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An effort-based evaluation of pedestrian route choice

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Route choice is one of the main challenging problems from theoretical and practical viewpoints in the realm of pedestrian behaviour. A prime underlying concern of researchers in this field is to identify criteria or discover principles that pedestrians use to select their routes. Despite the fact that there are infinite possible routes between two given destinations in space, pedestrians in real situations tend to choose a certain finite number of available trajectories. As a consequence, there is a high demand for theoretical framework and models to describe route choice. The fundamental assumption is that pedestrians follow a route over which effort is optimized. The existing criteria in the literature to predict route choice of pedestrians are mainly related to route length and travel time. In this paper, we consider physical effort as a new criterion, which indicates the pedestrian's metabolic energy expenditure that pedestrians may consume during their walk from origin to destination. A case study is included to illustrate the pertinent concepts and ideas introduced. Our discussion concludes with an overview of how this reconceptualization builds the foundations for a model that will enable improved operations, planning, and design of public transport facilities.

Key words: Pedestrian behavior, route choice, metabolic energy expenditure, effort, trajectory.

INTRODUCTION

The problem of pedestrian route choice (PRC) is of central importance and highly-demanding to the fields of transportation. The pedestrian choice among route alternatives is a complex activity, which involves many aspects of psychological, behavioural, and environmental characteristics.

Many researchers have investigated the problem of route choice. Consequently, several pedestrian route choice modelling approaches have been proposed and empirically validated. Gipps and Marksjö (1985) described a number of algorithms to predict pedestrian flows within and around constructed facilities. The model uses the physical layout to generate a number of nodes, a pedestrian walks between origins to his destination in straight line and he/she has to make a decision to next node. The choice is limited by a straight line between the present node and the next node dose not intersect fixed obstacle. Borgers and Timmermans (1986a) formulated a model that gives satisfactory description of pedestrian route choice and allocation behaviour within inner-city shopping area.

Cheung and William (1998) investigated the pedestrian choice between escalator and stairs in the Hong Kong MTR stations. It is assumed that the travel time functions

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for the escalator and stairs form an important factor in estimating the pedestrian split between escalator and stairs. Hughes (2000) stated that pedestrians seek to minimize their estimated travel time, but temper this behaviour to avoid extremely high densities. The psychological state of pedestrians can completely change the behaviour.

Hoogendoorn and Bovy (2004) developed a model that pedestrians schedule their activities, the activity area, and the paths between the activities simultaneously to maximise the predicted utility of their effort and walking. Presently, route choice models are based on the minimum distance, that is, pedestrians tend to choose the shortest route (Ciolek, 1978; Vaziri et al., 1983; Seneviratne and Morrall, 1985; Hewawasam, 2013).

Helbing and Molnár (2001) reported that pedestrian prefers the shortest route even if that route is crowded. Hill (1982) reported that the most influential factor in route selection was the minimization of the travelled distance. Pedestrian’s routes selection based on shortest distance received the highest rating in empirical studies (Golledge 1997).

Other researchers further pointed out that a pedestrian walks from origin to destination moves in a straight line (Liu et al., 2010). The choice is limited to those that are visible from the pedestrian present position and may vary from one pedestrian to another (Burgess, 1983). Some studies have shown that a pedestrians route choice model choose the route depends on the minimum time from origin to destination, this route often be the shortest route (Seneviratne and Morrall, 1985; Guy et al., 2010).

More recently, some researchers attempted to apply the principle of least effort to pedestrian route choice behaviour problem (Silder et al., 2012; Farris and Sawicki, n.d.; Kramer and Sylvester, 2011). The model proposed in Guy et al. (2010) is very simple and lacks many real considerations like friction and resistance in walking. McNeill (2002) reported based on his experimental observations that we may plan our routes over soft ground and over hill to minimise energy cost. The model we propose here is comprehensive and can handle pedestrian walking through grass, mud, hills or other surfaces that impede movements by incorporating these environmental factors into the energy functions.

When assessing the design of transport facilities, it is important to be able to anticipate the attributes pedestrian movement to the configuration of passable open spaces and in particular their visibility caused by the urban layout. The term configuration refers to the way every space in the environment relates to every other (Hillier et al., 1993).

Factors identified from the literature that have been linked to influencing pedestrian route choice include walking distance, walking time, effort, pleasantness, crowdedness, age and a level of familiarity with the environment. Our routes will be different depending on how well we are familiar with the environment (Seneviratne and Morrall, 1985). Some researcher investigated the environmental conditions influences of the chosen route, which are not evaluated as important factors (Seneviratne and Morrall, 1985; Saneinejad et al., 2010).

Two approaches can be followed to handle PRC problem: deterministic or probabilistic. In this paper, we follow the deterministic approach, which assumes that the perceive utility of a route is deterministic and that pedestrians will only choose the alternatives having minimum average cost (Cascetta, 2009). On the other hand, probabilistic choice models assume that the perceive utility of a route in a random variable and express the probability that pedestrians will choose each of the available alternatives (Borgers and Timmermans, 1986b).

In general, pedestrians choose among the possible routes based on their route cost which can be indicated by time, traveled distance or consumed effort. The effort has a cost equivalent in the real world and so we devised a formula capable of encapsulating this. As indicated in the literature, route choice models are inherently limited in that they focus on shortest distance and minimum time, whereas in reality other variants are likely to exist. There is a need for a more comprehensive model that can describe pedestrian route choice based on foreseeable variants such as physical effort that pedestrians may consume during their travel from origin to destination.

We propose in this paper a more comprehensive model that incorporates the route surface into a newly proposed energy formulation. The model represents the effort that pedestrians will put in when walking on different surfaces as a cost that added to the energy function.

The paper is organized as follows, Section 2 discussed the problem statement, and Section 3 elaborates on evaluation criteria. Section 4 presents a comparison between criteria. In Section 5, a case study is studied and investigated. Finally, Section 6 concludes the paper.

Problem statement

In principle, pedestrians usually move freely in their environment choosing a route from an infinite set of alternatives as shown in Figure 1. However, among all admissible routes, humans naturally select one specific route, which we will refer to as the optimum route. It is called optimum as it minimizes some quantities over the selected path. In this case, a route is the trajectory of a pedestrian that started at the origin and ended at a destination. A pedestrian's trajectory is usually obtained by saving his coordinates at each time step and finally connecting all the points.

During the pedestrian walk, the specifications of his/her positions as a function of time are called a trajectory or a route. Such a route should be a sufficiently smooth function of time, and it should follow any environment

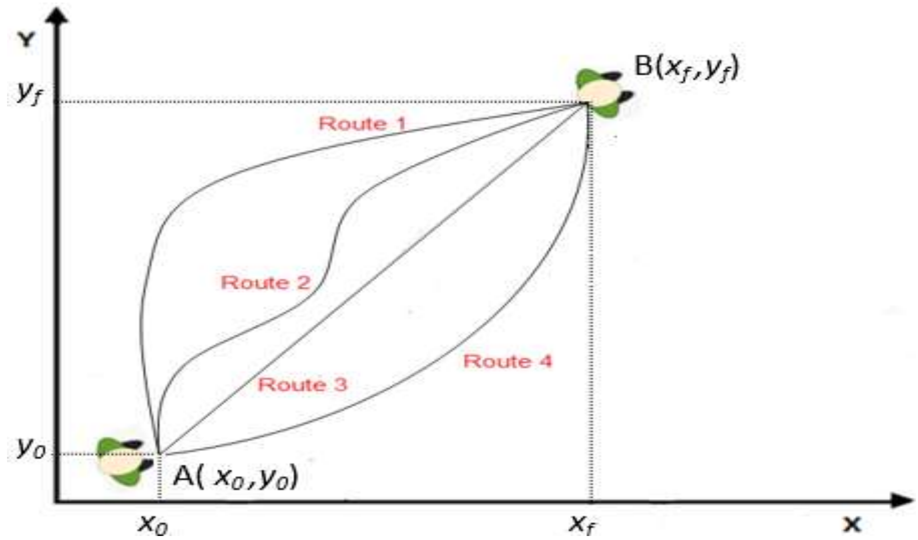

Figure 1. Possible routes between two destinations

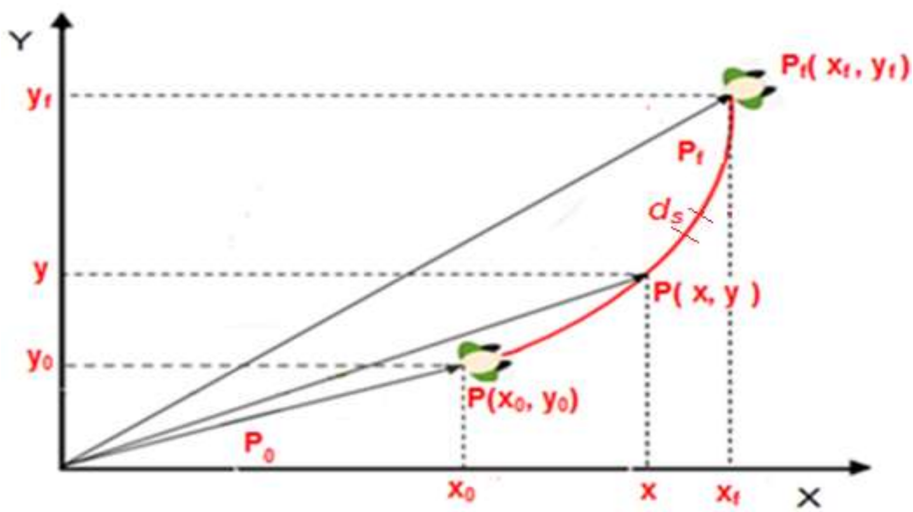

Figure 2. Route describtion.

limits or constraints to avoid obstacles. Here, we considered the route as the combination of a path, geometric description of a sequence of configuration achieved by the pedestrian, and a time scale, which specifies the times when the configuration is reached.

The location of a pedestrian, at any time *t* can be described by a pair of coordinates $x(t)$ and $y(t)$, which define the position vector $\vec{p}$, namely,

$$\vec{p}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \quad (1)$$

The speed of a pedestrian is defined as the magnitude of the time derivative of position vector (Hibbeler, 2010) and can be expressed as:

$$\vec{v} = \left\| \frac{d\vec{p}}{dt} \right\| = \frac{ds}{dt} = \sqrt{\dot{x}^2 + \dot{y}^2} \quad (2)$$

where $\|\,.\,\|$ is the magnitude of its argument and ds is an infinitesimal distance travelled along the route chosen as shown in Figure 2.

The problem of PRC can be stated formally as find a route, described by equation $f[x(t), y(t)] = 0$, that a pedestrian traces, while traveling from point A (the origin), specified by the coordinates (x_0, y_0), to point B (the destination), specified likewise, by the coordinates (x_f, y_f), as shown in Figure 2.

EVALUATION CRITERIA

Existing route choice models, as mentioned in section I, are based on the shortest distance or minimum time criteria. In this work, we resort to the concept of physical effort as newly proposed criteria.

Traditionally, the route choice has been assumed to be the result of minimizing some quantities such as selecting the shortest route, the quickest or the least effort route. To determine what would be an effective route choice criterion, we have undertaken an evaluation of this criterion for pedestrian route choice.

Shortest distance criterion (SDC)

The route selection criterion described in this section is based on shortest route (in terms of distance). Specifically, the length *L* of a route can be expressed as,

$$L = \int_{s_0}^{s_f} ds \quad (3)$$

where the integration limits s_o and s_f refer to the initial and final positions, respectively, of the pedestrian, along the route, at the initial time t_0 and the final time t_f.

Using Equation 2, we can write,

$$ds = v\,dt = \sqrt{\dot{x}^2 + \dot{y}^2}\,dt \quad (4)$$

Moreover, using the aforementioned equation, Equation 4 can be rewritten as,

$$= \int_{t_0}^{t_f} v\,dt = \int_{t_0}^{t_f} \sqrt{\dot{x}^2 + \dot{y}^2}\,dt \quad (5)$$

Apparently, the equation involves variables of route choice, that is, $x(t)$, $y(t)$.

The matter of fact is that the shortest route between any two points is the straight line connecting them, provided that no kinematic or geometric constraint is imposed, as reported in (Burgess, 1983; Verlander and Heydecker, 1997).

Minimum time criterion (MTC)

The minimum time criterion is related to the quickest or fastest route, which is usually measured as the shortest travel time route. The time *T* was taken to travel over a route can be expressed as:

$$T = \int_{t_0}^{t_f} dt \quad (6)$$

Referring to the speed definition of Equation 2, the aforementioned expression of *T* can be rewritten as,

$$T = \int_{s_0}^{s_f} \frac{ds}{v} \quad (7)$$

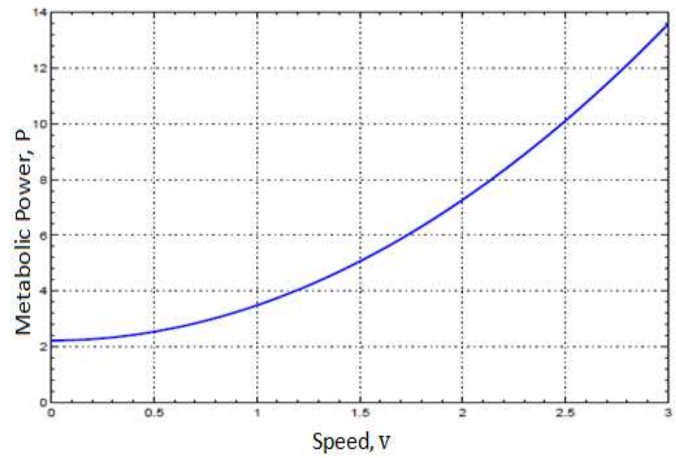

Figure 3. A Characteristic curve of power *P* versus speed *v*.

Least effort criterion (LEC)

Physical effort can be formulated in terms of the amount of energy a human body needs to expend in order to perform activates or physical tasks, which is also known as metabolic energy. The former indicates the sum total of the chemical processes that occur in living organisms, resulting in a production of energy. The metabolic energy expenditure of walking may vary within a wide range of individual limits and also for a given individual depending on the factors that encompasses total weight, walking speed, type of surface, and grade (Givoni and Goldman 1971). Resorting to experimental data and literatures (Cotes and Meade, 1960; Zarrugh et al., 1974), it is reported that the relationship between the metabolic power *P* and the walking instant speed v takes the quadratic form.

$$P = P(v) = Av^2 + Bv + C \quad (8)$$

Coefficients *A*, *B*, and *C* are evaluated as,

$$A = 1.5\,\mu\,(W + X) \quad (8a)$$
$$B = 0.35G\,\mu(W + X) \quad (8b)$$
$$C = 1.5W + 2(W + X)(X/W)^2 \quad (8c)$$

where v denotes the walking speed (m/s) as defined in Equation 2, *X* the external load (kg, m/s^2), *W* the individual weight (kg, m/s^2), *G* the grade (%), and μ the terrain factor defined as 1 for free walking.

The characteristics curve of power *P* versus speed v for a specific case of flat walking (G=0), no external load (*X=0*), and $\mu = 1$, is as shown in Figure 3.

Now recalling that the power is the time rate of the energy, that is,

$$= \dot{E} = \frac{dE}{dT} \quad (9)$$

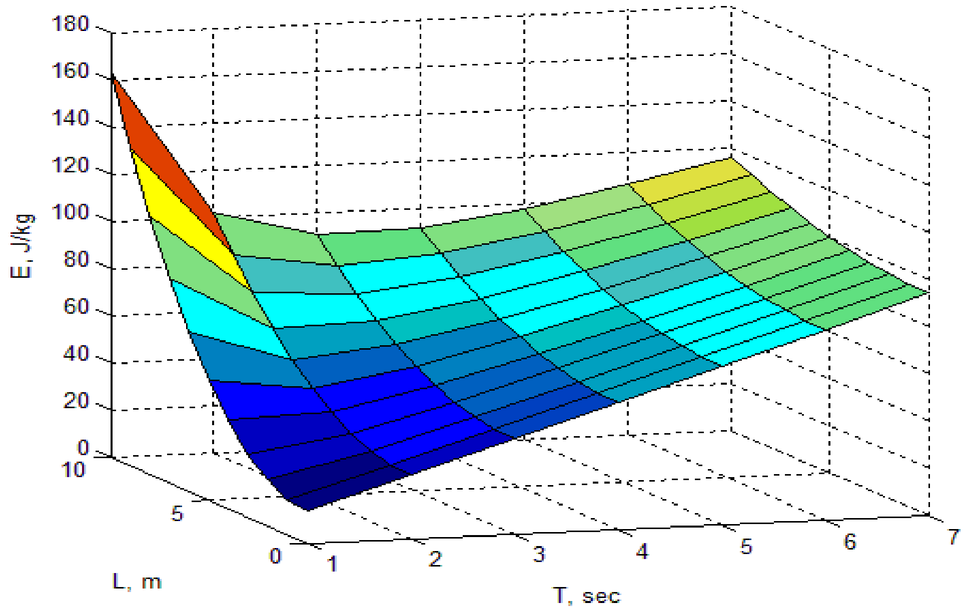

Figure 4. The surface of effort *E* versus the time *T* and the length *L*.

Accordingly, we can write,

$$dE = P\,(v)dt \tag{10}$$

Upon integrating both sides of the above equation from initial time t_0 to final time t_f, we obtain the corresponding total consumed metabolic energy E, while moves along a path starting from the original destination (x_0 ,y_0) to the final destination (x_f ,y_f), namely,

$$E = \int_{t0}^{tf} P\,(v)\,dt \tag{11}$$

Or, equivalently, we can write using it Equation 8.

$$E = \int_{t0}^{tf} (Av^{\,2} + B\,v + C)\,dt \tag{12}$$

A comparison between criteria

In this section we investigate the relationship between the three criteria mentioned in section 3 for the case of quadratic form of the power defined in Equation 8. For this sake, this equation can be is expanded as:

$$= \int_{t_0}^{t_f} Av^{\,2}\,dt \; + B\int_{t_0}^{t_f} v\;dt + C\;\int_{t_0}^{t_f} dt \tag{13}$$

Using integration by parts, we can write

$$= Av\int_{t_0}^{t_f} v\;dt\; - A\int_{t_0}^{t_f} s\,dv + B\int_{t_0}^{t_f} v\;dt + C\int_{t_0}^{t_f} dt \tag{14}$$

Or

$$E = (Av + B)\int_{t_0}^{t_f} v\;dt\; + C\;\int_{t_0}^{t_f} dt - A\int_{t_0}^{t_f} s\;dv \tag{15}$$

Referring to Equations 5 and 6, the aforementioned equation turns out to be

$$E = (Av + B)L + CT - A\int_{t_0}^{t_f} s\;dv \tag{16}$$

Now, for a certain case of constant speed V = L / T, we can write.

$$E = (AV + B)L + CT \tag{17}$$

Substituting *V* = *L* / *T* into the above expression, we obtain

$$E = \left(A\,\frac{L}{T} + B\right)L + CT \tag{18}$$

After expanding,

$$E = A\,\frac{L^2}{T} + BL + CT \tag{19}$$

The aforementioned equation relates the effort criterion to the time and length criteria. Figure 4 shows variation of *E* with changes in *L* and *T*. Clearly, the function of *E* is bowel-shaped and has a minimum. Moreover, the function increases quickly starting from the *X* and moving up-right or down-left, and slowly moving up-left or down-

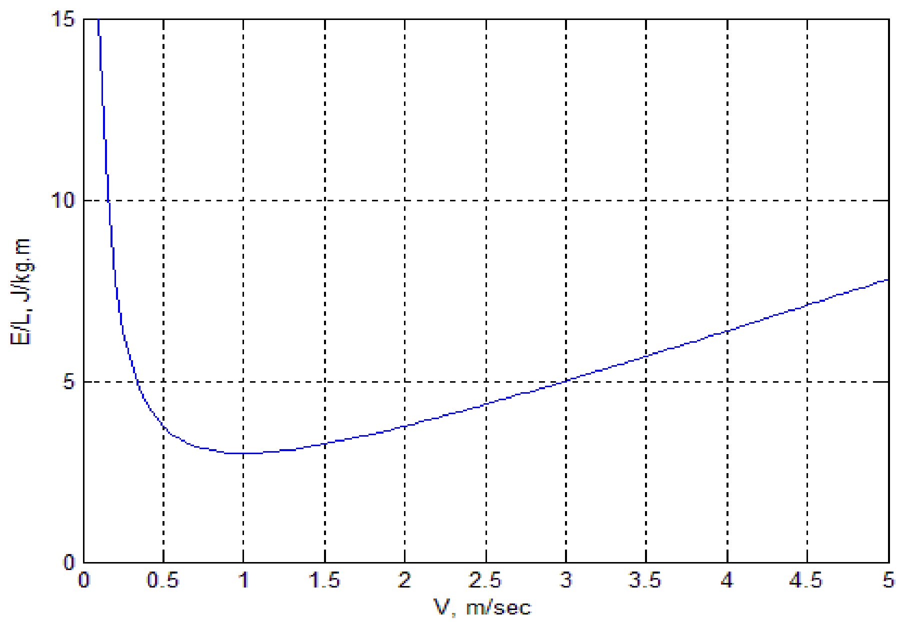

Figure 5. The relation between the speed *V* and the effort *E*.

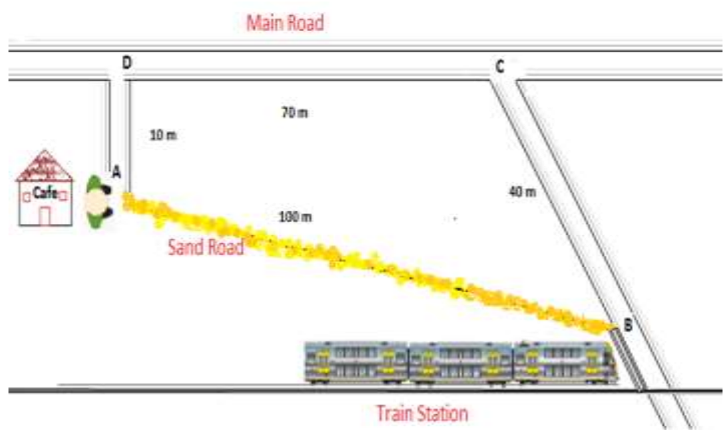

Figure 6. Comparison between two Routes.

right.

Moreover, for the case of constant speed, Equation 12 can be expressed, using Equation 7, as:

$$E = \left(AV + B + \frac{C}{V}\right) \int_{s_0}^{s_f} ds \quad (20)$$

or, equivalently

$$\frac{E}{L} = \left(AV + B + \frac{C}{V}\right) \quad (21)$$

The aforementioned relationship is as shown in Figure 5 for G=0, X=0,$\mu = 1$.

A CASE STUDY

To illustrate the application of the methodology proposed in this paper, we consider a comparison between two routes as shown in Figure 6, in which a pedestrian is to move from the origin *A* to destination *B*. For the route choice process, two options are available, namely, Route *AB*: with sand all the way, and Route *ADCB* with no sand.

Figure 7 shows a schematic diagram of the two route options: in Figure 7A, the pedestrian travels from origin to destination, where pedestrian chooses the route with direct shortest length AB, while in Figure 7B, the pedestrian travels from origin to destination through

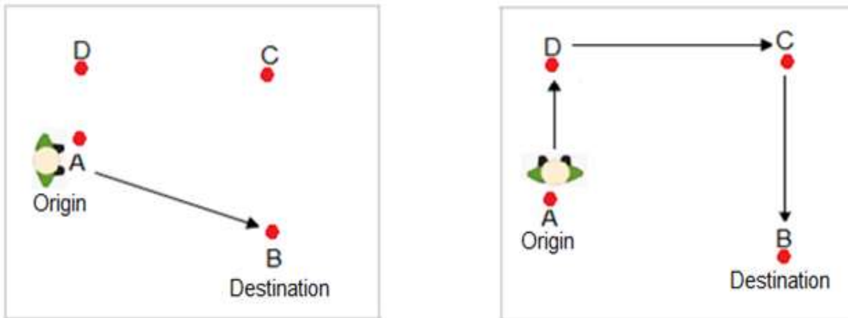

Figure 7. Illustration of key direction of route choice possibilities.

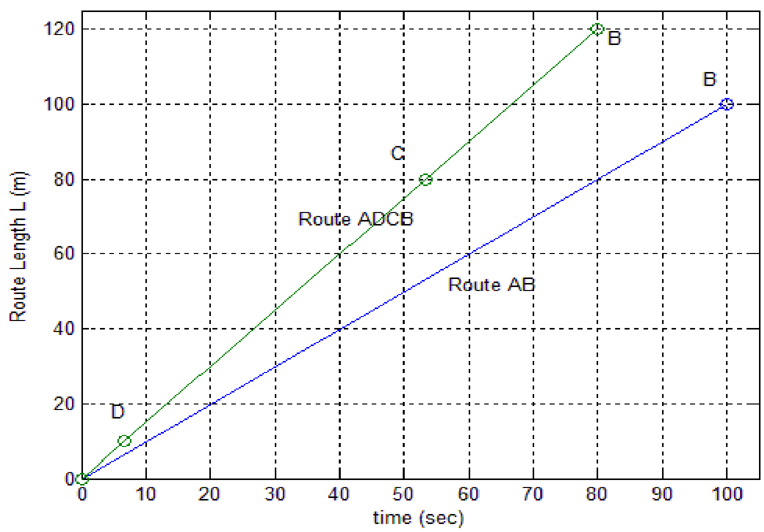

Figure 8. The relation between route length and time.

points D and C.

For Route AB, the distance from point A to point B is 100 m, with μ = 9, V =1.0 m/s, zero grade (G=0), and no extra load (X=0). The time, distance and effort route costs can be computed as,

$$T_{AB} = \frac{100}{1.0} = 100\ sec$$
$$L_{AB} = \overline{AB} = 100\ m$$
$$E_{AB} = 1500\ J/Kg$$

For Route ADCB, the distance from destination A through D and C to final destination B is 120 m, with μ =1, V=1.5 m/s, and zero grade and no extra load, then,

$$T_{ADCB} = \frac{120}{1.5} = 80\ sec$$
$$L_{ADCB} = \overline{AD} + \overline{DC} + \overline{CB} = 120\ m$$
$$E_{ADCB} = 585\ J/Kg$$

Figure 8 shows the distance traveled for the two routes, as a function of time, while Figure 9 shows the effort consumed for the two routes. It is apparent that the total effort consumed over the route *ADCB* is 585 and 1500 J/kg for route *AB*. This means that route *ADCB* saves around 60% of the total energy consumed over route AB.

Referring to Table 1, which includes a comparison between two routes, it is apparent that even though Route AB is shorter than Route ADCB, the effort cost of Route AB is greater than that of Route ADCB. Apparently, the minimum-time route is ADCB; the shortest-distance route is AB, while the minimum-effort route is ADCB.

Apparently, the two possible routes have different cost of time, distance, and effort, of walking through each of route. Referring to Figure 7, using the shortest distance approach probably the pedestrian chooses route AB. However, if we consider the sand, which is viewed as an obstacle, between points A and B, it is reasonable that at least some pedestrians, due to their personal perceptions of an obstacle, choose route ADCB, to avoid obstacles.

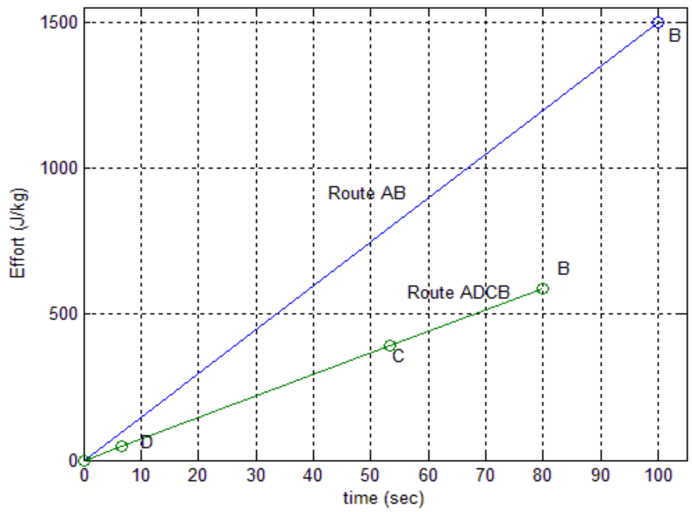

Figure 9. The relation between effort and time.

Table 1. A Comparison between various criteria.

Criteria	Time [T (s)]	Route length, L (m)	Effort [E (J/Kg)]
Route AB	100	100	1500
Route ADCB	80	120	585

Clearly here the obstacle is a co-variant, this model would benefit from the inclusion of obstacle at the time of decision. Likewise, walking time, where passengers choose the route with the shortest length, but an obstacle on this route will foreseeable change the time and effort it takes; again, however, this effect of retarding pedestrian through rates is likely to vary considerably between pedestrian. The key point is that this individual pedestrian will have an awareness and appreciation of this prior to the route choice point. In other words, the perception of obstacles will weight differently for each irrespectively of whether their underlying route choice is based on the same factor (shortest distance in this example).

Conclusions

The fundamental concept of physical effort consumed over travel is used here and applied to solve the pedestrian route choice problems. For predicting route choice, the Principle of Least Effort offers a pattern of route choice different from that of the shortest or quickest routes. It is demonstrated that physical effort has a cost in the real world, which can be incorporated in pedestrian route choice models can exploit this to describe the pedestrian behaviour as a cost that is represented using the metabolic energy. We have devised a formulation capable of encapsulating this complex interplay utilizing the Principle of Least Effort.

The main contribution of the presented work is a comparison between the three evaluation criteria of shortest-distance, minimum-time and minimum-effort, and showed the rationale behind the proposed least effort criterion in the real life scenario.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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