Network design of a transport system based on accelerating moving walkways

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Abstract

Pollution, congestion and urbanistic considerations are leading to a change in the use of private vehicles in dense city centers. More frequently, the *last-mile* is covered with systems such as public transport, car sharing and bike sharing as well as an increase in walking and cycling. Following this trend, we assume a hypothetical scenario where the use of private cars is strongly limited in dense urban areas, and innovative transport modes must be used. This work investigates a futuristic system based on a network of accelerating moving walkways (AMW) to facilitate the movement of pedestrians in city centers where cars have been banned. Unlike constant speed moving walkways, AMWs can reach speeds of up to 15km/h thanks to an acceleration section. This paper presents a rigorous description of the system characteristics from a transportation point of view, develops a heuristic algorithm for the network design problem, and tests it on a real case study. Given a network of urban roads and an origin-destination demand, the optimization algorithm, which combines traffic assignment and supply modification, explores the trade-off curve between the total travel time and capital cost of the infrastructure. The results give practical insight on the possible dimensioning of the system, show the optimal network designs, and how these vary with a reduction of the available budget. This paper investigates for the first time the use of AMWs at a network scale, and provides results useful for analyzing the system feasibility. The results on travel time, investment budget and payback period, indicates that AMWs could be an effective mode of transport in cities.

Keywords: accelerating moving walkways, network design, innovative transport system, urban mobility.

1 Introduction

Vehicular traffic contributes to pollution, congestion and the risk of accidents for road users, especially in urban areas (Calthrop and Proost, 1998). For these reasons, public authorities adopt various strategies to promote a reduction of private vehicles, such as congestion charges, construction of pedestrian areas and cycling infrastructure, and incentives for public transport (Poudenx, 2008).

Moreover, the current threats to our modern societies caused by global warming, the shortage of energy supply and the population growth justify considering disruptive solutions for the mobility of people. Several municipalities have created new neighborhoods in cities where the entire mobility system strongly limits the use of private motorized vehicles. Successful examples of these areas are the car-free districts of Vauban in the city of Freiburg, Germany, and the district of Floridsdorf in Vienna, Austria (Coates, 2013; Ornetzeder *et al.*, 2008). The idea of proposing completely new transportation systems able to replace the role of private cars has been investigated for decades (Urry, 2008; Rigal and Rudler, 2014). For example, referring to private cars, Mumford (1963) states that "the only cure for this disease is to rebuild the whole transportation network on a new model".

In order to explore new modes of transport without restrictions, we assume a scenario where private vehicles are strongly limited in city centers (PCW, 2015). In this scenario, besides traditional systems like buses, metros, trams and taxis, walking and cycling play a much more important role, together with innovative systems like bike-sharing and car-sharing. In addition, futuristic modes of transport can be part of this modal mix. For example, projects of urban cable cars and personal rapid transport systems are increasingly studied as a solution for the future mobility (Brand and Dvila, 2011; Cottrell, 2005).

The focus of this project is a possible futuristic system: an urban network of accelerating moving walkways (AMW). Moving walkways, also referred to as moving sidewalks, are capable of facilitating pedestrian movements, and their use has been imagined since the late 19th century by urban planners, engineers and science-fiction writers (Asimov, 1954). The first real implementations of moving walkways were presented in exhibition events such as the *Exposition Universelle* in Paris, France, in 1900 (Avenel, 1900). Nowadays, they are mostly installed in transportation hubs such as airports and train stations. Among the possible futuristic modes of transport, we investigate AMWs because this technology is fully electric, has a low energy consumption, a high capacity and requires limited space. In many cities, the available space for transportation is scarce, and conflicts are present for the allocation of this space, which is usually primarily devoted to car traffic (Gossling *et al.*, 2016). This makes moving walkways suitable for dense city centers with a high passenger demand. Furthermore, this system could be a catalyst for a more sustainable transport system, having limited greenhouse gas emissions and promoting walking (see Section 2).

Unlike traditional constant speed moving walkways (CMW), AMWs present an acceleration section at the embarking area that accelerates passengers to a speed higher than that of CMWs. Examples of accelerating walkways show that the system can reach 12-15 km/h (Kusumaningtyas, 2009), a speed competitive against urban bus and tram services, as well as private vehicles, which travel at an average speed of 15 km/h during peak hours (Christidis and Rivas, 2012). The use of AMWs is "competitive to that of the discontinuous transport systems [such busses and light rails] when the walking time, waiting time, and dwell time in stations are taken into account" (Kusumaningtyas and Lodewijks, 2008). Kusumaningtyas and Lodewijks (2008) conclude that AMWs can be competitive thanks to their capacity, speed, energy consumption, safety and possibility to be integrated into the urban environment.

We design a network, not only individual paths, of AMWs using a heuristic algorithm, which combines traffic assignment and supply modification. Each urban road has the possibility to be equipped with an AMW. Besides AMWs on single roads, we envisage AMWs able to span over intersections without requiring disembarking and re-embarking on the next AMW. We refer to these direct links as *expressways*. This allows the study of a complex network of AMWs.

This paper has three main contributions. It is the first time that the AMW system is approached at a network scale. This innovative system is receiving increasing attention as a possible solution to reduce transfer time in transportation hubs, incentivize walking in metropolitan areas and reduce pollution. However, it has never been studied as a possible integrated transportation system at the urban scale. The second contribution is the identification of an appropriate optimization framework specific for the AMW system. Although many mathematical formulations and solution methods have been proposed in the transit and road network design fields, AMWs have particular characteristics not present in any other transport system. Thus, taking inspiration from existing approaches, we propose an adapted framework for optimizing a network of AMWs. The final contribution is given by the results on the real case study. The resulting optimized network designs cannot be considered ready-to-use configurations of the AMW system. However, they provide a valid starting point for discussions with decision makers and town planners to evaluate the potential of AMWs as a possible transport mode in urban areas. We want to underline that the present work is a fundamental research project, and it does not aim to give a practice-ready solution.

The remainder of this paper is structured as follows. Section 2 reviews the transportation characteristics of the accelerating moving walkway system. Optimization frameworks in the fields of transit network design and road network design are reviewed in Section 3. Section 4 and Section 5 propose a mathematical model and describe the solution methodology for designing a network of AMWs, respectively. The results of the optimization on a real case study are presented in Section 6. The paper closes with the main conclusions in Section 7.

2 Review of Accelerating moving walkways

Since the 1960s, several ideas on how to achieve a speed higher than that of CMWs have been proposed (Kusumaningtyas, 2009). In the 1970s and early 1980s, some of these ideas were made into prototypes of AMWs and tested. Although none of them were commercialized, their working principles were later adapted for subsequent AMW designs. Prototypes of these later designs were built and tested in the late 1990s and early 2000s. For example, in 2000 an AMW was installed in Montparnasse station in Paris, connecting the subway station to the train station (Gautier, 2000). In 2007, an AMW was built in Toronto Airport between Terminals 1 and 2 (Gonzalez Alemany *et al.*, 2007).

The topic of AMWs has received increasing attention in the scientific literature in recent years. Gonzalez Alemany and Cuello (2003), Ikizawa *et al.* (2001), Saeki (1996) and Shirakihara (1997) present the system from a technological point of view. Abe *et al.* (2001) propose a technical solution that allows the system to cover inclined or even curved routes. Rockwood and Garmire (2015) study a possible integration of AMWs with urban infrastructure. Kusumaningtyas *et al.* investigate the system from a transportation point of view (Kusumaningtyas and Lodewijks, 2008; Kusumaningtyas, 2009; Kusumaningtyas and Lodewijks, 2013). They suggest that AMWs are competitive against other modes of transport based on a comparative evaluation of their characteristics.

In the following, we define the characteristics of the AMW technology in a rigorous way. We formulate the system mathematically by reviewing the relevant literature. Then, this formulation is used by the optimization framework in Section 4.

2.1 Characteristics of the accelerating moving walkway technology

The accelerating moving walkway is functionally divided in three sections: (i) the acceleration section, (ii) the constant speed section and (iii) the deceleration section. An AMW can have one or multiple lanes. We define a single lane as an AMW with handgrips on both sides. Therefore, a multiple-lane AMW is composed of single lane AMWs of the same length side by side, with shared handgrips between adjacent lanes. We refer to an AMW installation including all its lanes as an AMW or an AMW-arc, and to a single lane as an AMW-lane.

Figure 1 shows the width, acceleration and speed profile as well as some fundamental

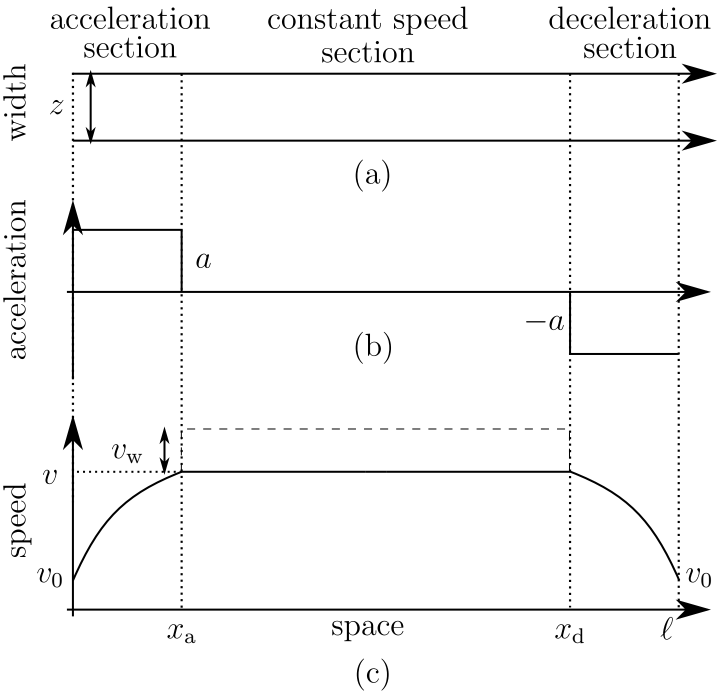


Figure 1: Accelerating moving walkway characteristics: (a) width profile, (b) acceleration profile and (c) speed profile over space.

characteristics of an AMW (Boissac and Cote, 2001). Figure 1(a) shows the top view of an AMW with a constant width z along the entire length ℓ. The width of a single lane is z_0, and the total width of an AMW is $z = xz_0$, where x is the number of AMW-lanes. The total width is slightly overestimated, because we do not consider the overlap of the handgrips. The three functional sections present different accelerations as shown in Figure 1(b). The acceleration section, from the start of the AMW to position d_{a}, is characterized by a constant positive acceleration a. The constant speed section, from d_{a} to d_{d}, has zero acceleration, and the deceleration section, from d_{d} to the end of the AMW ℓ, presents a constant negative acceleration $-a$ (deceleration). These variations in acceleration produce changes in the speed along the three sections, as observable in Figure 1(c). In the acceleration section, the speed increases from the entry speed v_0 to the maximum speed v followed by a section of constant speed, where passengers can walk at walking speed v_{w}. Then, the speed v decreases to the exiting speed v_0, which is equal to the entry speed. The speed profile is not linear in the acceleration and deceleration sections because it is plotted against space instead of time, as it is often done for motion under constant acceleration. The space representation is chosen because the design of the system is space-based and not time-based, i.e. the dimensioning of the system is based on the lengths of the different sections and not the time that passengers spend on them. This should be remembered for understanding the calculation of travel time.

As of today, technology limits some geometrical characteristics such as the minimum length $\ell_{\min} = 120$ m and the maximum length $\ell_{\max} = 350$ m. AMWs also have limitations on the maximum inclination, both uphill and downhill. The maximum inclination $\iota_{\max}$ is equal to 15 degrees. Moreover, AMWs cannot easily curve. The minimum curvature $\gamma_{\min}$ is equal to 80 m radius curves. This limitation implies that at a standard intersection, which is 11 meters wide (DfT, 2011), expressways can span over streets only if the angle between these streets is greater than 137 degrees. We define the minimum angle between streets at intersections that allows the presence of expressways as $\varphi_{\min} = 137$ degrees (Abe *et al.*, 2001; Lechner, 2011).

The entering speed v_0 is a critical parameter that has significant consequences on the speed profile, the capacity and the comfort of passengers. Constant-speed moving walkways typically operate at speeds between 0.6 m/s and 0.75 m/s, and minimum and maximum values have been set at 0.5m/s and 0.8 m/s in AMW implementations (Donoghue, 1981; Fruin, 1992). A high entry speed decreases the travel time, increases capacity and allows a shorter acceleration/deceleration section to reach the same v. However it has negative effects on safety, and it increases the discomfort of passengers. Ikizawa *et al.* (2001) show results of an experimental evaluation of the perceived danger, which can be associated with discomfort, for different entry speeds v_0.

The speed profile of real installations presents a more complex shape than the one in Figure 1. In addition to the sections shown in Figure 1, real installations have a constant speed entry section and a gradual acceleration section during which the acceleration increases from 0 m/s^2 to a (Boissac and Cote, 2001). For the present research, the presented simplified speed profile is chosen in order to have a simpler model for the optimization framework. Thus, the acceleration a is considered constant in the entire acceleration and deceleration sections. This simplification has a low impact given that the total travel time in a typical AMW is overestimated by only approximately 0.2 seconds. Acceleration is crucial for comfort and for the definition of the speed profile. High accelerations can cause imbalance, falling down and lead to a rejection of the system. The European standard on safety of escalators and moving walkways (EC, 2010) prescribes a maximum acceleration of 1 m/s^2. However, in real implementations, the acceleration varies from 0.14 m/s^2 to 0.43 m/s^2 (Dembart, 2003; Gonzalez Alemany *et al.*, 2007; Kusumaningtyas and Lodewijks, 2008, 2013).

Equation (1) defines the speed on the constant speed section v as a function of the entry speed v_0, the time spent on the acceleration section t_e and the acceleration along this section a:

$$v = v_0 + at_\mathrm{e}, \tag{1}$$

where t_e is defined by Equation (4). The speed v is subject to a constraint on the maximum speed $v_{\max}$ for safety reasons. It has been reported that v itself is not perceived as a problem by passengers because in this section there is no acceleration involved (Donoghue, 1981). The European standard on safety of escalators and moving walkways prescribes a maximum speed $v_{\max} = 4.7$ m/s (17 km/h) (EC, 2010). However, in real installations v is set between 2 m/s and 3 m/s, a value lower than the maximum allowed (Gautier, 2000; Gonzalez Alemany *et al.*, 2007).

AMWs have a constant width defined by z. Typically widths are between 0.8 and 1.6 meters (Kusumaningtyas, 2009). The width z is associated with the capacity k. The capacity, expressed in passengers per hour [pax/h] per direction, depends on the entry speed v_0 [m/s], the width of the AMW z [m] and a conversion factor for the units. The resulting empirical equation defined by CEN (1998) is

$$k = 2250v_0(5z - 1). \tag{2}$$

However, according to Kusumaningtyas (2009), travelers prefer having access to the handgrips while embarking/disembarking. This implies that the capacity is an almost constant value regardless of the width. It has been shown that a minimum of 1.2 meters is necessary to allow two lines of passengers (Davis and Braaksma, 1987; Fruin, 1992), and this value is used in existing installations (Gautier, 2000; Gonzalez Alemany *et al.*, 2007). Following this consideration, it is more appropriate to relate the capacity to the number of lanes x of an AMW rather than its width z. Fixing the width and entry speed for an AMW-lane to $z_0 = 1.2$ m and $v_0 = 0.7$ m/s respectively, the capacity of a AMW-lane is $k_0 = 7{,}875$ pax/hour, as calculated using Equation (2). We define the capacity of an AMW with x lanes as

$$k = k_0 x. \tag{3}$$

The last variable represented in Figure 1(c) is the walking speed v_w. For safety reasons associated with the acceleration and deceleration sections, pedestrians are allowed to walk only on the constant speed section of the AMW. Many studies are present on the average walking speed in free-flow (Browning *et al.*, 2006; Daamen, 2004; Levine and Norenzayan, 1999; Mohler *et al.*, 2007) and a widely used value is 1.34 m/s. Young (1999) shows that the walking speed on CMW decreases to an average of 1.04 m/s. However, we assume that with a large deployment of AMWs, pedestrians could became familiar with this technology, and they walk at the same speed both on streets and AMWs.

While the technical parameters of the system such as length, acceleration and width are fixed, the parameters associated with pedestrian movements such as walking speed vary among individuals as well as the resulting capacity on AMWs. This is due to the heterogeneity of pedestrians (Nikolic *et al.*, 2016). For example, pedestrians have different walking speeds due to differences in age, gender, trip purpose, etc. In addition, the behavior on CMWs and AMWs is different, with some passenger walking and others not. As usually done in the planning phase of infrastructure, in this work, we assume a deterministic representative value for these parameters, and we do not consider their distributions.

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. To compute the overall travel time on an AMW, denoted by t_a, we first compute the embarking time, which is the time spent on the accelerating part:

$$t_\mathrm{e} = \frac{v - v_0}{a}, \tag{4}$$

which gives the embarking distance, i.e. the length of the acceleration section:

$$d_\mathrm{a} = \frac{1}{2} a t_\mathrm{e}^2 + v_0 t_\mathrm{e} = \frac{v^2 - v_0^2}{2a}. \tag{5}$$

Finally, considering that embarking and disembarking are symmetric, and adding the travel time on the constant speed part, we get:

$$t_\mathrm{a} = \frac{\ell - 2d_\mathrm{a}}{v + v_\mathrm{w}} + 2t_\mathrm{e}. \tag{6}$$

Equation (6) gives the travel time of a single passenger over an AMW. Therefore to obtain the total travel time, it should be multiplied by the flow of passengers, which we denote by q. We define the total travel time on an AMW as:

$$T = t_\mathrm{a} q. \tag{7}$$

The equations of travel time, capacity and speed are valid in the absence of congestion. We discuss the role of congestion in Section 4.

Kusumaningtyas (2009) reports that an AMW requires three times more energy than a CMW, but no link function has been established between energy consumption of an AMW and its high speed v, or its acceleration section length d_{a}. However, a functional relationship between energy consumption and speed profile is needed for our study, as it will be further explained in Section 4. We can estimate the energy consumption of an AMW (per unit of flow) using the following consideration. Assuming that the augmentation of energy consumption is proportional to the high speed v, an interpolation can be made. We assume that:

$$e_{\mathrm{a}} = (1.25v + 0.1815)e_{\mathrm{c}}, \tag{8}$$

where e_{c} is the energy consumption of a CMW, and e_{a} is the energy consumption of an AMW. Given that CMWs have an entry speed $v_0 = 0.65$ m/s with an energy consumption of $e = 1e_{\mathrm{c}}$, and existing installations of AMW have $v = 2.25$ m/s with reported $e = 3e_{\mathrm{c}}$, Equation (8) is the resulting linear regression on these values. Note that the energy consumption on CMWs and AMWs has the unit of energy per passenger per length. This is due to the fact that the energy consumption depends on both the length of the moving walkway and the number of passengers. If more passengers use the moving walkway, the energy consumption increases due to the increased weight.

Considering the average cost of electrical energy in Euro per megajoule, estimated at $c_{\mathrm{e}} = 0.06$ EUR/MJ (BFE, 2012), and the energy consumption of a CMW in megajoule per passenger per meter, estimated at $e_{\mathrm{c}} = 3.5 \cdot 10^{-4}$ MJ/pax·m (Kusumaningtyas, 2009), the cost related to the energy consumption for operating an AMW per unit of time is:

$$c_{\mathrm{a}} = (1.25v + 0.1815)e_{\mathrm{c}}c_{\mathrm{e}}\ell q, \tag{9}$$

where q is the flow of passengers.

Knowing that the capital of an AMW is about 20% more than a CMW (Kusumaningtyas, 2009), a similar consideration to the energy consumption can be applied to estimate the capital cost, denoted by c. The resulting function from a linear regression is:

$$c = (0.125v + 0.9188)\, c_{\mathrm{c}}\ell n, \tag{10}$$

where, $v = \sqrt{v_0^2 + 2ad_{\mathrm{a}}}$ from Equation (5), and c_{c} is the capital cost of a CMW.

To facilitate the comparison between AMWs and other modes of transport, we report the average speed, capacity, capital and operational cost, and corridor width for buses in mixed traffic, light rail services and AMWs in Table 1. We start from the main findings of the comparison made by Kusumaningtyas and Lodewijks (2008). Given that the literature on AMWs is present since 1977, we updated the costs according to the price inflation of cost index values such as capital and electricity costs, and commodities price indexes in Switzerland (FSO, 2016). We compare the costs of the bus and light rail systems implemented in the city of Geneva, Switzerland (TPG, 2014). From the data in Table 1, we conclude that AMWs have a speed competitive with urban bus and tram services. Although buses and trams have higher top speeds, the discontinuous nature of these systems decreases their average speed. Note that individuals can walk on AMWs, incrementing the top speed to 15-17 km/h. The resulting speed is also competitive with private cars, which travel at an average speed of 15 km/h during peak hours (Christidis and Rivas, 2012). AMWs are designed for a high traffic demand, and they have a maximum capacity larger than buses, but still lower than light rail services. In comparison with buses, AMWs have a greater capital cost and a similar operational cost. This is due

Table 1: Comparison among the characteristics of transport systems.

System	Average speed [km/h]	Capacity [pax/h]	Capital cost [M EUR/km]	Operational cost [EUR/pax-km]	Corridor width [m]
Bus	15-20	1,000- 5,000	0.3-13.4	0.09-0.95	3.0-4.2
Light rail	15-45	1,000-30,000	8.5-83.5	0.07-0.28	2.5-3.2
AMW	5-12	4,500- 8,000	20.4-88.2	0.08-0.59	1.2-2.3

to the fact that buses use the already built infrastructure if operated in mixed traffic. AMWs require only a limited space for installation in comparison with the other modes of transport. This is an advantage for the integration of the system in the urban environment. Finally, AMWs are fully electric, they have a low energy consumption and a low noise level in comparison with the other modes of transport (Kusumaningtyas and Lodewijks, 2008).

The presented characteristics, parameters and the technological limitations of AMWs may change in the future. In particular, the capital cost could drastically decrease with a large deployment of AMWs. However, although we are designing a futuristic transportation system, we decide to design it based on today's technology.

2.2 Intersections of accelerating moving walkways

Before introducing the assumptions on the intersection design, notice that there are two possibilities to cross an intersection. Either the AMW reaches its end, and the passenger disembarks the current AMW and embarks on the next one, or the AMW allows going straight to the next stretch of road without disembarking. We call such AMWs *expressways*. An expressway is an accelerating moving walkway that spans over several roads without decelerating at intersections and without the possibility to disembark.

The use of expressways for going straight not only eases the traffic by reducing the amount of people involved in the transfer zone, but also significantly reduces the travel time. We can compute the difference in travel time if we use an expressway to get through an intersection without decelerating, and the time taken to disembark, walk the intersection, and then embark on the next AMW until we reach the top speed again. To quantify this difference, we assume the following values for the AMW characteristics, i.e. $v_0 = 0.7$ m/s, $v = 4.7$ m/s and $a = 0.4$ m/s^2, a pedestrian speed of $v_\mathrm{w} = 1.34$ m/s and a standard length of 11 meters for a two-way vehicular intersection (DfT, 2011). A walking pedestrian on an expressway takes 10.8 sec to travel the resulting 65 m (2 $\times$ 27 m for the deceleration/acceleration section calculated using Equation (5) + 11 m for the intersection), while the process of disembarking, walking and re-embarking takes 28.2 sec for the same distance. This gives a travel time reduction of 17.4 sec (62%) for each intersection using expressways. This significant reduction in travel time motivates the study of possible intersection designs in a network of AMWs, and the inclusion of expressways in the optimization process.

No literature is present on possible intersection designs for CMWs or AMWs. Thus, we study existing configurations of embarking/disembarking and intersection systems from other technologies, and we propose hypothetical designs. Inspiration is drawn from reviewing solutions implemented for conveyor belts used for goods (Alspaugh, 2008), futuristic ideas of intersections for pedestrian and vehicular traffic such as the cross intersections, rotating platforms, circular walkways, and real life implementations (DfT, 2011).

Analyzing similarities and differences, we envisage several designs, from a simple approach where everyone is slowed down, to a complex intersection with multiple expressways at different levels. We refer to Rojanawisut (2015) for a detailed review of the intersection designs. The optimal intersection design is not part of the optimization framework. In addition, the implications on the slope of AMWs in the case of multiple-layer intersections are not considered. The only assumption used in this work is the possibility to have multiple expressways spanning over an intersection, independently from the design itself.

3 Review of network design

To the best of our knowledge, the design of a network of AMWs has not been proposed in the literature. However, several network design problems for various transportation modes have been proposed. We review them here.

The AMW system can be seen from two different perspectives. The first one is to consider an AMW as a vehicle with constant availability (or infinite frequency). In this sense, the problem of finding where to put AMWs on the roads has similarities with the problem of identifying the best bus lines in a city. The second perspective is to consider an AMW as a parallel shortcut road. Indeed, using an AMW shortens the time taken to travel through the road. Similar to roads, they are constantly available. Building an AMW would thus be similar to adding a new road, and the width characteristic of AMWs is identical to the width of roads. Following these two perspectives, we first explore the literature on the transit network design problem (TNDP), which aims to improve public transport by optimizing routes, frequencies and timetables, and then, we focus on the road network design problem (RNDP), which deals with finding where to build new roads or expand existing ones. This section aims to review the mathematical modeling formulations and the solution methods in order to identify the most appropriate approach for the optimization of a network of AMWs.

3.1 Transit network design problem

If we consider AMWs as bus lines, the optimization problem can be seen as a TNDP. Three of the fundamental elements of transit planning are (i) the design of routes, (ii) the setting of frequencies and (iii) the timetabling (Guihaire and Hao, 2008). Following the global reviews of Desaulniers and Hickman (2007), Fan and Machemehl (2006), Farahani *et al.* (2013), and Guihaire and Hao (2008), we can identify the following aspects.

The models dealing with this design problem can be categorized as *single-modal* network design problems and *multi-modal* network design problems (MMNDP), with regard to the number of transportation modes considered. Within the MMNDP, we have *bi-modal* network design problems (BMNDP) that can be split into two sub-categories: *single-mode* trips, and *combined-mode* trips.

The interactions between the flows, the transportation modes and the decisions are also categorized as *no interactions* between flows of different modes, *flows & modes interactions* and *flows & decisions interrelations* where road network design decisions are considered. For example turning a two-way street into a one-way street affects the bus routes on that street.

The TNDP is a *bi-level* problem or a *leader-follower* problem. The upper-level problem, or leader problem, is the network design problem. The lower-level, or follower problem, is the problem of computing the travelers' modes and routes. The network design problem considers the travelers' reaction but has no direct control on their choice. On the other hand, travelers react to the current network design after the network is built.

The lower-level *trip assignment problem* can also be categorized based on the transportation mode used (roads or transit lines), the route choice behavior (user equilibrium or system optimal), congestion (congested or uncongested, i.e. all-or-nothing), the class of travelers (single or multiclass), and the choice of transportation mode (uni-modal or multi-modal).

The planning problem is multi-objective considering both the demand and financial aspects. Several approaches have been developed, dealing with different constraints and objectives. Given an origin-destination demand, a geographical area with the topology of the road network and a set of busses and drivers, the objective is to find the set of lines and associated timetables. The resulting problem is NP-hard even if the forming sub-problems are considered independently (Magnanti and Wong, 1984).

A large number of different mathematical formulations have been proposed to solve this category of problems. Bookbinder and Desilets (1992) propose a quadratic semi-assignment problem focusing on minimizing the "inconvenience" of passengers while transferring between lines. Klemt and Stemme (1988) use a similar approach while keeping the investment constant and assuming cyclicity in the timetables. Deb and Chakroborty (1998), and Jansen *et al.* (2002) formulate the problem using mixed integer non-linear programming with continuous variables for the arrival and departure times. The objective is to minimize the total waiting time of transferring and non-transferring passengers. The use of multi-commodity flow models based on passenger routes is proposed by Borndörfer *et al.* (2005), where the public transport lines are generated dynamically.

Several solution methods have been proposed to solve the TNDP. Exact methods are used when the problem can be formulated as a mathematical model. For example, Constantin and Florian (1995) propose a non-linear non-convex mixed integer programming model and use a projected sub-gradient algorithm to find the solution. The main limitations of exact methods are their limited flexibility and the strong assumptions that should be made to simplify the problem. For these reasons, heuristic and metaheuristic methods are generally preferred (Reeves, 1993). *Ad hoc* heuristic approaches are developed often following a greedy logic. Sonntag (1977) starts with a network containing a line for each origin and destination. Then, lines are removed in an iterative process until an appropriate size network is found. Mandl (1980) adopts a similar approach, but an empty network is used as a starting point. Neighborhood search methods such as simulated annealing and tabu search, and their integration are investigated by Zhao and Ubaka (2004). In the category of evolutionary search methods, Chakroborty and Wivedi (2002) present a method to evaluate the fitness function of a candidate solution based on different criteria such as total travel time and number of total transfers. Deb and Chakroborty (1998) propose a genetic algorithm to identify additional routes for an existing network.

3.2 Road network design problem

The second perspective of the problem considers AMWs as parallel shortcut roads and solves a RNDP. In this field, Yang and Bell (1998) offer an overview of the different approaches with specific focus on road network design, while Farahani *et al.* (2013) present a broader review of urban transport network design problems.

The majority of road network design problems deal with improvement of the existing road networks and consider only a single mode of transport. The main inputs are the network topology, the street characteristics and the origin-destination demand. The constraints incorporate budget limitations, political considerations such as maximum increase in capacity, and space limitations. A discrete or a continuous mathematical formulation can be established, depending on whether the capacity is considered in terms of number of lanes or in terms of width. Dimitriou *et al.* (2008), and Gallo *et al.* (2010), propose examples of discrete models, while Drezner and Wesolowsky (2003), and Miandoabchi and Farahani (2011) of continuous formulations. Mathew and Sharma (2009), and Wang and Lo (2010) model the system with a mix of discrete and continuous variables. Time-dependent models have also been proposed considering dynamics in the demand and land use (Lo and Szeto, 2009; O'Brien and Yuen, 2007). For discrete and mixed models, the resulting problem is NP-hard and non-convex.

Like for the TNDP, solution methods for the RNDP can be classified into exact methods, heuristics and metaheuristics. Exact methods can be applied only to small and medium-sized problems. Drezner and Wesolowsky (2003), and Long *et al.* (2010) use variations of branch-and-bound. Heuristics and metaheuristics such as simulated annealing and genetic algorithms have a higher computation speed, and they can be used for larger problems. A vast range of heuristic and metaheuristic approaches has been developed. For example, Marcotte and Marquis (1992) propose a heuristic based on an iterative optimization and assignment method, and Mathew and Sharma (2009) use a genetic algorithm where the budget limit is the main constraint. Marcotte (1986) proposes to solve the network design problem using bi-level programming. This methodology can be interpreted as a generalization of the min-max problem, and the network design can be accommodated into this framework without separating the traffic assignment and network modification phases (Colson *et al.*, 2007).

Yang and Bell (1998) review three different heuristic approaches: the iterative optimization assignment algorithm (Asakura and Sasaki, 1989), the link usage proportion based algorithm (Yang, 1997) and the sensitivity analysis based algorithm (Friesz *et al.*, 1990). These three seemingly different approaches share the same iterative structure. The first step is to assign the demand to the network solving a traffic assignment problem. The second step updates the road network modifying the infrastructure using specific logic, e.g. a greedy algorithm. The two steps are repeated until the stopping criteria are met, e.g. no further decrease in travel time. The algorithm returns an optimized road network.

3.3 Specificities of a network of AMWs

Since AMWs are a new transportation system, the scientific literature does not classify this system in any of the reviewed categories. The AMW system presents specific characteristics that are not shared with traditional transport modes. Based on the AMW system characteristics, we identify our problem as:

- Network design and capacity setting problem. Where the capacity, i.e. the width of AMWs, could be equivalent to setting the frequency of a transit system, or a road capacity.

- Multi-modal with combined-mode trips. Travelers can walk or use an AMW in different sections of their routes.
- There is no interaction between the flows of the different modes. The fact that people walk next to an AMW does not affect the dynamics on the AMW and vice versa.

From a vehicle-like perspective, according to different reviews on the TNDP, few papers directly address our multi-modal transit network design and frequency setting problem with independent flows and fixed demand. Those papers generally use heuristics and metaheuristics like genetic algorithms, simulated annealing or tabu search. These approaches focus on the identification and selection of core-lines through the network, together with finding their capacity. However, the notion of core lines does not make so much sense when considering an AMW network, since an AMW cannot turn easily and can only cover a small amount of consecutive roads. Each AMW should be considered as a different bus line, but no single AMW is expected to satisfy a specific origin-destination demand completely, as is the case for bus lines. Moreover, in our case, the presence of expressways creates extra complexity, which is not included in the reviewed papers.

For this reason, road network design approaches are more suitable for our case. From a road-like perspective, several papers have studied heuristics for solving the RNDP. However, we need to adapt the existing approaches to our specific case, and none of the reviewed methods could be used directly. Due to these differences, this paper proposes a framework suitable for the optimization of a network of AMWs taking inspiration from the algorithms used for road network design.

4 Optimization framework

Given a network of interconnected roads and an origin-destination demand, we are looking for the configuration of a network of accelerating moving walkways that satisfies the travel demand with the minimal travel time for different capital costs. We want to investigate the trade-off curve between the total travel time and the capital cost. This Pareto front indicates the possible travel time saving for different levels of investment in building a network of AMWs. It is important to investigate total travel time and capital cost jointly. Otherwise, ignoring costs, the optimal solution is to build an expressway for each individual OD pair. On the other hand, ignoring travel time, the optimal solution is to build nothing. Both this extreme solutions are investigated and used as benchmarks.

To do so, for each road, we decide whether the road is equipped with an AMW, and if so, we determine its capacity. The capacity is determined by the number of parallel AMW lanes x, all having the same standard width z_0. In the scope of this study, the only metric for traveler satisfaction is the total travel time as defined by Equation (7). No other aspects, such as comfort or safety, are considered. We consider only the capital costs as defined by Equation (10). Other costs, for example operational costs, are disregarded being several orders of magnitude lower. For the sake of simplicity, the interactions with other modes of transport are ignored. Passengers can only walk or use AMWs.

We identify the AMW network designs on the Pareto front using the optimization framework summarized in Figure 2. The details of the framework and a rigorous description of the components are presented in the next sections. Here, we provide a general overview. We start building a graph, denoted by $\mathcal{G}$, representing the road network with

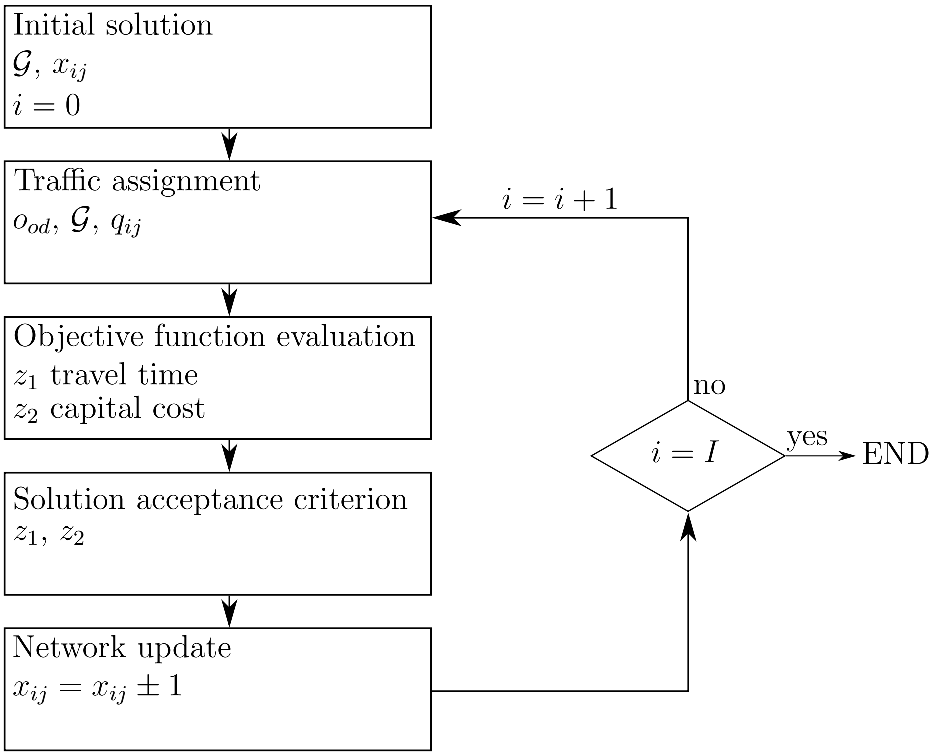


Figure 2: Optimization framework main components.

an initial configuration of AMW-lanes on each arc, denoted by x_{ij}. We set a counter $i = 0$ to keep track of the number of iterations of the optimization algorithm. The second step is a traffic assignment. Given the demand of passenger for each origin and destination, denoted by o_{od}, and the graph $\mathcal{G}$, the traffic assignment calculates the flow of passengers on each arc, denoted by q_{ij}. Then, the objective functions are calculated, namely the travel time, z_1, and the capital cost, z_2. The quality of the network design is evaluated based on an acceptance criterion. If the current solution is better than the previous evaluated solutions (not dominated), this new network is accepted and added to the current set of Pareto optimal solutions. The network design of the last accepted solution is modified in the "network update" phase. In this phase, an AMW-lane is added or removed from a randomly selected arc. When the maximum number of iterations, denoted by I, is reached, the procedure ends and returns all evaluated solutions, as well as the solutions on the Pareto front.

In the following sections, we describe the different components of the optimization framework. First, we introduce the procedure used to model the road network and build the graph $\mathcal{G}$. Then, we define the model representing the optimization problem with the two objective functions z_1 and z_2. The methodology used to solve the optimization model, including the traffic assignment, the network update and the acceptance criterion are presented in Section 5.

4.1 Network model

To model the multi-modal aspect of the problem, i.e. the fact that travelers can either walk on the street or on an AMW, we use a graph combining AMW arcs and walking arcs. Formally, we define the problem on a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{A})$ representative of the road network. We assume that the road network is connected, i.e. every pair of nodes is connected with a path. $\mathcal{N}$ is the set of nodes, and $\mathcal{A}$ is the set of arcs. Each node in the set $\mathcal{N}$ represents an intersection in the road network, an origin or a destination. The set of arcs $\mathcal{A}$ contains both the set of walking arcs $\mathcal{A}^{\mathrm{w}}$ and the set of AMW arcs $\mathcal{A}^{\mathrm{a}}$ that can be equipped with an AMW. Thus, $\mathcal{A} = \mathcal{A}^{\mathrm{w}} \cup \mathcal{A}^{\mathrm{a}}$. Expressway arcs spanning over all feasible intersections are included in the set $\mathcal{A}^{\mathrm{a}}$. It is assumed that an AMW-arc can be completely equipped or not equipped with an AMW. It is not possible to have an AMW partially covering the length of an arc, therefore ℓ indicates both the length of the physical street and the length of the AMW on the arc. Additional nodes are added to $\mathcal{N}$ in the case specific embarking/disembarking points or origin/destination nodes are needed.

The graph $\mathcal{G}$ contains all possible configurations of AMWs and walking routes. In order to create $\mathcal{G}$, we use the following procedure.

Step 1: nodes. The road network of a case study, e.g. a city center, is mapped into nodes and arcs. Each intersection and origin/destination is added to the set of nodes $\mathcal{N}$.

Step 2: walking arcs. Each road connecting two nodes is represented as two arcs, one arc per direction. We define an arc connecting node i to node j as (i, j). Therefore, for each road we add two arcs, (i, j) and (j, i), to the set of walking arcs $\mathcal{A}^{\mathrm{w}}$. This implies that pedestrians can always walk on roads in both directions.

Step 3: AMW arcs. Then, we add all feasible AMWs for each direction to the set $\mathcal{A}^{\mathrm{a}}$, conditionally to the geometrical constraints, reviewed in Section 2. AMWs always follow existing roads, i.e. the walking arcs in $\mathcal{A}^{\mathrm{w}}$. The constraints to respect are different for AMWs that connect two adjacent intersections, referred to as elementary AMWs, and expressways, which span over several intersections.

a. Elementary AMWs. In case of elementary AMWs, a direct road from node i to node j must exist, i.e. i and j are adjacent and $(i, j) \in \mathcal{A}^{\mathrm{w}}$. The length of the walking-arc, which is equivalent to the length of the AMW-arc, has to be between $\ell_{\min}$ and $\ell_{\max}$.

b. Expressways. In case of expressways, a set of connected roads between the non-adjacent node i and node j must exist. None of the angles at the intersections between the roads from i to j should be lower than the minimum allowed angle $\varphi_{\min}$. The sum of the length of the arcs in the sequence should be between $\ell_{\min}$ and $\ell_{\max}$. In case multiple different paths are possible for the construction of an expressway between two intersections, i.e. nodes, we choose the shortest one in terms of distance.

The graph created with the described procedure defines the search space of the problem. Based on this representation, the problem is narrowed down to finding which of the AMW arcs should be equipped, and if so what is the capacity, given that the geometrical constraints have already been incorporated in the graph $\mathcal{G}$. The decision variables are the number of AMW-lanes, $x_{ij} \in \mathbb{N}_0$, for each AMW-arc in the set $\mathcal{A}^{\mathrm{a}}$. The streets that cannot accommodate AMWs are excluded from the set $\mathcal{A}^{\mathrm{a}}$. For example, streets with geometrical limitations, or reserved exclusively for public transport, vehicular, bike or pedestrian traffic.

4.2 Optimization model

This section develops the mathematical model for our optimization problem. It introduces the parameters, decision variables, objective function and constraints.

The optimization problem sets are:

$\mathcal{N}$	set of nodes
$\mathcal{A}$	set of walking and AMW-arcs

The optimization problem parameters are:

v_{w}	walking speed [m/s]
a	AMW acceleration [m/s^2]
v_0	AMW entry/exit speed [m/s]
v	AMW top speed [m/s]
z_0	width of an AMW-lane [m]
k_0	capacity of an AMW-lane [pax/h]
c_{c}	capital cost [EUR/m]
$q_{ij}(x_{ij})$	the flow of passengers on the arc (i,j), $\forall(i,j) \in \mathcal{A}$ [pax/h]

The decision variables are:

x_{ij}	number of AMW-lanes on the AMW-arcs (i,j), $\forall(i,j) \in \mathcal{A}^{\mathrm{a}}$ ($x_{ij} \in \mathbb{N}_0$, integer)

x_{ij} indicates both if the arc $(i,j) \in \mathcal{A}^{\mathrm{a}}$ is equipped with an AMW, i.e. $x_{ij} > 0$, or not, i.e. $x_{ij} = 0$, and the capacity of the AMW [pax/h]. The capacity k_{ij} is expressed on a discrete scale using the number of AMW-lanes on the arc, considering that they all have the standard width z_0 and capacity k_0.

As already mentioned, we want to investigate the Pareto front between travel time and capital cost. This implies having two conflicting objectives, minimizing the travel time and minimizing the capital cost. The objective function for the total travel time is:

$$\min \quad z_1 = \sum_{(i,j)\in\mathcal{A}} t_{ij}(v, v_0, v_{\mathrm{w}}, a, \ell_{ij}) q_{ij}(x_{ij}), \tag{11}$$

where the travel time t_{ij} on AMW arcs (i,j) is defined by Equation (6), and the travel time on walking arcs is simply the time needed to walk the arc, i.e.

$$t_{ij}^{\mathrm{w}}(\ell_{ij}, v_{\mathrm{w}}) = \ell_{ij}/v_{\mathrm{w}}. \tag{12}$$

The objective function for the total capital cost is:

$$\min \quad z_2 = \sum_{(i,j)\in\mathcal{A}^{\mathrm{a}}} c_{ij}(x_{ij}, \ell_{ij}), \tag{13}$$

where the cost c of a AMW-lane is defined by Equation (10).

The two objective functions have no associated constraints. This is due to the fact that the geometric constraints regarding the length, angle and inclination of possible AMWs are included in the graph $\mathcal{G}$.

The flows of passengers $q_{ij}(x_{ij})$ on the directed arc $(i,j) \in \mathcal{A}$ are specified as external parameters in Equation (11). They are obtained by an assignment algorithm that assigns the demand to the graph $\mathcal{G}$. The resulting flows are a function of the graph characteristics including the decision variables x_{ij}, i.e. the number of AMW-lanes on each arc. It is the traffic assignment that relates the flows q_{ij} to the decision variables x_{ij} solving a shortest path problem. This modeling choice of decoupling the mathematical model and the traffic assignment is done to ensure a flexible framework. In this way, the mathematical model of the problem is completely separated from the specific implementation of the traffic assignment, and only the flows q_{ij} are shared between the two. In Section 5.1, we describe the traffic assignment.

The problem is a multi-objective optimization with two objectives z_1, i.e. travel time, and z_2, i.e. capital cost. There are different possibilities to investigate the trade-off curve between these two conflicting objectives (Deb, 2014). One example is to convert the multiple-objective problem into a single-objective optimization problem using weights, and then varying them in order to explore the Pareto front. Another example is to use one of the objective function as a constraint, and optimize the other objective while varying the value of the constraint on the first one. We use an acceptance criterion based on non dominated solutions on the trade-off curve that evaluates both travel time and capital cost of the solution. In Section 5.3, we describe this procedure.

5 Solution methodology

Heuristic and metaheuristic methods are mostly used to solve the problem of network design, as shown in Section 3. We propose an algorithm with a structure similar to the ones used in the field of road network design. This algorithm has two main steps: traffic assignment and network update. The traffic assignment is used to calculate the flows q_{ij} on the network with a defined configuration of AMWs specified by x_{ij}. The flows are used to calculate the total travel time associated width the first objective in Equation (11). The network update modifies the current network, and this new solution is evaluated by the acceptance criterion.

5.1 Assignment algorithm

The mathematical model is general enough to accommodate any classical traffic assignment procedure that returns the flows on the network arcs, such as the Frank-Wolfe algorithm (Frank and Wolfe, 1956). These procedures rely on the existence of a relationship between the volume of traffic and the travel time, which increases with an increase in volume. Unfortunately, this function for AMWs is not available in the literature. For this reason, we use an heuristic procedures based on the shortest path assignment (Christofides, 1975). We take into account congestion and arc capacity by splitting the demand, as explained below.

The passenger demand is defined by an origin-destination matrix. All origins and destinations are nodes in the set $\mathcal{N}$. The demand matrix indicates the number of passengers, defined by o_{od}, going from the origin node o to the destination node d for all origin-destination pairs in the set $\mathcal{O} \subseteq \mathcal{N}$, in a fixed time horizon.

Before describing the assignment procedure, we remind that the graph $\mathcal{G}$ contains both walking arc and AMW arcs. Every walking arc has an infinite capacity, and every AMW-arc has capacity k_{ij}. For each origin-destination (OD) pair, we identify the shortest path, in terms of travel time, connecting o to d in the graph $\mathcal{G}$. If all AMW-arcs in the path have enough residual capacity, the flow associated with the individual OD pair, i.e. o_{od}, is assigned entirely on the arcs forming the shortest path. The resulting total flow of on each arc is the sum of all already assigned o_{od} pairs passing by the arc. In case, one or more AMW-arcs in the shortest path do not have enough capacity to accommodate entirely the o_{od}, only the fraction of flow equal to the minimum residual capacity on the path is assigned. The shortest path of the unassigned demand is recalculated ignoring the AMW-arcs at full capacity, and assigned to the next available shortest path. Given that walking arcs have infinite capacity and the original road network is connected, the demand is always fully assigned.

The resulting assignment depends on the order in which the OD pairs are processed. However, given the great number of OD pairs, each of them carries a limited demand. This limits the sensitivity of the resulting assignment to the order of the ODs.

5.2 Network update algorithm

The second step of the solution methodology is the network update. The goal of this step is to add or remove AMW-lanes in order to move to a new solution.

In our case, we start with the graph $\mathcal{G}$ equipped with all feasible AMWs. The initial number of AMW-lanes, i.e. the decision variables $x_{ij}, \forall (i,j) \in \mathcal{A}^{\text{a}}$, is set by performing an assignment without imposing limits on the AMW capacities. The number of AMW-lanes on each AMW-arc is set equal to the minimum number of AMW-lanes that can accommodate the resulting flow.

From this initial solution, we adopt a strategy similar to the Variable Neighborhood Search (VNS) (Mladenovic and Hansen, 1997). We define four neighborhood structures, i.e. simple operations to modify the current network:

Remove-random-lane: removes an AMW-lane on a AMW-arc (i,j) selected randomly with an uniform probability among the AMW-arc that have $x_{ij} > 0$. Formally, $x_{ij} = x_{ij} - 1$.

Add-random-lane: adds an AMW-lane on a AMW-arc (i,j) selected randomly an uniform probability among the AMW-arc that are utilized at full capacity. Formally, $x_{ij} = x_{ij} + 1$. An AMW-arc is utilized at full capacity when the flow of passengers on the arc is equal to its capacity.

Remove-worst-lane: removes the *worst* AMW-lane. The worst AMW-lane is the least used lane in the network. This means that removing this lane will increase the total travel time in the network the least. An AMW-lane is removed from the associated AMW-arc (i,j), i.e. $x_{ij} = x_{ij} - 1$.

Add-best-lane: adds the *best* AMW-lane. The best AMW-lane is the lane whose addition will decrease the total travel time in the network the most. An AMW-lane is added to the associated AMW-arc (i,j), i.e. $x_{ij} = x_{ij} + 1$.

The first two operators ensure a diversification of the tested solutions, removing and adding AMW-lanes randomly. On the other hand, the last two operators follow a greedy approach toward a local optimum. The worst/best AMW-lanes are selected using bounds on the loss/gain related to their removal or addition, respectively. This logic is inspired by the second heuristic for finding an optimal subset of routes by Dubois *et al.* (1979). To identify the *worst* AMW-lane, we assume that all travelers who were on an AMW-lane that is removed will walk on the road instead, and the ones on expressways will use the elementary AMWs resulting from the breaking up of the expressway. This gives an upper bound on the possible loss associated with the removal. The calculated loss is the upper bound because if a shorter alternative path exists, the passengers will use it. More precisely, for each AMW arc, we compute the maximum loss in total travel time u_{ij} if we remove the least used AMW lane on the arc. For example, if there are $Q = 3k_0 + q$ passengers on an arc with 4 lanes ($q < k_0$), we are interested in the loss related to the removal of the 4^{th} lane, which is partially used by q passengers. The travel time loss is calculated differently for elementary AMWs and expressway lanes. For expressways, we consider the time loss obtained when breaking the expressway intersections but keeping the sequence of AMW spanning over the single arcs. Meanwhile, for elementary AMWs, we compute the time loss assuming that travelers walk on the road instead. Similarly, to identify the *best* AMW-lane, we calculate the flow that would like to use each AMW-arc, and we identify the gain in travel time if an AMW-lane was added. To calculate this flow, we use the information of the previous traffic assignment. For each OD pairs that was not assigned to its first shortest path due to capacity constraints, we keep the information on the fraction of the flow that was diverted to other paths. We define $\bar{q}_{ij}^{od}$ as the fraction of flow from o to d that is diverted from the arc (i, j). The sum of all ODs re-directed from their first shortest path gives the flow that would like to use each AMW-arc, i.e. $\sum_{(o,d)\in \mathrm{OD}} \bar{q}_{ij}^{od}$.

Using these four neighborhood structures, we iteratively transform the network. The type of modification to perform to the solution is selected randomly with a uniform distribution among the four neighborhood structures. We denote by I the total number of modifications done to the network, i.e. the number of solutions explored.

Traffic is reassigned every r steps, and not at every network update. This is because the traffic assignment is computationally expensive. Thus, the speed of the algorithm is highly correlated to its update frequency. In case $r > 1$, r network modifications are performed before the flows are recalculated.

5.3 Acceptance criterion

After each traffic assignment, we decide if to accept the modified network as a new solution, or reject the modifications done and test r new modifications. We use a filter approach on the Pareto front as the acceptance criterion. If the new solution is not dominated by any other previous solution on the trade-off curve between total travel time and total capital cost, the solution is accepted, otherwise it is rejected. This procedure links the two conflicting objective functions z_1 and z_2 in Equation (11) and Equation (13), respectively. Figure 3 illustrates the acceptance criterion.

We have tested several variations of the solution methodology to evaluate the performance and the sensitivity of the solution to the parameters. Examples of these variations are: (i) reassign traffic every time that an expressway is divided into its elementary AMWs; (ii) progressively reduce the expressway length by removing the least important elementary component instead of dividing it into its elementary AMWs; (iii) start with an empty network and iteratively build AMWs on the network, instead of removing AMWs from a complete network; (iv) variations of the acceptance criterion such as randomly accepting solutions that are dominated. Synthetic networks with interesting characteristics (non-trivial shortest paths, multiple potential expressways and a small but reasonable number of intersections) and different synthetic OD matrixes have been used to see if the variations and the demand structure influence the performance of the algorithm. In addition, different tests regarding the choice of the reassignment period have been made. The different algorithm variations exhibit similar performance (Rojanawisut, 2015).

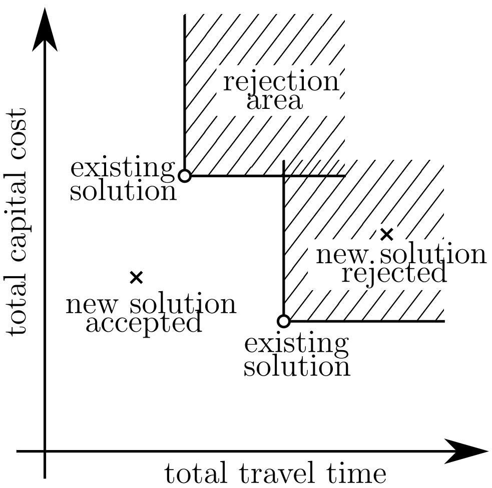


Figure 3: Acceptance criterion of new solutions. New solutions dominated by existing solutions are rejected.

6 Case study

We apply the optimization algorithm to a real case study. Even though real world data are used as input, this work has no ambition of engineering a realistic system. The idea is to explore the concept of an AMW network on a case study resembling the real world.

Geneva, Switzerland, is chosen given its road network and demand characteristics. The city has a population of about 200,000 inhabitants, an area of 15.9 km^2 and is mostly flat. One interesting feature is the large number of commuters entering the city in proportion to its size.

The aim is to explore the network designs of AMWs for the morning peak hour. This section first introduces the parameter values and the input data needed, i.e. the OD demand and the road network, then it presents the resulting optimized AMW networks on the Pareto front.

6.1 Parameter values and data

Section 2 reviews the parameters related to AMWs. In some cases, a range of values for each parameter is given. For these cases, we set a parameter value using the following considerations. As a trade-off between travel time and comfort, we choose $v_0 = 0.7$ m/s (2.5 km/h). Assuming a development in the technology, we set the maximum speed to the upper bound $v = 4.7$ m/s. Given the limitation on safety, we set $a = 0.43$ m/s^2. We assume that in a future where AMWs will be widely used, the walking speed on AMWs is closer to the normal free-flow walking speed, the passengers being more comfortable using this system. Therefore, the value of 1.34 m/s (4.8 km/h) is chosen for v_{w}. We set the capital cost equal to the lower bound proposed by Kusumaningtyas (2009), $c = 34.8$ M EUR/km.

For the optimization algorithm, we chose the re-assignment period $r = 10$ and the number of iterations i =10,000 as a trade-off between accuracy and computation time. The resulting computation time is of 30 hours on a 64-bit operating system with an eight-core processor 2.70 GHz.

The road network is provided by the geographical information system of the canton of Geneva (SITG, 2015). As shown in Figure 4(a), it classifies the roads into three categories

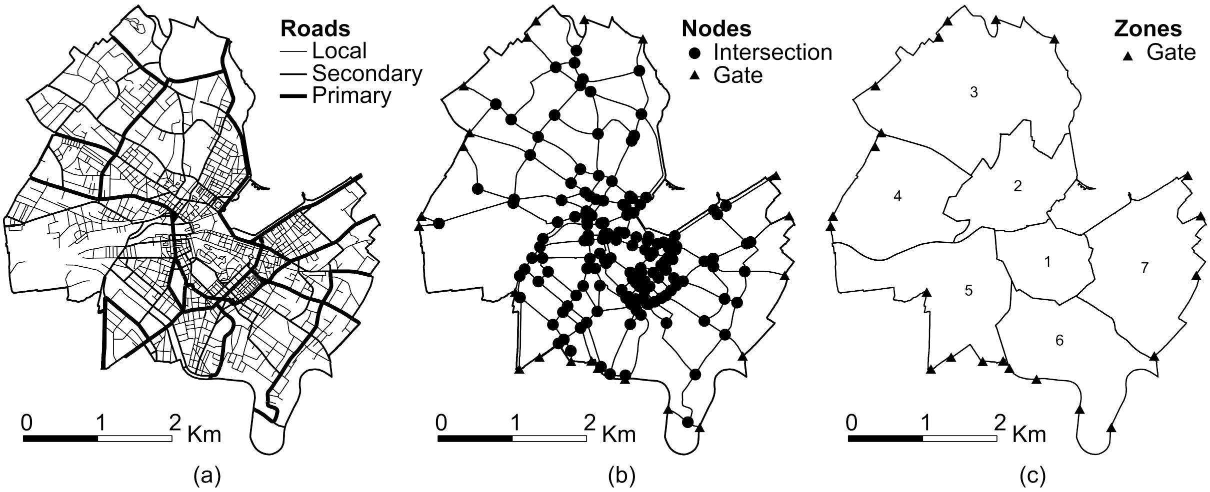


Figure 4: Case study road network. (a) Original road network, (b) simplified road network with intersections and gates, and (c) OD zones and gates.

(primary, secondary, and local roads), and it contains information about the number of lanes in each direction for each road.

To simplify the network, we remove local roads. The choice was also influenced by the spatial characteristics of the primary and secondary roads. The larger road sections, adapted to vehicular traffic have infrastructural characteristics more suitable for the installation of AMWs compared to local roads. Only the roads within the city of Geneva are considered. Nodes are created at each intersection. Gates are placed at the end of unconnected arcs at the city border through which incoming and outgoing traffic can flow. Figure 4(b) shows the simplified road network, and its characteristics are the following.

Number of arcs:	278
Number of nodes:	181
Total length of road:	72 km (non directed arcs)
Number of gates:	22

The OD matrix is provided by the Cantonal Office for Transport Planning (DGT, 2015). The matrix contains daily OD data separated by mode (public transport, personal vehicle driver, personal vehicle passenger, two-wheel drive, bicycle, walking). The origins and destinations are separated into twenty-six zones corresponding to the official statistical sub-sectors used for the cantonal statistics. The zones one to seven cover the city of Geneva, the zones eight to eleven cover the rest of the canton of Geneva, and the zones twelve to twenty-six are outside of the canton of Geneva (canton of Vaud and France).

All the different modes of transport are first added together. We design a network adapted to the morning peak-hour, which is the busiest hour of the day. A report of the Mobility Department of the Geneva authorities states that the morning peak-hour from 7:00am to 8:00am concentrates 14% of the daily traffic (Niggeler and Prina, 2011). The daily OD matrix is hence scaled down to 14% to obtain a pseudo-peak-hour OD matrix.

The OD matrix is aggregated in zones, as visible in Figure 4(c). In order to obtain a disaggregated demand over the nodes, we distribute the demand equally among all the nodes in each zone inside the city (zones 1-7). Given the absence of accurate data on the factors influencing the generation and attraction of mobility demand (population density, economic activities, places of interest etc.), we use the assumption that the trip starts or ends are distributed uniformly among the nodes.

We use the following rules to assigning the demand to the external gates. Firstly, the traffic that has an origin and a destination outside of the city is not taken into consideration. It is considered that, in the scenario with an AMW network in the city, a negligible number of people would travel through the city rather than going around it. Secondly, the traffic coming in and out of the city is distributed depending on the destination or origin inside the city. The possible gates are chosen based on their proximity with the zones. For example, the demand from external zones directed to Zone 7 in Figure 4(c) is distributed on the four gates located in this internal zone. Finally, the demand is distributed uniformly onto all the possible gates for each zone. The resulting aggregated characteristics of the OD demand are the following.

Number of daily trips:	3,725,296	trips/day
Number of trips during peak hour (p.h.):	521,260	trips/hour
Number of trips staying in the city during p.h.:	117,349	trips/hour
Number of outgoing and incoming trips during p.h.:	90,982	trips/hour

6.2 Results

Applying the optimization algorithm, we can analyze the resulting AMW networks. Figure 5 shows the main characteristics of the explored solutions. All investigated solutions are plotted on the trade-off curve between the total travel time and capital cost in Figure 5(a). The Pareto front is composed by the set of points that are not dominated by any other solution, i.e. the solutions closest to the origin. The Pareto front is shown in Figure 5(b). When the capital cost is zero, i.e. no AMW are installed, the total travel time is maximum. This scenario indicates the total travel time in the network when every individual walks. With a small increase in the capital cost, there is a strong decrease in total travel time. This indicates that the addition of a few AMWs greatly improve the travel time, capturing the flows in an efficient manner. This is true until the curvature of the Pareto front changes to the point that a large increase of capital cost correspond a small decrease in travel time. At this stage, only marginal improvement to the network can be done, and the newly added AMWs serve only few passengers.

Figures 5(c)-(e) show the exploration of the solution space over the 10,000 iterations of the algorithm. These images represent the "itinerary" that the algorithm used to investigate the solution space. The algorithm investigates the full spectrum of possible travel times and capital costs. The exploration starts with a solution with a minimum total travel time, Figure 5(c), and maximum capital cost Figure 5(e). Following the selection criteria on the Pareto front, solutions with less AMW-arcs are accepted, Figure 5(d). These solutions, although have greater travel times, have lower capital costs. Around iteration 7,500, the opposite extreme solution in comparison with the starting solution is reached, i.e. zero capital cost and maximum total travel time. From this iteration until the end, the algorithm further explores solutions with a low capital costs.

We can calculate the payback period of the investment with simple considerations on the value of time. The payback period is the length of time required to recover the cost of an investment (Weingartner, 1969). The value of time in Switzerland for public transport commuting is estimated equal to 27.81 CHF/hour (approximately 25 EUR/hour) (Axhausen *et al.*, 2008). Knowing the total travel time saving for each capital cost investment, it is possible to calculate the payback period. The result is shown in Figure 5(f).

The Pareto front shows interesting results that can be useful in supporting decision makers in the choice of an effective investment budget. For high capital costs, the relative decrease in total travel time is minimal. Therefore, any investment above 8 billion EUR can be considered not effective. Instead, every other solution on the Pareto front with a lower investment can lead to a substantial decrease in total travel time and a short payback period. The payback period is much shorter than the lifetime of the infrastructure. Moving walkway equipment should last for thirty years if combined with a good maintenance program Cross (2007). Clearly, maintenance and operational costs should be included for a complete analysis of the investment feasibility.

To give a practical idea of the possible solutions, we present two network designs on the Pareto front with 2 years and 1 year payback period, respectively. The solution labelled as A in Figure 5(b), is composed of 315 AMW-arcs with a total of 318 AMW-lanes, for an overall length of 167 km. This solution has an investment of 5.8 billion EUR and a payback period of approximately 2 years. The total travel time is reduced by 55% in comparison with the solution without AMWs. The resulting network is represented in Figure 6(a). Figure 6(b) shows a close-up of a few intersections, with elementary AMWs, and expressways, which span over some intersections. Another possible solution, with an investment of 1.2 billion EUR and a payback period of 1 year, is labelled as B in Figure 5(b). This smaller network is composed of 53 AMW-arc, all with one AMW-lane, for a total length of 35 km, and a reduction of total travel time of 24% in comparison with the solution without AMWs. Thanks to the high capacity of the system, the maximum number of parallel AMW-lanes is lower than three in all solutions. Therefore, given the width of 1.2 m for a single AMW lane, the space limitation or urban road is not problematic.

7 Conclusions

This paper tackles the accelerating moving walkway (AMW) system at a network level for the first time. It bases the definition of the system on a review of the technical characteristics and the implemented installations. It identifies an appropriate optimization framework composed of a mathematical model and a solution method taking inspiration from existing algorithms in the fields of transit and road network design. Finally, the present work analyses the results on a case study.

We conclude that approaches related to road network design rather than transit network design are more suitable for designing and optimizing a network of AMWs. The most computationally demanding step is the traffic assignment, therefore the computation time depends strongly on the reassignment period.

The application of the optimization framework on the case study shows interesting results for the dimensioning of a network of AMWs. The information provided can be useful for discussion with decision makers and town planners to envision a possible configuration of AMWs in a city center. The results on the necessary investment and payback period support the idea that this system could be part of the future mix of modes of transport.

The present research is based on several assumptions that limit the scope of this investigation. Further work will focus on relaxing some of them. The most important

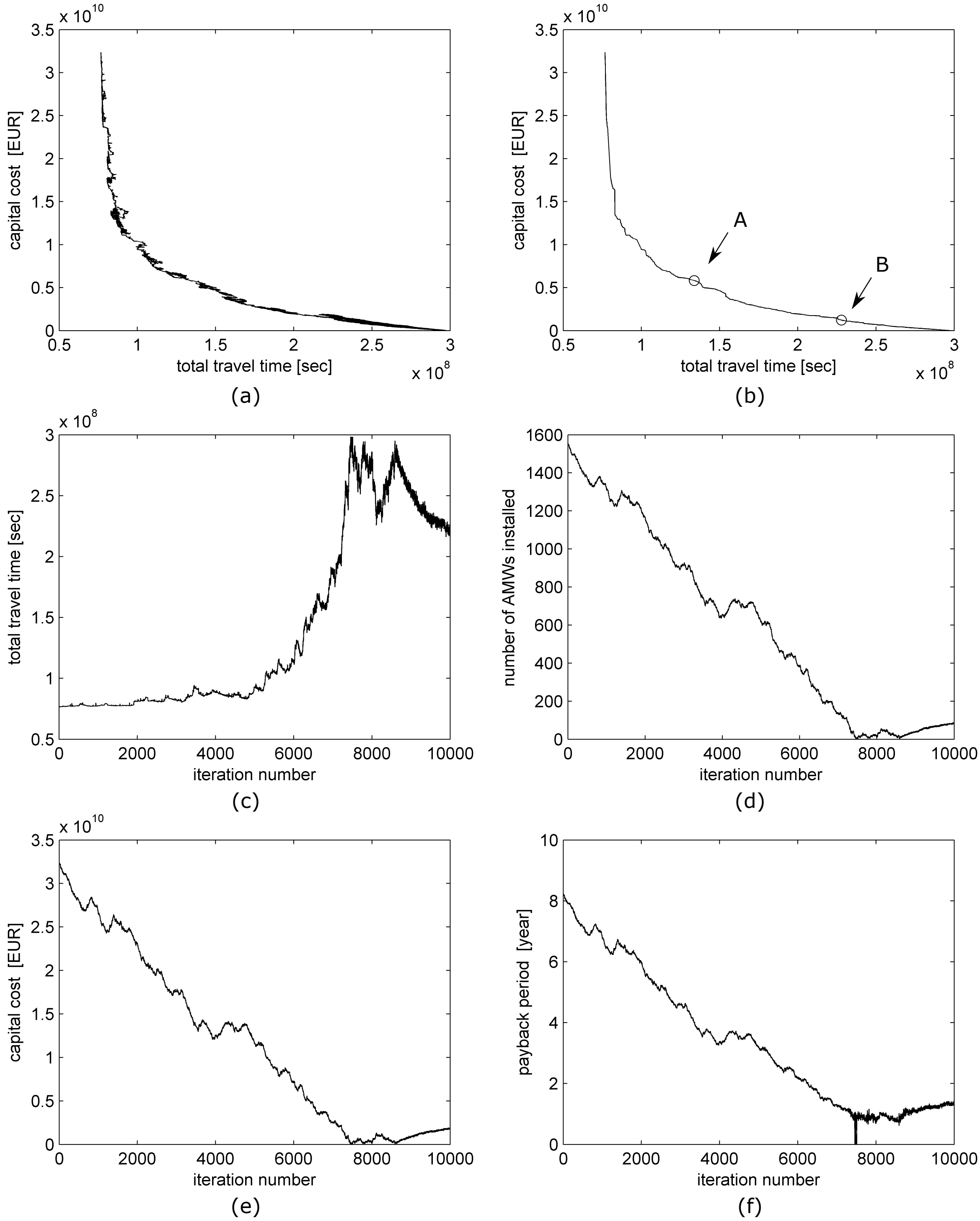
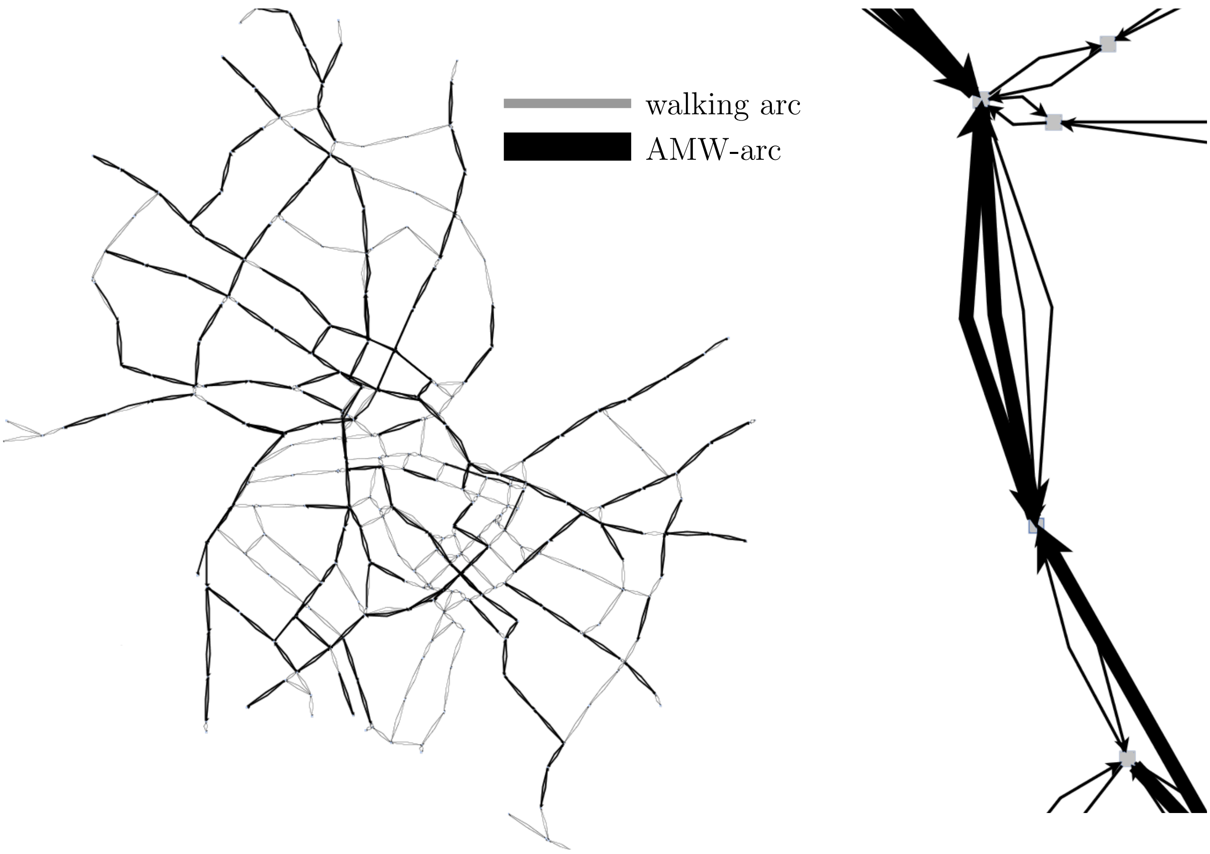


Figure 5: Case study results. (a) Trade-off curve between total travel time and capital cost of all tested solutions and (b) Pareto front. (c) Total travel time, (d) number of AMWs installed, (e) capital cost and (f) payback period over all iterations.



(a) (b)

Figure 6: Case study results. (a) Example of AMW network corresponding to Solution A in Figure 5(b). (b) Close-up a few intersections, with elementary AMWs, and expressways.

ones are the route choice and congestion. For now, a simple route choice approach is used. The model is deterministic and passengers always take the first available shortest path. The estimation of the relationship between the volume of traffic and the travel time could improve the assignment procedure. We also ignore the induced demand by adding or removing AMWs on the trip generations. Regarding the heuristic method, several improvements can be done, for example on the acceptance criterion or the neighborhood structures. The investigation of more complex neighborhoods could improve the search in the solution space. In particular, it could be interesting to define neighborhoods that use the concept of *core lines* of AMWs, and modify some sort of principal directions in the network.

An interesting further work is the consideration of the elevation. AMWs could greatly incentivize walking on steep paths in hilly cities, where the walking speed and comfort are function of the road inclination. However, we should consider that AMWs have inclination constraints that may strongly affect the possible network design. In this case, the integration with elevetors and escalators could be considered. Finally, a more dynamic use of the AMWs could be investigated. Besides reversing directions during morning and evening peaks, active traffic management strategies could be evaluated, such as dynamic opening and closing of AMW lanes, modifications of speeds and directions aimed at reducing congestion and improving efficiency.

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