only undertaken with companions chosen by the traveller. PRT are initially intended for city and urban transportation. Recently, there are also plans to use them for transport within airports, for example to serve passengers from parking areas to the main terminal.

4.5. Accelerating Moving Walkway

An Accelerating Moving Walkway (AMW) is a passenger-conveying device that continuously moves passengers by accelerating them from a low speed at the entrance to a higher speed at the mid-section of the walkway, and then decelerating them to a low speed again at the exit. In such a system, there is no waiting time, unless the capacity of the system is exceeded; then passengers may need to briefly pause before stepping onto the treadway. All installed moving walkways are now still providing transport along straight lines. However, there have been developments of spiral escalators and curved moving walkways, so the development of AMW routes with curves is possible.

The high-speed section of AMWs has speed ranging between 1.3 and 3.3 m/s. The entry and exit speeds are the same as those of the conventional moving walkways, which are between 0.5 and 0.83 m/s. A single AMW span currently can have lengths up to 300 m. The treadway width of a moving walkway is usually 1 m, but a width of 0.6 and 0.8 m are also available. AMWs with a 1-m treadway width or less are not very suitable for mixed standing and walking traffic, particularly in airports. Luggage-carrying passengers often find difficulties to walk pass other luggage-carrying passengers standing still on the conveyor. Recently, a clear trend towards wider walkways is apparent through the development of treadways with widths of 1.2, 1.4, and 1.6 m. This will allow passengers to pass each other freely, even with a trolley.

Based on the NEN-EN 115:1998 (CEN, 1998), the theoretical capacity of a moving walkway is determined using the equation:

$$C_t = v \times 3600 \times k/0.4$$

where C_t is the theoretical capacity (p/h/d), v is the rated speed (m/s), and k is a factor related to the nominal width of the treadway, z. The rated speed v is limited by the maximum speed that allows safe entry of passengers onto the moving walkway, which is 0.91 m/s (Donoghue, 1981; Fruin, 1992). The factor k represents the number of people who can enter the walkway in abreast. It is assumed that on every 0.4 m visible length of a pallet or belt in a walking walkway, there are 1 person carried at a nominal treadway width of 0.6 m, 1.5 persons carried at a nominal treadway width of 0.8 m, and 2 persons carried at a nominal treadway width of 1 m. Therefore, $k = 1$ for $z = 0.6$ m, $k = 1.5$ for $z = 0.8$ m, and $k = 2$ for $z = 1$ m. The figure 0.4 m for the visible length of the pallet or belt in a walking walkway is taken based on the plan view of the human body depth, which is 330 mm (Fruin, 1992). The factor k for treadways of 1.2, 1.4, and 1.6 m width has not yet been determined by the NEN-EN 115:1998. By extrapolation, it may be expected that $k = 2.5$ for $z = 1.2$ m, $k = 3$ for $z = 1.4$ m, and $k = 3.5$ for $z = 1.6$ m.

Manufacturers of moving walkways usually determine theoretical capacities based on the area of treadway per unit time, which is obtained by multiplying the speed of the moving walkway with its width. This, in essence, agrees with the equation above. Turner (1998) allocates 0.23 m^2 area of treadway per person for the calculation of the theoretical capacity. Taking the common treadway width of 1 m and an entry speed between 0.5 and 0.83 m/s, a moving walkway can have a theoretical capacity between 9000 and 15,000 p/h/d. Wider moving walkways will provide higher system capacity, theoretically reaching up to 26,000 p/h/d.

The theoretical capacities of AMWs are generally much higher than the practical capacities. Practical capacity occurs due to slight pauses in the boarding of a moving walkway and greater space allocations for those who walk on the treadway rather than stand (Leder, 1991). Al-Sharif (1996) also stated that the human buffer zone, which is the area that surrounds a person, leads people to avoid touching each other, thus reducing the capacity of the moving walkway. Furthermore, in practice, the entry of passengers onto the moving walkway is not always continuous. The practical capacity of a moving walkway is thus primarily dependent on its width at its entrance, as this determines the number of people who can enter the walkway in abreast. The entry speed of the moving walkway only affects the capacity to the extent that it determines the spacing of the passengers as they step onto the walkway (Kittelson & Associates et al., 2003). Consequently, systems that accelerate passengers to higher speeds do not increase the capacity compared to a conventional moving walkway of the same width because the capacities of both systems at the entrance are the same, being controlled by the entry rate (Loder, 1998). Furthermore, walking on a moving walkway increases the passengers' travel speed and reduces travel time, but does not affect capacity because it does not affect the entry rate into the moving walkway.

For estimation of the practical capacity, Turner (1998) allocates 0.46 m^2 area of treadway per person. This implies that the practical capacity is estimated to be about 50% of the theoretical capacity. The practical capacity of AMWs with 1 m treadway width is thus expected to be around 4500–7500 p/h/d. For wider treadways, a practical capacity up to 13,000 p/h/d may be reached.

Saeki (1996) and Shirakihara (1997) stated that the cost to construct an AMW with parallelogram pallets is about 1.3–1.5 times that of the conventional moving walkway. For an AMW with in-line accelerating belts, Loder (1998) estimated that the cost will range in per unit length price up to a ceiling of 20% more than a single speed system for short lengths and will generally be less expensive for longer lengths. It is approximated that the capital cost for building a conventional moving walkway, including the surrounding structure, will be around $29–36.3 million/km (Venter, 1997). Therefore, it may be expected that an AMW system will approximately cost $37.7–54.45 million/km for the parallelogram type and $34.8–43.56 million/km for the in-line type. No figure was found on the operational cost of an AMW. However, for a conventional moving walkway, it is said to be very similar to a PRT (Muller and Allee, 2005). If a factor of 1.2–1.5 is also applied, then the operational cost for the AMW will be around $0.08–0.42/passenger-km and $0.13–0.17/vehicle-km.

The environmental impacts of AMWs are comparatively low. Since it is powered electrically, there is no local pollution. The noise level of AMWs is also claimed to be low, particularly in systems that apply rubber-belt treadway. However, quantitative data were hardly found. The only data available stated that the noise level of moving walkways is approximately 54 dB(A) (ThyssenKrupp, 2004). Loder (1998) stated that an AMW will use about 3 kWh of power to transport 1000 passengers as far as 100 m. This equals to about 0.11 MJ/passenger-km.

AMWs are not very suitable for wheelchair users (with the exception of wheelchair users with attendants) or other mobility-impaired passengers. Furthermore, they are inflexible to modify and they can become a barrier for cross-concourse movements. Nevertheless, the system is believed to be safe and simple, and may be easily integrated into any environment. It needs only a small installation space. A two-way AMW system with a treadway width of 0.6–1 m will consume around 2.5–3.3 m of the corridor width (Turner, 1998). For a treadway width of 1.6 m, the required width is 4.7 m. Maintenance of AMWs is simple, although careful planning is required to avoid disturbance of passenger transport.

5. Comparative evaluation

The characteristics of the AMWs were evaluated and compared to those of buses, light rails, APMs, and PRTs. A summary of the characteristics are given in Table 2.

As discontinuous transport systems, buses, light rails, and APMs need to make intermediate stops. The stop spacing influences the speed of these systems and the walking time of their passengers. Large stop spacing increases the walking time, while small stop spacing reduces the overall travel speeds due to the time lost in accelerating and decelerating. An optimal distance between stops offsets between walking time and average speed. Nevertheless, the average speed of buses, light rails, and APMs will still be much lower compared to their maximum speeds. Furthermore, intermediate stops may lead to an increase in waiting time and headway (Warren and Kunczynski, 2000). The transport system thus becomes prone to delays.

Table 2
Characteristics of the transport systems

Systems	Average speed (km/h)	Maximum system capacity (p/h/d)	Capital cost ($ M/km)	Operational cost ($/passenger-km)	Operational cost ($/vehicle-km)	Corridor width (two-way) (m)	Headway (s)	Stop spacing (m)	Noise level (dB(A))	Energy use (MJ/ passenger-km)
Bus										
Mixed traffic	15–20	1000–4500	0.14–6.75	0.09–0.95	1.22–14.75	6–8.5[a]	60–1800	200–600	70–84	0.3–1.56
Bus lane	15–25	4500–7500	1.14–26.41	0.09–0.95	1.22–14.75	6–8	60–1800	200–600	70–84	0.3–1.56
Busways	22–50	4500–25,000	4.38–38.65	0.09–0.95	1.22–14.75	8–13	60–1800	500–1000	70–84	0.3–1.56
Guided bus	30–50	4500–25,000	2–7	0.09–0.95	1.22–14.75	5.8–6.2	60–1800	500–1000	56–59[b]	0.3–1.56
Light rail	15–45	1000–30,000	8.5–83.5	0.15–5.42	2.95–22.44	5–6.5	60–1800	250–1000	60–74	0.7–2.5
APM	15–50	1000–30,000	12.5–147.9	0.15–11.77	10.1–45.6	4.4–6.5	60–180	500–1500	54–72	1.62–12.78
PRT	20–25	1800–7200	4.21–15.99	0.07–0.28	0.11	4–5	0.5–30	250–500	35–65	0.55
AMW	4.75–12	9000–15,000[c] (up to 26,000[d])	34.8–54.45	0.08–0.42	0.13–0.17	2.5–4.7	0	0	54	0.11

Note: Costs are given as 2005 US dollars.
[a] Refers to a minimum road width.
[b] On the guideway.
[c] For a treadway width of 1 m.
[d] For a treadway width of 1.6 m and a speed of 0.83 m/s.

The maximum speed of AMWs is lower than that of the other transport systems. However, AMWs do not have intermediate stops so they can operate at their nominal speed. The absence of delay does to some extent offset the lower running speed. Hence, in terms of total travel time, a conveyor running at 16 km/h is competitive with an underground train (Browning, 1974). This speed is still within the allowable range for AMWs, as the maximum speed of AMWs is set to 16.45 km/h (equal to 4.57 m/s) by the ASME A17.1 standard (Donoghue, 1981). When the walking time to reach the transport mode, the waiting time for the vehicle, the dwell time at each station, and the walking time to reach the final destination are also taken into account, the total travel time of AMWs are not much different to that of buses, light rails, and APMs. However, the total journey time of AMWs is still below that of PRTs. Because PRTs do not have to make intermediate stops and their average speed is fairly higher than that of AMWs, passengers can safe time. Yet, it seems that the system carries too few passengers compared to the other modes.

For AMWs, the additional walking time depends on the distance from the origin to the entrance of the first AMW span, the length of the landings between the AMW spans, and the distance from the exit of the last AMW span to the final destination. However, the landing is usually only a few metres long and AMWs can be installed very close to the arrival and departure points of passengers. Hence, a short walking time can be expected. As a continuous transport system, AMWs also provide better service in terms of minimum waiting time. AMWs are always readily available for use, making them suitable for any passenger arrival pattern. This is certainly an important feature that cannot be provided by the discontinuous transport systems. Buses, light rails, and APMs are not very suitable for situations that have irregular passenger arrival pattern. In such cases, it may happen that a vehicle has arrived at a station while not many passengers are present, or it has not arrived while many passengers have already waited. Whereas for PRTs, the key question that still remains to be answered is whether they can effectively handle large number of passengers requesting service at approximately the same time, for example when a plane or a train has just arrived (Lowson, 2005).

In a cost–benefit analysis, the walking time from the origin to a stop or station, the waiting time for the service, and the walking time from a stop or station to the destination are usually weighted to the in-vehicle time by a factor of about two (Brand and Preston, 2003b). This can indicate that passengers are more tolerant to a long in-vehicle time than to a long walking and waiting time. In this aspect, the AMWs accommodate better.

AMWs have higher maximum capacity than PRTs and buses in mixed traffic, bus lanes, and airports. On the other hand, its maximum capacity may be lower than that of buses in busways, guided buses, light rails, and APMs. The comparison above also holds true for the practical capacity of the systems. For AMWs with a 1-m treadway width, the practical capacity was estimated to be around 4500–7500 p/h/d. The practical capacity of PRTs was estimated to be between 1800 and 3600 p/h/d. If 75% of the maximum capacity is assumed for the practical capacity of bus-based systems, light rail, and APMs, then their practical capacity will be around 750–3375 p/h/d for buses in mixed traffic, 3375–5625 p/h/d for buses in bus lanes, 3375–18,750 p/h/d for buses in busways and guided buses, and 750–22,500 p/h/d for light rails and APMs. However, a high capacity for bus-based systems can only be achieved with multiple stopping bays and lanes. Similarly, higher capacity for AMW systems can also be achieved by installing more than one lane per direction.

The system capacity of discontinuous transport systems can be limited by the capacities of the stations (Vuchic, 1981). For AMWs, the space available before the entrance and after the exit, i.e. the landing, may become the limiting factor. However, people normally only need to pause briefly to enter the moving walkway. So, unless there is a sudden peak of passenger arrival, the entrance landing is never fully occupied. At the exit landing, people also usually directly continue to walk away. Hence, the capacity of the exit landing is also never fully occupied, unless if someone pauses in front of the exit, which is rather unlikely.

The capital cost of AMWs is somewhat in the same range as that of light rails and APMs, but it is still quite higher than that of buses and PRTs. At this point, a methodological remark is necessary for further analysis of the capital cost. The cost per kilometre is subject to many variables, such as the number of stations and the number of trains/vehicles in the system, as is in the case of buses, light rails, APMs, and PRTs. For that reason, the capacity of the system should be taken into account in the comparison. This allows different systems to be compared on the basis of their design. Venter (1997) introduced the typical cost per passenger/hour to represent the cost of a system associated with the service provided. The typical cost per passenger/hour is calculated by dividing the total capital cost of the system with the maximum capacity provided by the equipment supplied. In this paper, the systems are represented by the typical cost per passenger-km/hour, which gives a more consistent comparison: it does not only consider the capacity of the system, but also the length. Hence, the typical cost per passenger-km/hour is determined using the capital cost per kilometre instead of the total capital cost. The typical costs of the different transport systems are presented in Table 3. They were calculated based on the data in Table 2 assuming that the high capital cost corresponds to the high system capacity and the lower capital cost corresponds to the lower system capacity.

From Table 3 we can see that buses still give the lowest range of cost, followed by PRTs and AMWs. However, by taking the system capacity and the length of the system into account, the typical cost of AMWs is now not so much higher than that of buses and PRTs. Light rails and APMs remain more expensive, most likely due to the higher costs for guideways and larger vehicles.

The operational cost of AMWs is lower than that of buses, light rails, and APMs, both in terms of cost per passenger-km and cost per vehicle-km. The operational cost of PRTs is just slightly lower than that of AMWs. The operational cost of AMWs can be low since, in terms of operation and maintenance, they are simpler than the other transport systems. Their simpler technology does not need expensive and complicated maintenance. Also, not many personnel are required to operate the system. The low operational cost is partly influenced by the system's low energy use. Although data on energy use per passenger-km were scarce, based on the obtained data it is seen that AMWs use the least energy. The energy consumption of buses and PRTs are somewhat in the same range, while light rails use slightly more. APMs consume the most energy.

For a two-way system, AMWs need the least space. Busways consume most space, while the other transport systems are in between. PRTs only require slightly more track width than AMWs, but the whole network may need more land-use. In airports and transit stations, the small installation space for AMWs makes it is possible to apply the concept of 'everything under one roof'. AMWs can be installed as close as possible to the arrival and departure points of passengers, so passengers do not need to step to other parts of the building to access the transport system.

Segregated transport systems are considered safer than transport systems in mixed traffic. Furthermore, automated systems are also considered safer than systems with drivers. This is mainly due to the risk of human error in mixed traffic situations and manual operations (Brand and Preston, 2003b). In this sense, the safety of passengers in conventional bus-based systems is lower than that in the other transport systems. APMs and PRTs are claimed to have very high safety, both being segregated and driverless. AMWs can also be considered driverless and segregated. Their safety is claimed to be high. The safety of a transport system can be judged by the number of accidents involving that system and the level of harm it caused (e.g. slight or heavy injury, or death). However, data were not available for all transport systems, so a complete comparison cannot be done.

AMWs as well as light rails, APMs, and PRTs are electrically powered so they produce no local emissions during operation. However, emissions are produced at the power stations when generating the electricity. The overall emissions produced, therefore, depend on the method used to generate the electricity. This can be almost zero if using renewable energy or significantly high if using coal. However, emissions of local pollutants at the power stations will generally have smaller impacts than at the location where the transport system

Table 3
Typical costs of the different transport systems

Systems	Typical cost ($ per passenger-km/hour)
Bus	
Mixed traffic	140–1500
Bus lane	255–3520
Busway	975–1545
Guided bus	280–445
Light rail	2785–8500
APM	4390–12,500
PRT	2210–2340
AMW	3630–3865

Note: Costs are given as 2005 US dollars.

operates, and are also easier to control because they come from a single source (Brand and Preston, 2003b). Buses, on the other hand, produce more pollutants since they are generally still powered by diesel engines.

Data on the noise levels of the transport systems were limited. Based on the obtained data, AMWs produce relatively lower noise level. This is an important aspect, since AMWs are likely to be installed indoors. The noise emission of PRTs is also generally low, although certain types of vehicle may produce higher noise level. Other transport systems emit higher noise levels than AMWs and PRTs.

AMWs, along with light rails, APMs, and PRTs, provide smooth transport for passengers because the internal vibration caused by these systems is low. However, the ground vibration caused by light rails and APMs are relatively stronger, which is likely due to the heavier vehicles. The ground vibration can disturb non-users and the surroundings. Buses do not cause as much ground vibration as light rails and APMs, but the internal vibration that affects the passengers can be higher. AMWs and PRTs, on the other hand, do not emit significant ground vibration that can disturb the environment.

The discussion above can be summarized as follows. AMW is a safe transport mode capable of providing a high-capacity people transport at relatively low costs. Compared to the discontinuous transport systems, the total travel time on AMW can be quite competitive when the walking time, waiting time, and dwell time in stations are taken into account. AMW is easy to integrate into any environment. Furthermore, the energy use and environmental impacts of AMW are low. Therefore, AMW is competitive to other (discontinuous) transport modes, though it should be noted that the choice of transport system is dependent on the nature of the application.

6. The potential application of AMWs

6.1. AMWs for long-distance people transport

The comparative evaluation has described the characteristics of the AMW compared to those of the discontinuous transport systems. Due to its competitive features, we envisage that AMWs can be an interesting alternative for the transport of people, i.e. pedestrians, over longer distances.

An example of the possible application of the long-distance AMW is to connect terminals in a large airport, such as the Amsterdam Airport Schiphol (AAS) in the Netherlands. Due to the expected expansion of the number of passengers by the end of this decade, the current terminal in the AAS, named the Schiphol Centrum, will reach its capacity limit. The AAS has plans to build a new terminal on the west side of the A4 highway that connects the cities Delft and Amsterdam. One of the success factors of the AAS is the fact that it has all its facilities under one roof due to the use of a one-terminal concept instead of a satellite concept. With the realization of the new terminal, named the Schiphol Northwest terminal, the one-terminal concept is left. The long-distance AMW can be applied to connect the two terminals so that passengers experience the Schiphol Centrum and the Schiphol Northwest terminal as one (Lodewijks et al., 2006).

In airports, the long-distance AMW can also be applied to connect the main terminal to the parking area, or to a nearby train, metro, or bus station. Other potential market sectors for the long-distance AMWs are underground railway/metro stations (e.g. to connect between two stations and their surroundings, so that the accessibility of the stations and the number of passengers increase), fair and exhibition sites (e.g. to connect separate showrooms or pavilions), and theme or amusement parks (e.g. to transport visitors from the parking area, bus/rail station, or hotel to the park's entrance). From these examples, we can see that the long-distance AMWs can be applied indoors as well as outdoors.

Travel time is a critical issue for a transport system. In the case of the AMWs, this results in a maximum distance that can be covered by the AMWs in order to maintain an acceptable travel time. The acceptable walking distance and walking time vary according to the nature of the pedestrian, the purpose and destination of the walk, and the nature of the walking environment (Pikora et al., 2001). For most purposes an acceptable walking distance is thought to be about 20 min walk, which equates to 1.5–1.6 km for an average pedestrian (Gleave and Halden, 2001). This agrees with the results of a study by Hydén et al. (1998), which state that people are still willing to walk between 1 and 2 km.

We will use the acceptable walking time of 20 min as the maximum travel time on the AMW. Hence, if the AMW applies a speed of 1.3–3.3 m/s in the high-speed section, a maximum travel distance of 1.5–4 km can be covered using the AMW. If passengers walk on the treadway, the travel time can be reduced. The travel time to cover a distance of 4 km, for example, can be reduced to around 14 min applying an average walking speed of 1.37 m/s (Fruin, 1992). As a comparison, the total travel time on the Central-Mid-Level Escalator in Hong Kong, a low-speed system with a total distance of 800 m, is also around 20 min if the passengers do not walk on the system. The difference is that the Central-Mid-Level Escalators consists of 20 escalators and three moving walkways with intermediate landings while the long-distance AMW system is expected to have a far less number of spans, with each span having a longer length than what is available now.

6.2. Issues for further research

The application of AMWs to transport people over longer distances is still a new concept. This paper has described an initial study on the competitiveness of a long-distance AMW. However, further research is required to investigate this idea in more details, including defining the issues that may arise in the development and application of long-distance AMWs. Investigation towards the non-technical aspects may involve a comprehensive assessment of the system's cost effectiveness, safety, access, effectiveness, reliability, flexibility, and environmental impacts (Parsons Brinckerhoff et al., 2001). These aspects are typical criteria commonly used in the evaluation of a transport system and will not be elaborated further in this paper. As for the technical aspects, the following discussion introduces some issues that should be considered.

To ensure the reliability of the long-distance AMW, it is preferred to use a design that is already a proven technology. From all of the available AMW technologies, it seems that the design that implements in-line accelerating belts is more reliable because it involves only a small modification from the existing conventional moving walkways. Other designs apply new concepts, which will require more real-time testing period to prove their robustness. In terms of construction cost, the in-line accelerating belt system can be competitive because only the ends are relatively expensive while the middle sections are relatively cheap (Loder, 1998). Hence, the system can have very long middle sections without significantly increasing the cost. It is also expected to be cheaper in terms of operational cost because the design is uncomplicated and does not consist of too many mechanical components. A simple design of the long-distance AMW is also preferred so that the maintenance can be done fast and cheap.

A long-distance AMW can be compared to a long-distance belt conveyor for bulk material transport. One of the interesting technologies of the long-distance bulk material conveyor is the application of distributed drives along the conveyor system, which limit the belt tension in the system and enable the use of low-stiffness rubber belt, lighter support structure, as well as standardized components. This, in turn, enables bulk material belt conveyors to have lengths up to many kilometres while keeping the capital and operational cost of the system reasonably low (Nuttall and Lodewijks, 2004). The implementation of such a technology to the AMW system should be investigated, as it can be useful in the effort to extend the length of the AMW without significantly increasing its costs.

An investigation towards the control of the drives in the AMW should be carried out, particularly in relation to the application of the distributed drives. An optimal control algorithm is important to obtain a smooth speed transition between the acceleration, high-speed, and deceleration sections. It is also essential to ensure a safe operation, particularly in the case of an emergency stop. Furthermore, the control algorithm should enable the supply of the drive power on an 'as-needed' basis, there where the load is present, such that the overall treadway tension and power consumption in the system can be minimized. The control algorithm for a bulk material belt conveyor cannot be applied to a people-carrying AMW due to the fact that the nature of the load on both systems is different, i.e. passengers on the AMW can move relative to the treadway, whereas bulk material remains on the same point. Since safety is a very important aspect for moving walkways, it is not possible to search for the optimal control algorithm experimentally. Therefore, a simulation should be set-up to study the effect of different control strategies on the dynamics of the AMWs. The control strategy is dependent on, among others, the distribution of the loads on the walkway, which in turn is influenced by the behaviour of the passengers using the system. This can be simulated by using a model that predicts pedestrian travel behaviour (Hoogendoorn and Bovy, 2004). The results of the simulation study can be used to determine a safe and reliable way of using distributed drives to control the long-distance AMW.

As an effort to reduce the travel time on a long-distance AMW, the possibility to increase the maximum speed of the system will also be investigated. The ASME A17.1 standard allows the maximum speed to be increased up to 4.57 m/s (Donoghue, 1981). Consequently, the influence of a higher speed towards the design of the system as well as the passengers's safety and comfort should be evaluated. Another aspect that should also be considered is the technical issue related to flexibility. This translates to the capability of the AMW to accommodate curves and inclinations in the route. Additionally, the possibility to exit from the long-distance AMW in the middle of the trajectory may need consideration. For example, if the long-distance AMW is applied to ease walking in a long airport terminal that has several boarding gates, then intermediate exits will be required. Or, if the long-distance AMW is applied to connect two terminals in a large airport and there are shops along the route, then the possibility to exit in the middle of the trajectory will be convenient for those who wish to visit the shops.

7. Conclusions

This paper presented the findings of a literature review on Accelerating Moving Walkways (AMWs) and evaluated the characteristics of the AMWs, as a continuous transport system, compared to those of discontinuous transport systems, namely buses, light rails, Automated People Movers (APMs), and Personal Rapid Transits (PRTs). Based on the study, we concluded that AMWs can be competitive to the other transport modes. AMWs are capable of providing a high-capacity people transport at relatively low costs. The total travel time on AMWs is quite competitive to that of the discontinuous transport systems when the walking time, waiting time, and dwell time in stations are taken into account. AMWs are considered safe and easy to integrate into any environment. Furthermore, AMWs are a sustainable transport mode due to their low environmental impacts and energy use.

We envisage that AMWs can be an interesting alternative of people transport system for distances up to 1.5–4 km, depending on the speed at the high-speed section. The maximum travel time on the AMW is projected to be 20 min, which is considered still acceptable for standing passengers. The travel time can be reduced by walking on the treadway or by increasing the speed at the high-speed section. It should be noted that the decision to implement the long-distance AMW is dependent on the nature of the application.

The application of AMWs to transport people over longer distances is still a new concept. Hence, further research is required to investigate this idea in more details. A comprehensive assessment of the system's cost effectiveness, safety, access, effectiveness, reliability, flexibility, and environmental impacts should be carried out. Some technical issues related to the concept of long-distance AMWs were introduced in this paper. These include the selection of a reliable design, the application of distributed drives to power the long-distance AMWs, and the importance of an optimal control algorithm for the drives.

There exist similarity in the concept of transportation of bulk material and people. Nevertheless, there is also a difference in the sense that bulk material remains on the same point on the belt during transport, while people may change their position relative to the treadway if they choose to walk. For that reason, the control philosophy for a moving walkway will be different than that for a bulk material belt conveyor. Further investigation in search of the optimal control algorithm for the AMW system should be based on simulations, since it may not be safe to do this experimentally. The simulation will study the effect of different control strategies on the dynamics of the AMWs. The results of the simulation study can be used to determine a safe and reliable way of using distributed drives to control the long-distance AMW.

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