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Abstract

Starting from the assumption of a future where the use of cars will be limited in dense urban areas, and thus streets could be used for innovative transport modes, this project investigates a system based on accelerated moving walkways (AMW). Differently from constant moving walkways, AMW can reach speeds up to 15km/h thanks to an acceleration section. This paper, after a review of existing AMW implementations, presents a description of this system and formulates an optimization problem to identify the optimal design of a network of AMW. Decision variables and parameters are defined for a general scenario, and five criteria are considered for the formulation of the objective function: travel time, discomfort, energy consumption, construction cost and operational cost. The resulting multi-objective mixed integer nonlinear optimization problem is evaluated for the simple case of a single link, and results of optimal speed profiles for different parameter values are presented. A network of accelerated moving walkway in a car-free urban environment may present an innovative solution, and further research at a network level could delineate the system feasibility.

Keywords

Accelerated moving walkway, network optimization, futuristic transport mode

1 Introduction

In a hypothetical future where the use of private cars will be limited in dense urban areas, the need of movement will be satisfied by a mix of traditional, innovative and futuristic transport modes. Beside traditional systems like bus, metro, tram and taxi, walking and cycling will play a much more important role in the future, together with innovative systems like bike-sharing and car-sharing. Also futuristic modes of transport will be part of the modal mix of tomorrow. For example, projects of urban cable cars and personal rapid transport systems are increasingly studied as a solution for the future mobility.

The focus of this project is another possible futuristic system: an urban network of accelerating moving walkways (AMW). Differently from the traditional constant speed moving walkways (CMW), AMW present an acceleration (deceleration) section at the embarking (disembarking) area that accelerates pedestrians to a speed higher than a CMW in the central section. Examples of accelerating walkways show that the system can reach 12-15 km/h (Kusumaningtyas, 2009), a speed competitive with urban bus and tram services, as well as private cars which travel at an average speed of 15 km/h during peak hours (Browning, 1974). Although several implementation of traditional moving walkways and few trials of accelerating walkways exist, see Section 2, in particular in metro stations, airports and dense urban areas, this project studies and optimizes this system starting from a new radical approach. A future without the use of private cars is assumed, and a network, not only individual paths, of moving walkways is studied as one of the transport systems to be adopted to replace private cars. In this scenario, each road has the possibility to be equipped with an accelerated moving walking, and an extended network could be created.

This project aims to design and to optimize a network of AMW, identifying the optimal system characteristics that could satisfy at best the demand. The innovation of this research is the study of the possible application of AMW at a network level, in a scenario where the space nowadays used by traditional mean of transport can be used for different purposes. This research is part of the more wide project Post-Car World (PCW, 2014) with the goal of exploring the future of mobility through the role of the car, where the sociological and urbanistic implications of a network of AMW will be investigated together with technological and transportation aspects.

The present paper reports the initial research phases and focuses on the definition of the system variables, the formulation of the optimization problem at a link level considering several aspects like travel time, discomfort, energy consumption, construction cost and operational cost. A review of AMW and CMW implementations is carried out to define the technological assumptions necessary to the mathematical description of the system that will lead at the identification of the optimal system design.

Section 2 reviews existing implementations of AMW, and Section 3 presents the system description and characteristics. The formulation of the optimization problem, and a discussion on the decision variables and parameters is reported in Section 4. The preliminary results at a link level are presented in Section 5, and the case study, that will be investigated in further research is introduced in Section 6. The paper finishes with main conclusions and further work in Section 7. Abbreviations and notation are included at the end.

2 Review of AMW types and existing implementations

Although the CMW appears to have found its niche in the transport market, the interest to have a transport system continuously moving at a speed higher than walking pace did not fade. Even since the 1960s, several ideas on how to achieve a higher transport speed have been proposed. In the 1970s and early 1980s, a few of these ideas were made into prototypes and were tested. Although none of them were commercialized, their working principles were later adapted for subsequent Accelerating Moving Walkway (AMW) designs. Prototypes of these later designs were built and tested in the late 1990s and early 2000s.

This section first presents the different types of AMW based on the technology used in the acceleration section and then reviews existing case studies.

2.1 Types of AMW

Based on the method used to achieve acceleration and deceleration, these systems can generally be categorized into the following four types: in-line belts, sliding parallelograms, sliding pallets and accelerating/decelerating rollers.

In-line belts

A number of belt conveyors with slightly different speeds are placed one after another, end to end. The in-line belts have increasing speeds at each entrance, such that they accelerate passengers to a high-speed belt conveyor in the middle section. Approaching the exit, another series of belts with decreasing speeds decelerate passengers, see Figure 1*(a)*. This mechanism was used in the Loderway system (Loder, 1998), which was tested for public use in Brisbane Airport, Melbourne Airport and Degraves Street Subway in Melbourne. A similar system, named Speedmove, was also built by Fujitec (Kazuo *et al.,* 2003).

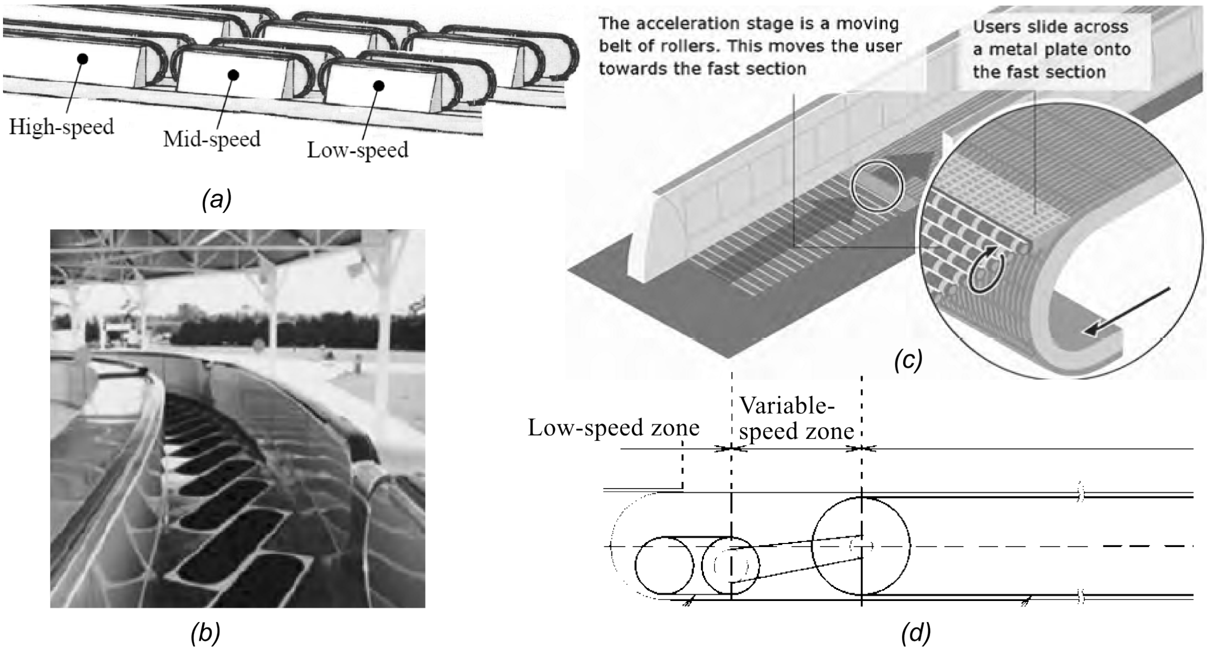

Figure 1: Accelerated moving walkway types. *(a)* in-line belts, *(b)* sliding parallelograms, *(c)* accelerating/decelerating rollers and *(d)* sliding pallets.

Sliding parallelograms

A series of parallelogram pallets form a continuous treadway. At the entrance, the pallets move at a low speed for a short distance. Then, while continuing to move forward, each pallet begins to slide progressively sideways with regard to the pallet behind it. The resultant of the forward moving and the sideway sliding creates an accelerating speed, see Figure 1*(b)*. The pallets will stop sliding sideways once they reach the target high speed. The method is reversed for deceleration at the exit. This mechanism was used in the Dunlop Speedaway (Todd, 1974), which was installed for public trial at the Expo '70 in Osaka, Japan, and at the Battelle Institute in Geneva, Switzerland. The Mitsubishi Speedwalk (Shirakihara, 1997), which was demonstrated at the Seaside Park in Fukuoka, Japan, also adopted this mechanism. This system uses parallelogram pallets forming an S-shape treadway. At the curves, the sideway sliding and the forward moving of each pallet results in an accelerating or decelerating speed.

Accelerating/decelerating rollers

In this mechanism, a "carpet" of metal rollers at the entrance accelerates passengers onto a high-speed belt conveyor. Approaching the exit, another series of metal rollers decelerates the passengers, see Figure 1*(c)*. The mechanism was adopted by the Gateway system (Cote and Gempp, 1998), which was installed in 2002 for public demonstration in the Paris Montparnasse metro station.

Sliding pallets

There are a number of different variations in the way the pallets slide. One system accelerated and

(a) *(b)*

Figure 2: Accelerated moving walkway real implementations. *(a)* TurboTrack, Toronto airport and *(b)* Gateway Paris subway.

decelerated individual main pallets by sliding them over continuous auxiliary pallets (Ikizawa *et al.,* 2001). Another design uses an array of pallets that slightly overlap one on top of the previous at the entrance, each of which then progressively slides forward to accelerate passengers (Abe *et al.,* 2001). These two systems were only tested in the factory. The more successful variation is the TurboTrack system (Gonzalez Alemany and Cuello, 2003), which employs auxiliary pallets and main pallets, see Figure 1*(d)*. The auxiliary pallets "hide" underneath the main pallets at the entrance and exit, and progressively extend or retract to accelerate or decelerate the passengers. The auxiliary pallets are fully extended at the high-speed section, forming a continuous treadway with the main pallets. This system is now installed at the Toronto Pearson International Airport in Canada.

2.2 Existing accelerated moving walkways

In this section two case studies of AMW deployment are presented, underlining working characteristics and implementation problems.

TurboTrack, Toronto airport

The TurboTrack is a successful installation of an AMW currently in service, Figure 2*(a)*. It is located in Toronto Airport, between Terminals 1 and 2, and it was built in 2007 by ThyssenKrupp Elevator. The technology of this AMW is based on "pallets sliding" type. At the entrance and exit, the TurboTrack looks like present-day metal-pallet CMWs. However, its sliding pallet mechanism enables it to extend and retract each pallets for accelerating or decelerating the passengers. Each individual pallet has two parts: the main pallet and the extensive and retractive part. In the low-speed zones, extensive parts are non-visible, and main pallets have no space between them. In the high-speed zone, extensive parts are visible and much larger than the main pallets. The mechanism is a complex set of roller attached to pallets, where they are very close in the low-speed zones, and then spread each other. This mechanism allowed different speeds for the boarding and inside zones. The entry speed is 0.65 m/s, which is like conventional moving walkways. That speed assure safety as much as CMW for boarding. The high speed is 2 m/s in the middle area, and it is three times faster than the entry speed. When pallets are fully extended, people can walk on it to travel even faster. The length of the TurboTrack is 270 m, and one AMW for each direction is built.. It allows people to travel that distance in only 140 seconds, while previous CMW took 415 seconds, so cutting the travel time by two thirds. Acceleration and deceleration zone, i.e. the transition between low-speed and high-speed zone, measure about 13 m each. In about 10 seconds, AMW start from 0.65 m/s to reach 2 m/s. Of course, this implies acceleration, where people are "push forward" to reach the maximum speed with an acceleration of about 0.14 m/s^2. The width choose for the TurboTrack is 1.2 m large, which is the most common width use for CMW as well. This width is the minimum admitted value to allow two columns of passengers on moving walkways or on elevators. It allows people to pass each other, when for example walking people want to pass standing people.

Gateway Paris subway

The one-lane Gateway AMW in Paris, at Montparnasse station, was inaugurated in july 2002, Figure 2*(b)*. It was built to connect Paris's subway with the train station. Maybe not enough reliable at the time, and too avant-garde, it had very frequently breakdown, slow-down in speed and a lot of fall downs from passenger. People complained because it was always in maintenance, and that the direction of travel of the one-lane Gateway was always in the wrong side. Furthermore, it was considered not safe from many users. When tests were made before the Gateway open for the public, the initial high-speed of the Gateway could reach a maximum of 3 m/s, but was reduced due to safety problem to 2.5 m/s. As the entire system speed and acceleration profile was interdependent, the entry speed was also reduced proportionally from 0.75 m/s to 0.62 m/s. The main problems they deal with were on the acceleration and deceleration zones. The most problematic issues were not the maximum speed in the constant high-speed section, but with the acceleration itself. Initially, the acceleration was fixed to 0.43 m/s^2 (for high-speed of 3 m/s) but due to many problems in terms of unbalanced feelings or even falls, the value of 0.28 m/s^2 was chosen. The acceleration and deceleration parts measured about 10m, and as the TurboTrack from Toronto, the gateway's width was 1.2m, for the same reasons.

3 System description

This section presents the description of the AMW system in a formal way that will be subsequently used in the formulation of the optimization problem. A series of assumptions and

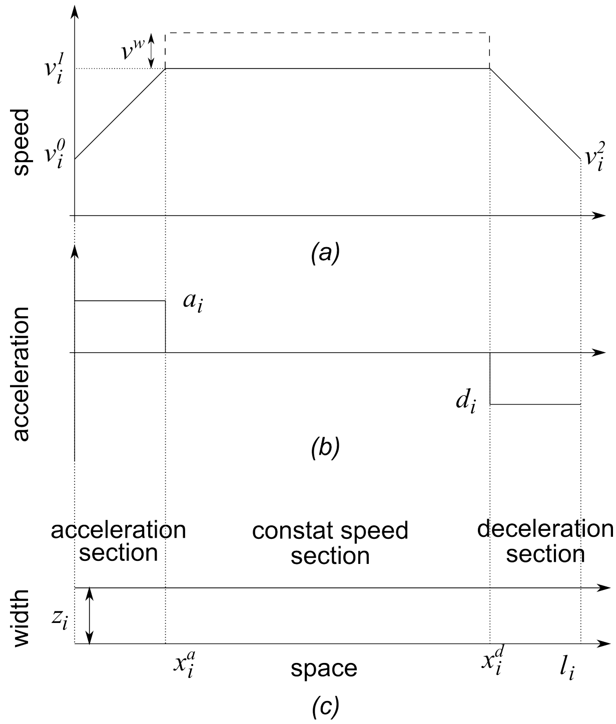

Figure 3: Accelerated moving walkway characteristics. *(a)* speed profile, *(b)* acceleration profile and *(c)* width profile over space of a standard AMW.

simplifications has been made starting from real implementations reviewed in the previous section in order to have a simpler mathematical formulation.

Figure 3 shows the speed, acceleration and width profile as well as some fundamental characteristics of an AMW. Figure 3*(c)* shows the top view of an AMW with a constant width z_i along the entire length l_i. The accelerated moving walkway is functionally divided in three sections: (i) the acceleration section, from the start of the AMW to position x_i^a, (ii) the constant speed section from x_i^a to x_i^d and (iii) the deceleration section from x_i^d to the end of the AMW l_i. As the names suggest, the three sections present different accelerations as shown in Figure 3*(b)*. The acceleration section is characterized by a constant positive acceleration a_i, meanwhile the constant speed section has zero acceleration and the deceleration section presents a constant negative acceleration d_i (deceleration). These variations in acceleration produce changes in the speed along the three sections, as observable in Figure 3*(a)*. In the acceleration section, the speed increases constantly from the entry speed v_i^0 to the maximum speed v_i^1 followed by a section of constant speed. Then, the speed v_i^1 decreases uniformly to the exiting speed v_i^2.

The characteristics and the notation of the AMW is summaried in Table 1, and the following is a discussion of the simplification and assumption for each of them.

In a urban network, not all streets (links) will be equipped with an AMW, but only the one that will provide an optimized configuration of the system. The Boolean variable y_i indicates if a

Table 1: Notation of the accelerated moving walkway characteristics

i	[-]	link ID
y_i	[-]	Variable (Boolean) indicating if the link is equipped with a moving walkway or not. 0 = not equipped, 1 = equipped
l_i	[m]	Length of the link
x_i^a	[m]	Length of the acceleration section
x_i^d	[m]	End of the constant speed section
v_i^0	[m/s]	Entering speed
a_i	[m/s^2]	Acceleration
d_i	[m/s^2]	Deceleration
v_i^1	[m/s]	Speed on constant part
v_i^2	[m/s]	Exiting speed
z_i	[m]	Width of the walkway
v^w	[m/s]	Walking speed

link i is equipped with a AMW or not (0 = not equipped, 1 = equipped). A non-equipped link is simply a normal street, where pedestrians move freely at their walking speed v^w without any assistance.

It is assumed that a link can be completely equipped or not equipped. It is not possible to have an AMW covering a partial length of a link, therefore l_i indicates both the length of the street and the length of the AMW on this link in the case it is equipped, i.e. $y_i = 1$.

The AMW is divided in the three sections described previously. The acceleration section is defined from the start of the link, position 0, to x_i^a. The constant speed section stretch from x_i^a to x_i^d and it length is defined by $l_i - x_i^a - x_i^d$ or equivalently by $x_i^d - x_i^a$, and finally the deceleration section starts from x_i^d until the end of the link l_i with length $l_i - x_i^d$.

The acceleration a_i is considered constant in the entire acceleration section x_i^a and equal to the deceleration d_i. Furthermore the exiting speed v_i^2 is assumed equal to the entering speed v_i^0; therefore, the speed profile is symmetric around the middle, and the length of the acceleration section is the same of the deceleration section.

The speed on the constant speed section is v^1. It is defined by the entry speed v_i^0, the length of the acceleration section x_i^a and the acceleration along this section a_i. v^1 is subject to a constraint of maximum speed $v^{\max}$ for safety reasons that will be further discussed in the next section.

AMW have a constant width along all length defined by the variable z_i. The width, as it will

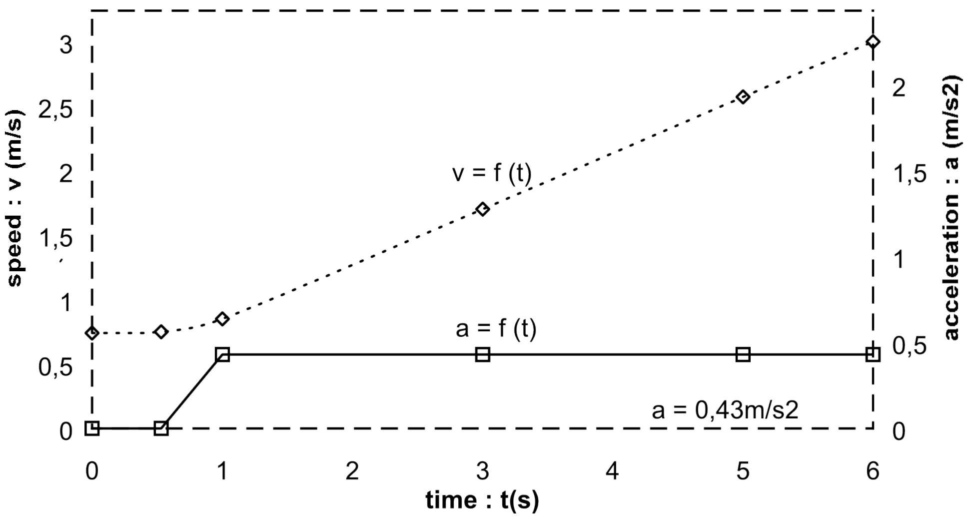

Figure 4: Complete speed profile of an accelerated moving walkway. Adapted from (Boissac and Cote, 2001).

be introduced in Section 4, is related to the capacity of the AMW allowing lane formation, and embarking and disembarking of the AMW side by side.

The last variable represented in Figure 3*(a)* is the walking speed v^w. For safety reasons associated to the acceleration and deceleration sections, pedestrians are assumed to walk only on the constant speed section of the AMW. Therefore, a proportion of pedestrians will walk in the central section, and this aspect should be considered in the calculation of the travel time and the resulting speed profile of the passengers on the AMW.

As visible from this system description and from the chart in Figure 3, the speed profile is drawn against space instead of time, as it is often presented for motion under constant acceleration. This because the design of the system is space-based and not time-based, i.e. the decision variable is the length of the different sections and not the time that passengers experience on them. This should be kept present for understanding the calculation of TT presented in the next section.

In conclusion, given the stated assumptions, the speed profile results symmetric around the middle, and it can be described univocally by the length of the acceleration section x_i^a, being all the other measurements derivable from this. The speed profile of real installations presents a more complex shape than the one used for this project. Figure 4 shows the complete profile, that in addition to the part presented in Figure 3 has a constant speed entry section and a gradual acceleration section during which the acceleration increase from 0 m/s^2 to x_i^a. For the present research, the simplified speed profile presented has been chosen in order to have a simpler model of the AMW to be used in the optimization problem. A more complex speed profile can then be used to refine the optimal solution found.

4 Optimization formulation

The aim of the present research is to optimize the design of a network of interconnected AMW. This paper focuses on the first stage of this process, and looks at the optimization problem at a link-scale instead than a network-scale. In further work, the optimization here presented will be expanded to a network level considering pedestrian demand, route choice and more explicitly budget constraints. This section first introduces the decision variables and the system parameters, and then presents the objective function reporting the criteria considered and constraints.

4.1 Decision variables and system parameters

The first step to formulate the optimization problem is to define which are the decision variables and which the parameters among the system characteristics reported in Table 1. At this early research stage, three decision variables have been chosen:

- y_i Boolean variable indicating if a link is equipped or not with a moving walkway
- x_i^a the length of the acceleration section
- z_i the width of the walkway

The solution of the optimization problem will identify if a link i is "worth" to be equipped with an AMW, i.e. $y_i = 1$. In the case the link is equipped, the optimal speed profile is identify by the decision variable x_i^a. Given the simplifications reported in Section 3 and the parameter choice, the length of the acceleration section x_i^a is enough to completely describe the acceleration and speed profile of a link of length l_i; since, v_i^0 and a_i are given as parameters and the speed profile is symmetric around the middle. The final decision variable is the width of the walkway z_i. Typically width are between 0.8 and 1.6 meter (Kusumaningtyas, 2009), and it has been shown that a minimum of 1.2 meter are necessary to allow two columns of passenger (Davis and Braaksma, 1987, Fruin, 1992). The width z_i is associated with the capacity k_i for each link equipped with AMW, and it should be evaluated in the optimization problem given the demand. The capacity k_i, expressed in passengers per hours [pax/h] in the empirical Equation 1, depends on the entry speed v_i^0 and the width of the link z_i (CEN, 1998).

$$k_i = 2250 v_i^0 (5z_i - 1) \tag{1}$$

At the present stage of research, this aspect is not considered, and in further research, this consideration will be implemented to define the optimal width z_i on each link.

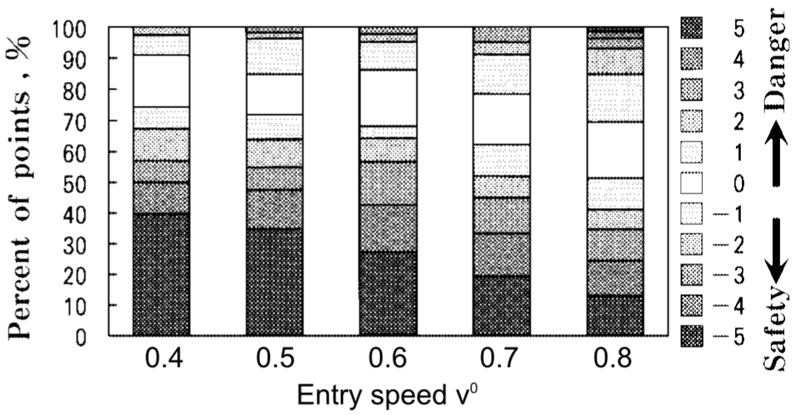

Figure 5: Perception of discomfort expressed by safety and danger of different entry speed v^0. Adapted from (Ikizawa *et al.,* 2001).

Having set the decision variables, the remaining system characteristic, i.e. l_i, v_i^0, a_i, v^w, $v^{\max}$, must be handle as parameters and input values. The notation can be simplified because some variables are not link specific but global for the entire network; so, the subscript i, indicating the link ID, can be removed from v_i^0 and a_i. The following is a description of each parameter and the chosen values.

The length of the link l_i is an input value provided by the topology of the case study, i.e. the existing road network. Eventually, long roads could be split into a sequence of shorter links to facilitate the road crossing. This consideration, that in the optimization problem results in specify the input network in a different way, will be investigated in collaboration with town planners and geographers in the broad context of Post-Car World project.

The entering speed v^0 is a critical parameter that has significant consequences on the speed profile, the capacity and the comfort of passengers. Conventional moving walkways typically operate at speed between 0.6 m/s and 0.75 m/s, and maximum and minimum values have been set in real implementation of AMW at 0.5m/s and 0.8 m/s (Donoghue, 1981, Fruin, 1992). An high entry speed will decrease the travel time, increase capacity and allowed a shorter acceleration/deceleration section to reach the same v_i^1, but it will increase the discomfort of passengers. Figure 5 shows the results from an experimental evaluation of the perceived danger, which can be associated to discomfort, for different entry speed v^0 (Ikizawa *et al.,* 2001). It is visible that high entry speeds are considered dangerous for a large percentage of participants. As a trade off between travel time and comfort, v^0 has been chosen equal to 0.65 m/s.

The acceleration a in the acceleration section is a sensitive value for comfort and definition of the speed profile. High acceleration can create imbalance, falls and bring to a rejection of the system. In real implementations, the acceleration varies from 0.14 m/s^2 to 0.28 m/s^2

(Dembart, 2003, Gonzalez Alemany *et al.*, 2007, Kusumaningtyas and Lodewijks, 2008, 2013), and the European standard on safety of escalators and moving walkways (EC, 2010) prescribes a maximum acceleration of 1 m/s^2. Given this consideration, the chosen value for a is 0.4 m/s^2.

Many studies are present on the average walking speed in free-flow (Browning *et al.*, 2006, Levine and Norenzayan, 1999, Mohler *et al.*, 2007, Daamen, 2004) and a widely used value is of 1.34 m/s. On CMW, the walking speed decreases to an average of 1.04 m/s (Young, 1999), but it can be assumed that in a future where AMW will be widely used, the walking speed will be closer to the normal free-flow walking speed, being the passengers more used to utilize this system. Therefore, the value of 1.30 m/s has been chosen for v^w.

The maximum possible speed v_i^1 on the constant speed section is $v^{\max}$. It has been reported that v_i^1 itself is not perceived as a problem by passengers because in this section there is no acceleration involved (Donoghue, 1981). Therefore a relative high $v^{\max}$ has been chosen following the European standard on safety of escalators and moving walkways (EC, 2010) that prescribes a maximum speed of 4.57 m/s equal to 16.45 km/h.

4.2 Objective function and constraints

The second step for the formulation of the optimization problem, after having identified the decision variables and the parameters, is the definition of the objective function. Five criteria have been considered for this:

- total travel time (TT)
- discomfort
- energy consumption
- construction cost
- operational cost

The travel time on an AMW is calculated using kinematic equations of motion uniformly accelerated in the acceleration and deceleration sections and motion at uniform speed for the constant speed section. Equation 2 reports the calculation of the TT, where t_a is the time spent in the acceleration and deceleration part and t_c is the time spent in the constant speed section.

$$TT_i = 2t_a + t_c = \frac{1}{a}\left(\sqrt{v_0^2 + 2ax_i^a} - v_0\right) + \frac{l_i - 2x_i^a}{\sqrt{v_0^2 + 2ax_i^a} + v^w} \tag{2}$$

Equation 2 gives the travel time of a single passenger over an AMW, therefore to obtain the total TT it should be multiply by the flow of passengers q.

The second criteria considered in the objective function is the discomfort. This is a function of the time spent in the acceleration and deceleration section t_a and a constant γ representing the discomfort of boarding an AMW. This can be estimated by experiments like the one reported by Ikizawa *et al.* (2001) whose results have been shown in Figure 5, and expressed mathematically by Equation 3

$$d_i = \delta 2t_a + \gamma = \frac{2\delta}{a}\left(\sqrt{v_0^2 + 2ax_i^a} - v_0\right) + \gamma \tag{3}$$

where δ is a conversion factor equal to 1 [disconfort/seconds].

Together with TT and discomfort, also energy consumption e_i is considered in the objective function. It has been reported that the acceleration and deceleration section of an AMW required three times more energy than a CMW e^{CMW} (Kusumaningtyas, 2009); therefore, the energy consumption of an AMW can be expressed as

$$e_i = \left(3(2x_i^a) + x_i^d - x_i^a\right) e^{\text{CMW}} = \left(3(2x_i^a) + (l_i - 2x_i^a)\right) e^{\text{CMW}} \tag{4}$$

The last two criteria considered in the objective function are the construction cost c^c and the operational cost c^o. Similar consideration to the energy consumption can be applied at the construction of an AMW instead of a classic CMW, and the resulting equation has a form similar to Equation 4, where the cost of the accelerating and decelerating part is 1.2 times higher than a CMW (Kusumaningtyas, 2009).

$$c_i^c = \left(1.2(2x_i^a) + x_i^d - x_i^a\right) c^{\text{CMW}} = \left(1.2(2x_i^a) + (l_i - 2x_i^a)\right) c^{\text{CMW}} \tag{5}$$

Instead, the operational cost per unit of time is function to the length of the AMW l_i, the flow of passengers q, and the entry speed v^0 (Kusumaningtyas, 2009)

$$c_i^o = 0.25 l_i q + 0.15 v_0 \tag{6}$$

The resulting objective function, stated in Equation 7, is a weighted multi-objective mixed integer nonlinear optimization problem.

$$f_i = y_i(w_1 TTi + w_2 d_i + w_3 e_i + w_4 c_i^c + w_5 c_i^o) + (1 - y_i) w_6 l_i / v^w \tag{7}$$

The optimization problem is multi-objective because it incorporates, in the case of an equipped link ($y_i = 1$), the five criteria weighted with the parameters w_1-w_5, nonlinear due to the complex form of the objective function and mixed integer because it incorporates the Boolean variable y_i

which identifies if a link is equipped or not with a moving walkway. As visible from Equation 7, in the case a link i is not equipped with a AMW ($y_i = 0$), the first term is equal to 0 and the objective function has the form $f = w_6 l_i / v^w$ indicating that the only relevant criterion is the travel time at normal walking speed, being this stretch of road not equipped with any walkway.

The first term of Equation 7 results greater than the second term for a large range of values of the weighing parameter, being the cost of time on an AMW w_1 similar or equal to the cost of time while walking w_6 and the remaining criteria (d_i,e_i,c_i^c,c_i^o) strictly positive. Therefore, in an unconstraint optimization problem, the optimal solution tends to be always not to equip a link ($y = 0$). The Boolean variable y has been introduced to allowed the flexibility to have as a result from the optimization problem both possibilities of equipping or not a link. This variable will play a more active role in the case of network optimization, where costs and budget will impose constraints to the optimization problem instead of requiring minimization.

The six weighing parameters w_1-w_6 can be chosen to transform all criteria to monetary unit. For example w_1 and w_6 are equal to the cost of time and w_3 the cost of energy. The weight w_2, associated to discomfort, is not of immediate identification and will required further research. It is clear that the solution of the optimization problem is sensitive to the weight choice, and therefore, an accurate sensitivity analysis will be carried out.

The optimization problem in Equation 7 is subject to three constraints. The first one is simply that the acceleration section cannot be longer than half of the link, i.e. $x_i^a \leq l_i/2$, to allow a long enough deceleration section $d_i = a_i$. The second is on the maximum speed of the constant speed section v_i^1 that cannot be higher than $v^{\max}$

$$v_i^1 \leq v^{\max} \tag{8}$$

$$\sqrt{v_0^2 + 2ax_i^a} \leq v^{\max} \tag{9}$$

Finally, the last constraint is on the maximum width z_i for each links that should not be greater than the available space on the road network $z_i^{\max}$. The list of the maximum available road space $z_i^{\max}$ is an input parameter specific of the case study.

In further research, the objective function will be extended at a network level, adding consideration on passenger demand, route choice, total travel time and AMW capacity to solve an optimization problem for a network of N link using the following equation

$$f = \sum_{i=1}^{N} f_i \tag{10}$$

5 Results

The optimization problem in Equation 7 has been solved for the simple case of one link, and this section presents the results for three parameter configurations. As stated in Section 4, the solution is sensitive to the choice of the five criteria weight w_1-w_6; thus, in order to make the presentation more clear and not depended by this choice, the results, presented in Figure 6, are reported for only one criterion: TT.

Figure 6*(a)* shows the TT, calculated using Equation 2, on a link of 200 meter in function of the acceleration section length x_a. In this scenario there is no constraint on the maximum speed v_i^1, i.e. $v^{\max} = \infty$, and it is assumed that pedestrians do not walk in any part of the AMW. As expected, with these assumptions, the TT is minimum with an acceleration section equal to half of the link length l_i and the deceleration section stretching on the other half; so, the resulting speed profile has a triangular shape as shown in Figure 6*(b)*.

In the case pedestrians can walk on the constant speed section, assumption close to reality, the TT is minimum for a shorter acceleration section, Figure 6*(c)*, since the v^w is added at the maxim AMW speed v_i^1. The speed profile, Figure 6*(d)*, instead of a triangular shape as in the previous case, presents a trapezoid shape with a constant speed section in the middle.

Finally, if the constraint on the maximum v_i^1 is introduced, Equation 8, the objective function remains unchanged, Figure 6*(e)*, but the acceleration section x_i^a is reduced, the admissible solution is not the optimal one, and the constant speed section is expanded with consequence increase of TT, Figure 6*(f)*.

Modifying the parameters and weights of the complete optimization problem in Equation 7, it is possible to obtain triangular speed profiles like the one in Figure 6*(b)*, trapezoid profiles with different length of the constant speed section, Figure 6*(d)* and *(f)*, and completely flat speed profiles having $x_i^a = 0$ and so a CMW with speed v^0. In the case the Boolean variable y_i is equal to 0, the optimal solution is not to deploy the AMW; and so, the link has a null speed profile.

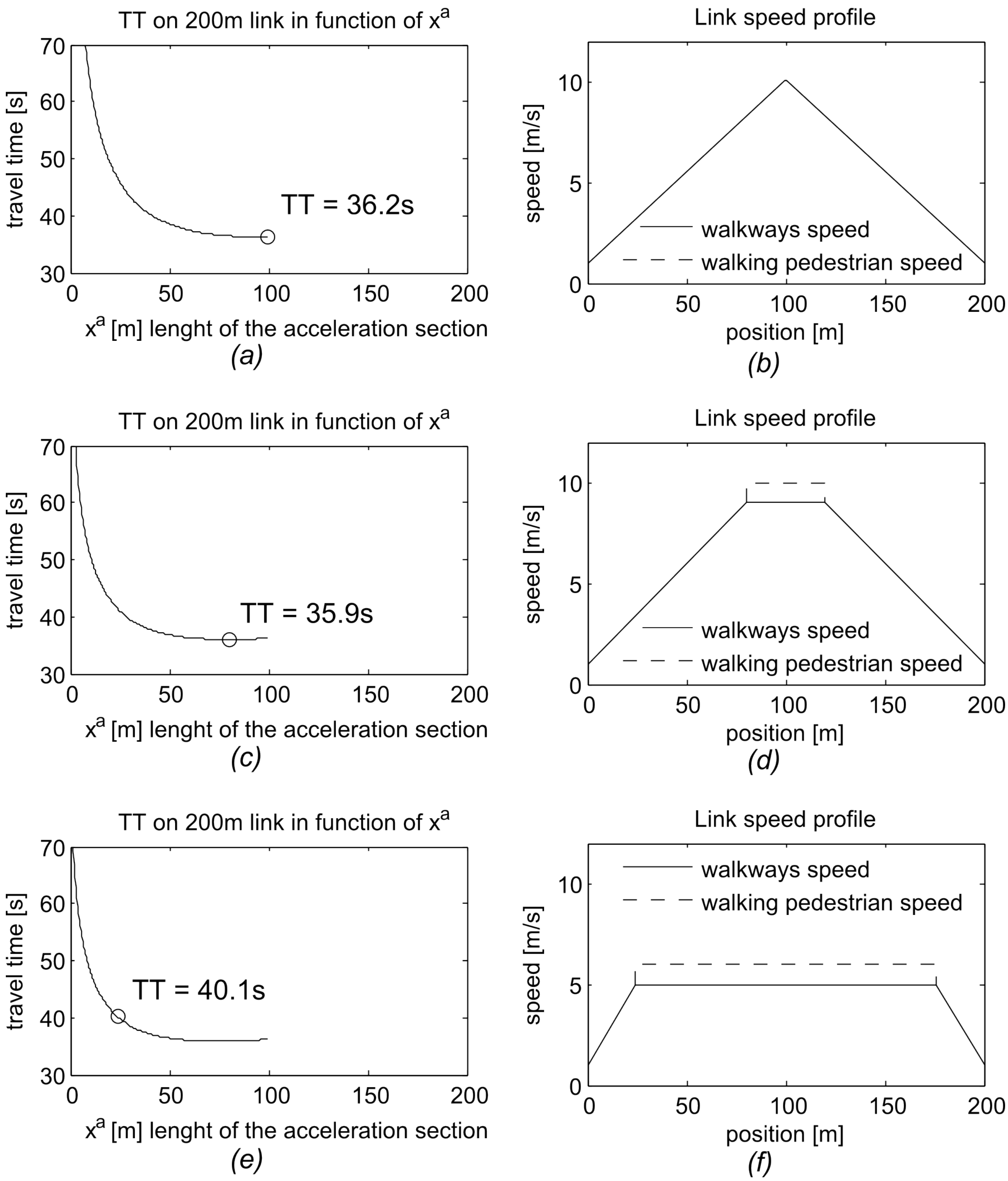

Figure 6: Objective function (left column) and resulting optimal speed profile (right column) in different scenarios. *(a)* and *(b)* no pedestrian walking and no constraint $v^{\max}$, *(c)* and *(d)* pedestrian walking at v^{w} and no constraint $v^{\max}$, *(e)* and *(f)* pedestrian walking at v^{w} and constraint $v^{\max}$.

6 Case study

The optimization problem can be solved for different case studies with increasing levels of complexity, from considering a simple objective function incorporating only some criteria, a subset of simplified system characteristics and constraints on a simple network to a comprehensive objective function, a full set of system characteristics and constraints on a real city network incorporating congestion and route choice models. The present paper formulates the problem in a general level, but, at the current research state, it investigates the problem on a simple level, identifying the optimal system configuration on a reduced set of characteristics on a link scale.

In further work, the city of Lausanne, Switzerland, will been used as a case study for the optimization of the network of accelerated moving walkways, since it has appropriate urbanistic and transportation characteristics. Lausanne (130,000 inhabitants) presents a dense urban environment formed by a compact city center with pedestrian areas and surrounding suburban residential, industrial and commercial areas with different attraction points, e.g. École Polytechnique Fédérale de Lausanne and Université de Lausanne campuses, that require commuting distances from the city center between 5 km and 8 km. The city has a widespread public transport system with several lines of conventional and trolley busses, two metro lines and a train station located in the city center. Furthermore, Lausanne has a significant change in altitude, from 372 meter on the Lake Geneva to the more than 900 meter in the north part of the city. This slope is particular influential for pedestrians and cyclists, the latter close to 4% of the modal share (Boillat, 2010). The innovative system of AMW could play an important role in integration with the already present public transport, pedestrian and cycling network. All these characteristics create an appropriate case study where to design and optimize a network of interconnected AMW. Figure 7 shows a conceptual example of a possible AMW network deployed in Lausanne city center.

7 Conclusions

This paper, after a review of existing implementations, describes the characteristics of an innovative transport system based on moving accelerating walkways (AMW) and formulates the optimization problem to obtain an optimal system network design considering total travel time, discomfort, energy consumption, construction cost and operational cost. The results of the optimization at a link level are presented showing the possible speed profiles, from triangular to trapezoid shape. Finally, the case study that will be used to investigate the system of interconnected AMW at a network level is presented.

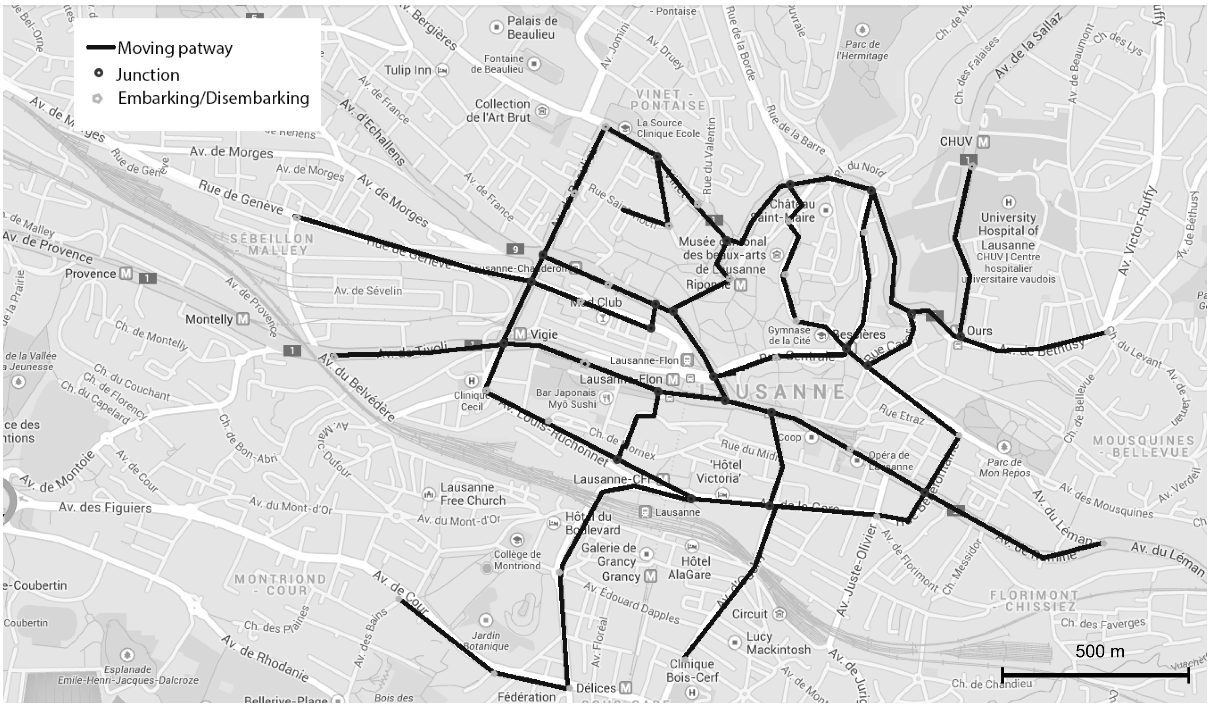

Figure 7: Map of the case study, Lausanne, Switzerland, and a conceptual example of AMW network design. Background image adapted from (TeleAtlas, 2013).

While this paper focuses on the optimization problem on a single link, the next step consists in expanding the optimization to a network level. Demand and route choice will be considered explicitly and the methodology will be applied to a real case study. In the more broad scope of Post-Car World project, the design of intersections, embarking and disembarking areas will be considered together with safety, comfort and urbanistic aspects. Also the active traffic management of the AMW system will be investigated, for example with the possibility to reverse the direction of an AMW on specific links to reflect the different demand during morning and evening peak hours.

This project, starting from the hypothesis of a world without private cars, investigates an innovative mean of transport that could be part of the future modal mix reusing the urban space not anymore occupied by cars thanks to the change in the transport paradigm.

8 Notation and abbreviation

AMW	Acceleration moving walkway
CMW	Constant speed moving walkway
i	link ID
y_i	Variable (Boolean) indicating if the link is equipped with a moving walkway or not. 0 = not equipped, 1 = equipped
l_i	Length of the link
x_i^a	Length of the acceleration section
x_i^d	End of the constant speed section
v_i^0	Entering speed
a_i	Acceleration
d_i	Deceleration
v_i^1	Speed on constant part
v_i^2	Exiting speed
z_i	Width of the walkway
$z_i^{\max}$	Maximum available width
v^w	Walking speed
k_i	Link capacity in passengers per hour
$v^{\max}$	Maximum allowed speed of a AMW
TT_i	Travel time
d_i	Discomfort
e_i	Energy consumption
e^{CMW}	Energy consumption CMW
c^c	Construction cost
c^{CMW}	Construction cost CMW
c^o	Operational cost
q	flow
w	weight parameter
f_i	Objective function for a single link
f	Objective function for the entire network
N	Total number of links in the network

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