國 立 交 通 大 學

運輸科技與管理學系

博 士 論 文

考量街道寧適性下步行可及性與移動性之研究

Walking Accessibility and Mobility with the Consideration of Street Amenities

研 究 生：蔡耀慶

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中 華 民 國 一 ○ 二年 六 月 十七 日

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研 究 生：蔡耀慶　　Student：Yau-Ching Tsai

指導教授：許巧鶯　　Advisor：Chaug-Ing Hsu

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致　謝

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摘 要

近年來，街道改善計畫常藉由提升街道空間寧適性以提升視覺、心理愉悅度進而提升步行意願，其對行人生理機制之影響亦受到關注，特別是當今社會高度重視步行對健康之效益。行人廊道為都市中常見的線型步行空間，主要用於進出交通場站或抵達鄰近活動發生點，其規劃設計議題大多聚焦在容量設計上，然而近年研究發現平面設計型態亦會影響行人流量。再者多數已開發國家未來都須面對人口老化問題，低速度的老年行人使用大眾運輸系統比例將增加，廊道內步行移動性差異逐漸擴大，增加碰撞與局部擁擠發生機率。

對此本研究分別從心理與生理量測法分析街道寧適性對步行可及性以及廊道空間平面設計對步行移動性之影響。以行人路權、夜間照明、綠美化、街道傢俱、沿途商業活動、鋪面以及水景等七個街道空間元素為主要寧適性因子，分別從心理與生理的角度探討街道寧適因子變動下對步行意願與距離之影響。心理層面同時設計顯示性與敘述性偏好問卷，調查不同起迄對步行路線選擇行為，以降低各因子共線性並提高資料變異度，校估步行效用函數，進而觀察各寧適性因子變動下對步行意願與距離之影響。生理層面則透過實驗設計，加入上述因素之影響，改善並應用 Pandolf et al.(1977)模式於捷運旅客步行能量消耗之調查，進而從能量分布函數推導出各街道空間下之步行可及距離。為確保步行安全性與系統效率，提升民眾步行意願，本研究以 Helbing et al. (2000)模式為基礎，並透過行為觀察構建步行模式，從真實案例歸納出六種替選方案，應用 C 語言設計代理人模擬程式，探討可有效提升行人流速的平面設計手法。

結果顯示綠美化與商業活動對於步行意願具有正效應，步行時間則為負效應，亦即規劃者在進行街道改善計劃時可優先從綠化與沿街商業活動著手改善；行人路權在敘述性偏好中具有極顯著的效應，但在顯示性偏好中則為不顯著，代表實際行為與假設性意願存在差異；另外，照明設計與街道傢俱手法，對於提升步行意願皆為不顯著。生理層面部分，經能量消耗實驗校估出 Pandolf et al.(1977)修正模式，應用於能量計算以求得次數統計並進行適配度檢定，結果發現步行能量消耗呈現 Gamma 分布，意謂行人於通勤旅次中普遍追求節能、省力之特性。應用花台進行中央分隔與推廣低速度行人靠兩側行走可有效提升行人流速；若應用座椅區隔出老人專用空間，雖然提高安全性卻大幅降低有效寬度，影響年輕行人之步行速度。本研究結果成果可提供規劃者從事步行可及性指標制定、街道改善方案評估以及步行行為分析之參考依據，也進一步解釋為何規劃者多傾向採用全開放式空間，但透過集體行為規範同樣可提高系統效率而又不影響廊道的有效寬度。

關鍵詞：步行意願、能量消耗、顯示性及敘述性偏好、路線選擇模式、代理人模擬法。

ABSTRACT

How to improve street amenities (SA) to both raise willingness to walk (WTW) and level of service (LOS) is a crucial issue for planners when designing a pedestrian-friendly environment in terms of accessibility and mobility. However, few studies have provided rigorous and systematic analysis to aid this practice.

Thus, this research addresses this issue with three topics: first, defining measures of WTW to represent variation across environments; second, estimating WTW for the varied levels of SA; third, designing the arrangement of SA to raise LOS when mobility difference is high. Attributes of street amenities are classified, such as right of way, lighting, planting etc., and WTW is defined with both physiological and psychological measure: energy expenditure (EE) and walking time. The WTW measures taking into account the effects of SA are estimated by designing energy expenditure and conducting revealed and stated route choice experiments. The Pandolf et al. (1977) model is used to analyze the walking energy expenditure (WEE). The terrain factor is adjusted using the calibrated regression function to fit the urban street space in the experiment. To avoid violation of the irrelevance of independent alternatives (IIA), random-parameters logit is applied to build route choice model. With respect to nature of pedestrians and data scale, Helbing's (2000) agent-based model is modified to model passing behaviors. The simulations are conducted with the designed simulator at Fruin's (1971) six levels of flow to fully represent pedestrian flow.

Results show that WEE sample suggests a Gamma distribution. The accessible walking distance pattern around a service facility should be designed based on the service contour lines which take into account the effects of SA. Results of pedestrian route choice show improvement for right of way, lighting, planting, retailing, and fountains, would significantly enhance WTW. The results of ABM indicate that a corridor in which a line of round objects, such as potted plants, are positioned to divide a bidirectional stream of pedestrian traffic, can result in a relatively smoother flow than if the objects were rectangular in shape, e.g., benches. It is worth noting that by promoting collective self-organizing when it comes to walking direction, and by providing a sub-lane along the wall for slower walking, a better performance can be obtained, even without reducing the effective width.

Key words: willingness to walk, energy expenditure, revealed and stated preference, route choice experiment, agent-based model.

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GLOSSARY OF SYMBOLS

m: body weight(kg)

$v(t)$: walking speed function(m/s)

$\mathbf{r}$: position

$\mu(\mathbf{r})$: friction function

g: the gravitational acceleration(m / s^2)

t: a period of walking time(s)

e_w: the consumed energy, the unit of e_w is in joule(J)

P: the amount of street type

s_p: walking distance on a type p street(m)

μ_p: the friction value on a type p street

W: the metabolic rate, energy expenditure per second (J/s, watts)

l: the load carried(kg)

G: the grade (%)

n: the terrain factor value

$\tilde{n}$: the observed value of n

$\Omega(\boldsymbol{x})$: the friction function consisting of a vector of street factors that significantly affect the WEE

M : the number of factors

C_i : the choice set of pedestrian i , consisting of several alternative routes

U_{io} : the random utility of alternative route o for pedestrian i

V_{io} : the systematic utility

ε : the error term in regression function

ε_{io} : the random component of utility function

o (o'): the alternative belonging to pedestrian i 's choice set C_i

θ : the scale factor

x_{ioq} : the value of street amenity q during pedestrian i 's route o

CV : compensating variation

α : the marginal utility of walking time(s)

η_i : the subject-specific stochastic component for each β

V_n^0 : the initial state of utility

V_n^* : the level of utility in the subsequent state

$\mathbf{r}_i^0$: the origin

$\mathbf{r}_i^*$: the destination

EPO^* : the maximum acceptable potential energy when s/he touches another person or an object

u_{ij} : pedestrian i and j produce a potential energy (J)

r_i : the radius of pedestrian i's personal space (m)

d_{ij} : the distance between the pedestrian i and j's center(m)

$\vec{e}_i$: the normalized direction vector

k : the direction that pedestrian i chose

CHAPTER 1 INTRODUCTION

In this chapter, I first illustrate the importance of building pedestrian-friendly environment and the issues existing in the practice. After it, the objectives are set. Then, I present the research framework to illustrate the relationship among the study subjects and the approaches I used.

1.1 Motivations and background

Reports have shown that transportation and land use change contribute a total of nearly 31.7% of the greenhouse gas emissions. These trends are increasingly quite dramatically, especially in the countries with emerging and newly developed economies such as mainland China, India and Brazil (USEPA, 2009; WRI, 2005). Walkable environment is regarded as a solution to this problem.

Mobility and accessibility are the two key concepts when planning transportation system and land use. For a walkable environment, the estimate of walking distance serves as an accessibility indicator for evaluating whether people decide to walk or not to a planned facility. This concept was launched by Howard (1902) who used an acceptable walking distance to determinate a reasonable town size. This concept extends to urban planning. Perry (1929) introduced the "neighborhood unit" idea (see Figure 1), with emphasis on walking accessibility, and with residences arranged around a service center within an acceptable distance.

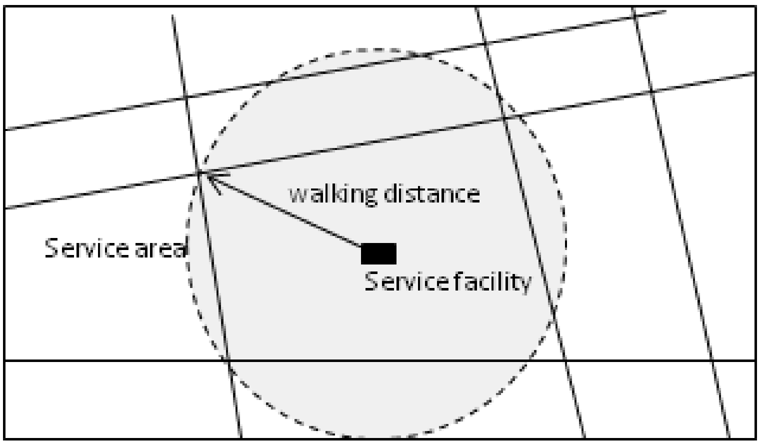

Figure 1 The concept of the traditional walking distance.

To-date, new planning paradigms, e.g., Transit Oriented Development (TOD), New Urbanism, Compact City, continue to apply walking distance not only to create a pedestrian-friendly environment but also to reduce greenhouse gas emissions by encouraging transit ridership and walking frequency (Banai, 1998; Calthorpe, 1993; Cervero and Kockelman, 1997; Cervero et al., 2009; WRI, 2005). Its application is also found in the retailing theory where it is used to estimate the number of walk-in customers and in location-allocation modeling studies where it serves as a parameter for designing the maximal covering model (Brown, 1996; Hsu and Chen, 1994; Owen and Daskin, 1998).

Although the method has been and still is applied in many fields, its measure does not reflect variability. In fact, there are various measures recorded in the literature, but few studies that explore their variation. Howard (1902) initially set it as a half mile; Perry (1929) used a quarter mile (5-minute walk) as the radius of a neighborhood unit; and in Sweden it was set as a range of about 300~500m (Lynch and Hack, 1984). The characteristics of the pedestrian, e.g., trip purpose, gender, and age, and urban context may alter the acceptable distances (Clifton and Krizek, 2004). For example, Pushkarev and Zupan(1975) compared the cumulative distribution of walking distances for a trip at two Manhattan buildings. They found that trips to eat had the shortest walking distance and that shopping trips had the longest ones among five purposes (eat, work, pleasure, business and shop). However, to-date few studies have explored the variation in walking distance and its implication for pedestrians. A useful method to express the variability of walking distance is the statistical distribution. As mentioned earlier, Pushkarev and Zupan(1975) applied this method to analyze walking distances. Seneviratne (1985) observed the distribution of walking distances by conducting a survey in the central business district of Calgary, Canada. It is worth noting that Seneviratne (1985) derived the critical distance of 243m (796 ft), at the maximum rate of change of the distribution function as the more reasonable estimate for the average walking distance of 250m (819 ft). This advanced application of statistical frequency for estimating walking distance inspired our later analysis.

However, contrary to the discussion on the variation in walking distance, there is much less concern regarding the variability across pedestrian environments. People generally agree that the higher the pedestrian environment quality (PEQ) the farther, within reason, they are willing to walk, and this finding is backed up in the literature (Untermann, 1984; Zacharias, 2001). Nevertheless, few studies have explored this issue with systematic analysis. Gehl (2001) and Untermann (1984) investigated the change of frequency based on the improvement of PEQ, but they did not include any change in walking distance. Lövemark (1972) recognized the effects of PEQ on willingness to walk and claims that a pleasant pedestrian environment encourages an up to 30 percent greater walking distance. To date his study is the one closest to the issue addressed here, but it still does not show any details.

In urban pedestrian environment, PEQ is associated with level of street amenities (SA), e.g., right of way, lighting, planting, pavement, street furniture, retailing, and fountains (Booth, 1983; Mitra-Sarka, 1994). Since better street space would encourage people to ride transit and to walk more frequently (or for longer), street improvement projects are broadly proposed. This could include enhancing street lighting, increasing the greenbelt area, and so forth. Even their benefits have been demonstrated in many studies with reference to the appreciation of real estate value (Cheshire and Sheppard, 1995; Correll, Lillydahl and Singell, 1978); planners have recently focused on the extent to which street improvement projects have raised WTW. However, similarly, few have conducted systematic investigations to demonstrate relationship between WTW and SA. The necessary requirements are a suitable measure of WTW, an analytical model, and adequate empirical data. Street improvement studies usually evaluate the effects of a single street amenity, such as lighting (Willis, Powe, and Garrod, 2005). They tend to either focus on economic valuation without link to users' behavioral intentions, or perform qualitative analysis, without specifically suggesting a useful planning tool.

Additionally, arrangement of SA also affects walking mobility. This can be observed in a corridor when mobility difference is very high. A substantial difference in mobility would cause uneven pedestrian flow, particularly when it is due to elderly pedestrians. The rapidly aging population, especially in the developed countries has changed the demographic profile in Taiwan, and will continue to have a drastic impact on transportation planning in the coming decade (Meyer and Miller, 2001). It will result in temporary and local congestions in high density pedestrian corridors. Consequently, commuters must spend more travel time in these corridors to bypass slow pedestrians and to avoid a collision. This type of congestion tends to happen around elderly pedestrians walking very slowly. Figure 2 shows a photograph of a local congestion being created on a street in Taiwan.

However, designing SA to raise corridor performance is rarely discussed. Unless a pedestrian corridor is a new construction, the space available for widening the corridor is extremely limited. In that situation, the improvement program should focus on space design. But, when planning a pedestrian corridor, planners must pay close attention to capacity design, because misallocation tends to be the major source of pedestrian congestion in high density areas (Pushkare and Zupan, 1975). Fruin(1971) characterized the quality of the pedestrian flow at various levels of maximum capacity as level-of-service (LOS) to aid capacity design. This method is still widely used today, and its assumptions allow us to explore any new issues that we have to face, now or in the future. It assumes that a pedestrian flow is an even or homogenous stream, but in reality it is usually uneven. Pushkarev and Zupan found that a platoon of pedestrians causes an uneven flow, and they improved the traditional LOS method by taking the platoon effect into account.

Figure 2 A real case observed in Hsinchu City where an elderly man walks very slowly, and some of the surrounding younger pedestrians try to bypass while keeping a buffer zone in order to avoid collision. Some of them slowed down or stopped to give him the right of way.

Mobility differences are also dangerous for the safety of the elderly on the streets. Although my observation showed that the young tend to give the right of way to the elderly, the potential risk for a collision to occur remains. Both the elderly and the younger generations require space arrangement not only to prevent possible conflict between the 2 groups, but also to maintain operation efficiency. This problem intensifies in and around downtown healthcare institutions. Although there are provisions for people with disability, many of the elderly I mentioned here can walk freely, but do so at low speed.

The reports of successful real-world cases can be of use in corridor design, but only a few of them performed systematic analyses which could benefit planners to rationally and broadly assess their design (Marcus and Francis, 1998). Fortunately, Helbing and his partners built agent-based models (ABMs) to study pedestrians. They found that geometric form and design elements can stabilize the flow pattern and make them more fluid (Helbing et al., 2001; Helbing et al., 2000). However, their discussions don't cover the issue addressed in this thesis.

1.2 Objectives

Thus, this research addressed the above issues in three ways: First, I aim to improve the definition of traditional walking distance by taking into account the effect of the PEQ. Based on this improvement, I could then show the various walking distances according to the values of PEQ. I introduced the concepts of willingness to walk (WTW) and walking energy expenditure (WEE) and used WEE as a physiological measurement of WTW. Pandolf et al. (1977) provided an applicable metabolic rate (energy expenditure per time) equation, and I used heart rate method to measure energy expenditure. However, the environmental factors in Pandolf et al. (1977) only involved slope and terrain, so this study developed a model to predict the adjusted terrain factor by incorporating the effect of PEQ.

Second, I aim to develop models to determine which attributes of SA would psychologically raise people's WTW and to estimate how much WTW a specific improvement would increase. Because better street space can encourage people to walk more frequently (or for longer), my analysis is based on the notion of linear correlation between SA and WTW (Cervero and Kockelman, 1997; Cervero et al., 2009; Gehl, 2001; Untermann, 1984). Then, I classified the attributes of SA into right of way, lighting, planting, pavement, street furniture, retailing, and fountains (Booth, 1983; Mitra-Sarka, 1994) to systematically represent an improvement project as systematic alternative. I denoted walking time as psychological measures of WTW, not walking distance, because it is more suited to a self-reporting survey. A higher WTW was considered as an effect of improved amenities from improvement projects and was measured by modeling pedestrians' route choices. I believe these results can be applied to aid planners' street improvement practices, such as project design or alternative evaluation.

Third, I aim at building an approach to explore which type of pedestrian corridor design can improve the congestions resulting from the high difference in mobility among pedestrians. This issue needs to be addressed to respond to Taiwan's rapidly aging population. I built ABMs and designed a simulation experiment using fine-scale data to investigate the issue of the difference in mobility among pedestrians. This takes individual characteristics into account and aids to planners' street improvement practices, such as project design or alternative evaluation.

1.3 Research framework and approaches

The research framework of the thesis is shown in Figure 3:

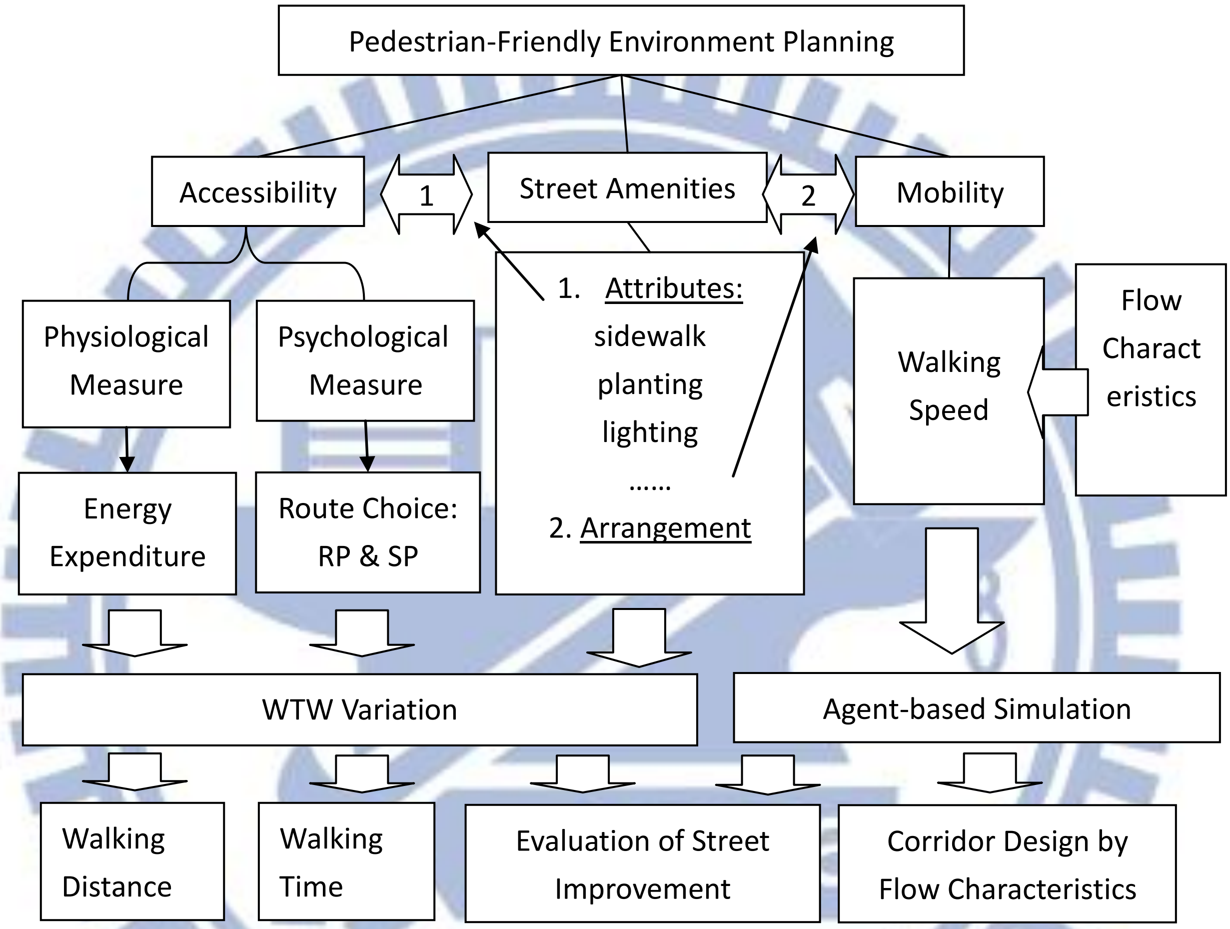

Figure 3 Analytical framework

As stated in the above, the research subjects include mobility, accessibility and street amenities. I first introduce the relationships among them and define willingness to walk. These may not be the first mentioned, but, here, I made a rigorous statement for it. Only based on it, the following systematic analyses can be successfully conducted. In term of physiology, WTW can be measured with walking energy expenditure (WEE). PEQ can represent the quality of street amenities. But how do I find an approach that enabled us to analyze the effect of PEQ on WEE? Heart rate (HR) can be a suitable indicator, and Pandolf et al. (1977) provides an applicable metabolic rate equation. However, the environmental factors in Pandolf et al. (1977) only involve slope and terrain. Previous studies categorized the values of the terrain factors based on the type of road surface. So this study developed a model to predict the adjusted terrain factor by incorporating the effect of PEQ. Statistical distribution was applied to observe the characteristics of the walking behavior and to estimate distances based on the cumulative probability levels of WEE. The level of WEE represents the level of effort expended during walking. This research assumes that the greater the effort required by the pedestrian to walk, the shorter the distance will be they are willing to walk. Thus, the distance that a certain proportion of pedestrians are willing to walk can be estimated from the cumulative probability of WEE.

Secondly, I introduce a psychological measure of WTW: walking time to meet the requirement when modeling pedestrians' route choices. Route choice commonly exists in people's daily walking trips, and has been applied to study pedestrian behavior, such as walking trajectory (Antonini et al., 2006). However, few studies have taken the effects of SA into account when modeling decision-making; thus, results would go for minimizing walking time (distance). I therefore designed a utility function to represent pedestrians' utility when completing a trip on a route of specified origin-destination (O-D), and take SA, walking time and individual characteristics into account. The route choice data included revealed (RP) and stated preferences (SP). RP is an approach to measure the real decision-making behavior, but it may be limited insofar the situation I tested entailed more than status. This usually happens when a project is intended to implement a great range of improvements that fall outside of respondents' experiences. The revealed preference method may suffer from colinearity among attributes. I therefore simultaneously survey SP data in which alternatives were designed as hypothetical routes with an orthogonal matrix to widen the test range of each attribute.

The case of Caogong Canal Regeneration was studied to validate the feasibility and application of our model. The case aims to improve SA by offering pedestrians street access to Fongshan Station of the Kaohsiung Mass Rapid Transit System (KMRT). All concepts and objectives of the case proved consistent with this research, and it actually attracts more pedestrians than before. As explained in the following section, I modeled route choice data using random-parameter logit due to the violation to the irrelevance of independent alternatives, and calibrated the utility function by applying the maximum likelihood estimation method. Then I estimated the increase of WTW of a project as the measure of effectiveness (MOE) for achieving walkability under budgetary constraints.

Thirdly, the analyses focus on the effects of street amenities arrangement on walking mobility. The street amenities arrangement is considered with six common types. Walking speed is the measure of walking mobility. In particular, the tested pedestrian flow varies with the percentage of the elderly to address the issue of aging population.

The method used to test performances among six common types of corridor is ABM, because it well represents the randomness and dynamic characteristics of walking, both of which are insufficiently represented using traditional estimation. Helbing and his associates made a great contribution to the application of ABM in walkway design. I modified their proposed agent-based pedestrian models (ABPMs) by adding a direction-choosing model to fit the passing behaviors in a pedestrian corridor. Then I designed a C program simulator to perform the experiment. A small sample was collected to verify the similarity between simulation and observation. I calculated the mean passing speed of a 30-run simulation for each situation and used it as the unbiased estimator of performance. Finally, the results of this study are shown as ex post Fruin's LOS for 20% of the elderly and suggestions are made for future planning studies.

CHAPTER 2 LITERATURE REVIEW

In the following contents, the definitions of WTW and SA are made for the following analyses. The previous literature is reviewed to address the issues and to aid to conclude principles for modeling and experiment design. The parameters used in agent-based modeling are also illustrated in this chapter.

2.1 Walking accessibility and mobility measures

In term of transportation, “accessibility” can be defined as: The means by which an individual can accomplish some economic or social activity through access to that activity (Meyer and Miller, 2001). Howard (1902) initially set walking accessibility measure as a half mile; Perry (1929) used a quarter mile (5-minute walk) as the radius of a neighborhood unit; and in Sweden it was set as a range of about 300~500m (Lynch and Hack, 1984). The characteristics of the pedestrian, e.g., trip purpose, gender, and age, and urban context may alter the acceptable distances (Clifton and Krizek, 2004). For example, Pushkarev and Zupan(1975) compared the cumulative distribution of walking distances for a trip at two Manhattan buildings. They found that trips to eat had the shortest walking distance and that shopping trips had the longest ones among five purposes (eat, work, pleasure, business and shop). However, to-date few studies have explored the variation in walking distance and its implication for pedestrians.

A useful method to express the variability of walking distance is the statistical distribution. As mentioned earlier, Pushkarev and Zupan(1975) applied this method to analyze walking distances. Seneviratne (1985) observed the distribution of walking distances by conducting a survey in the central business district of Calgary, Canada. It is worth noting that Seneviratne (1985) derived the critical distance of 243m (796 ft), at the maximum rate of change of the distribution function as the more reasonable estimate for the average walking distance of 250m (819 ft). This advanced application of statistical frequency for estimating walking distance inspired our later analysis.

“Mobility” can be defined as: The ability and knowledge to travel from one location to another in a reasonable amount of time and for acceptable costs (Meyer and Miller, 2001). For pedestrian, mobility indicator can be mean walking speed and acceleration. For example, Henderson stated that the desired speeds can be represented as a Gaussian distribution at 1.34±0.26 m/s (mean±standard deviation) (Henderson, 1971). Willis et al. calculated their observations and found that the data are distributed normally at about 1.47±0.299 m/s

(Willis et al., 2004). Imms and Edholm found that the mean speed of the elderly (60-99 years old) is about 0.74±0.29 m/s (Imms and Edholm, 1981). Rouphail et al. (2000) stated that if the elderly constitute more than 20 percent of the total pedestrians, the average walking speed would decrease to 0.9144 m/s (3.0 ft/s).

In short, walking mobility is the important characteristic that reflects age and health conditions. Studies have focused on accessibility and mobility measures, but the difference in mobility is rarely taken into account in public space design. This issue will be highlighted in the coming decades, because population rapidly ages in the most of developed countries.

2.2 Definitions of willingness to walk

This research defines willingness to walk (WTW) as a quantity that represents how much effort pedestrians are willing to spend to arrive at their destination. The following are some pertinent characteristics of WTW. First, WTW is associated with individual characteristics and the purpose of the trip (Clifton and Krizek, 2004). Second, the estimate of WTW varies depends on the estimator. A planner may estimate WTW from a different perspective than a user who must decide if s/he should make the trip or not. The discrepancy between these two estimates usually results in the planner's estimate not fitting that of the average user (usually too far for the user), and consequently the facility shows a low usage (Fruin, 1971). Third, WTW can be estimated using various measures. It has been estimated with distance and time (Howard, 1902; Perry, 1929). However, walking time is more suited to a self-reporting survey, because respondents can recognize time spent, but not distance traveled. Other studies looked at WTW in terms of how often people intend to walk. For example, Untermann (1984) proposed a negative exponential distribution to illustrate the relationship between frequency and walking distance, where about 70% of the people are willing to walk 500 feet, about 40% are willing to walk 1000 feet and only about 10% are willing to walk half a mile. A similar opinion can be found in Fruin(1971) and Gehl(2001). In addition, variations in walking distance or time spent walking are also important when assessing the need for improving street amenities. Nevertheless, this issue is rarely discussed in the literature.

2.3 Street amenities

The attributes of PEQ often include safety, comfort, attractiveness, and convenience and are associated with several street amenities (or elements), as summarized in Table 1(Fruin, 1971; Mitra-Sarka, 1994; Untermann, 1984). A higher level of street amenity will increase street space quality and give pedestrians a better walking experience. For example, a street with good lighting will reduce “fear”, a significant factor leading to a higher HR. Thus, energy will be expended at a lesser rate. If a pedestrian is used to expending a certain amount of WEE, his/her distance can be extended by improving the PEQ of the street.

Table 1 Attributes of pedestrian environment quality and their corresponding street amenities (source: Mitra-Sarkar, 1994; Untermann, 1984).

Attributes	Description	Amenities
Safety	Prevent conflicts and crime from vehicles or other activities through separation or protection	Sidewalk, lighting, signage
Comfort	Provide pedestrians protection from inclement weather by means of air and temperature control, protection from wind, rain etc.	Roadside trees, benches, arcade, pavement
Attractiveness	Attract pedestrians by the aesthetic arrangement of urban space, colorful design and visual diversity	Shop windows, retail activities, public art
Convenience	Reduce travel distance, enhance continuity of travel, and ensure good intermodal connection	Distance, pedestrian bridge, underground passages/walkways

There are seven physical attributes to represent SA: right of way, lighting, planting, street furniture, pavement, retailing, and fountains, as shown in Table 1. Although other attributes have been mentioned in previous studies, it is those selected that form a basic street space and significantly affect users’ behavior (Alexander, 1974; Appleyard and Lintell, 1972; Booth, 1983; Fukahori and Kubota, 2003; Gehl, 2001; Harris and Dines, 1997).

2.4 Variation to willingness to walk

Environmental factors will affect the WTW. Weather is a critical factor (Pushkarev and Zupan, 1975; Zacharias, 2001), but so is the design of the pedestrian environment. In turn, a higher WTW can be considered as an effect of improved amenities from improvement projects. Studies have found that the average acceptable walking distance can be readily be extended by creating a pleasant environment in the urban space (Lövemark, 1972; Untermann, 1984), as shown in Figure 4. It should be noted however that the environmental effect has limits. The upward trend tends to peak at the greatest distance people are willing to walk. In addition, the downward trend has a boundary as well, such as a bad street space where most pedestrians will not walk regardless of how short the distance is.

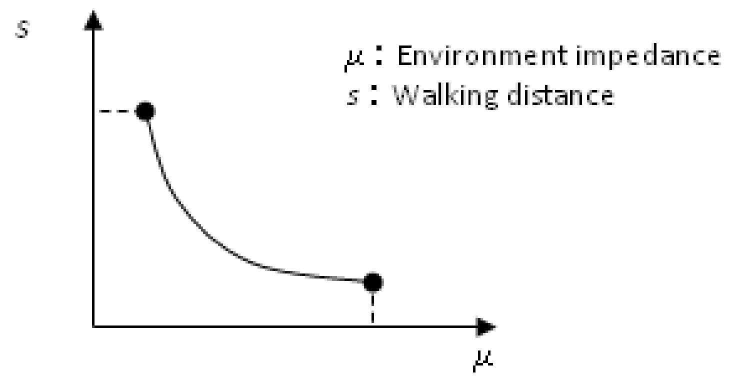

Figure 4 The trade-off between walking distance and the quality of pedestrian environment. *μ* is denoted as "environment impedance" the inverse of pedestrian environment quality.

2.5 Physiological effects

In the following, I argue that energy can be another measure of WTW. Energy expenditure is an important aspect of physiology. To measure WTW with energy, I must look toward the fields of exercise physiology and psychophysiology linking psychological perception and physiological response. The energy expenditure studies in exercise physiology have focused on specific groups (such as soldiers, people of a certain age group etc.), moving status (such as the walking speed), and the working environment (such as a moving platform to simulate ship motion) (Bastien et al., 2005; Demczuk, 1998; Heus et al., 1998; Rose et al., 1991). Methods to record EE often include the doubly labeled water technique, pedometers, oxygen consumption ($\dot{V}O_2$), carbon production ($\dot{V}CO_2$) and heart rate (HR). Among those, HR indicates the rate of oxygen consumption which relates linearly with HR (McArdle et al., 2007, pp. 206). It shows a close estimation and provides an affordable way to obtain reasonably accurate data in freely moving subjects (Spurr et al., 1988). Thus, this research uses HR to measure WEE.

Another question is how PEQ affects WEE through psychological perception. According to studies of psychophysiology, the effect from psychological perception can be observed by physiological measures, such as HR (Andreassi, 2007). HR indicates the arousal of the sympathetic nervous system (SNS). When a person walks on a street s/he perceives the PEQ, and this perception produces a specific emotion. This emotion causes an arousal of the SNS. Psychophysiology studies found that a negative mood state (such as fear) significantly increases a person's HR, thereby increasing energy expenditure at the same time. In contrast, a positive emotion, such as a pleasant feeling, will result in lowering the HR (Levenson et al., 1990). Since a good street environment results in pedestrians having a positive emotion, they spend less energy while walking.

2.6 Agent-based model in the dynamic pedestrian research

An ABM involves both the model and the simulator to observe the effect on the system of the interaction between agents as well as the interaction between agents and the environment (O'Sullivan and Haklay, 2000). The ABPM is one of the ABMs for pedestrians. Its strength lies in the use of fine-scale data and the "bottom-up" prediction (Bonabeau, 2002). Traditionally, the transportation models used the data scale to study pedestrians, but they focused more on O-D pair analysis and used a higher scale than the scale for walking (Batty, 2001). The traditional prediction models are aggregative and built with "top-down" thinking, while the emerging notion of prediction turns to the "bottom-up" thinking, where observed events are collected and to allow the development of superior systems. Thus, pedestrian movements can be simulated to predict a more global structure from the local action and reflect the actual characteristics of the local environment (Batty, 2005).

One issue when building an ABPM is how to choose a suitable scale for the spatial data. The types of spatial data in an ABPM can be categorized as discrete or continuous. Cellular automata (CA) is a widely-used discrete type ABPM and its successful application can be found in Batty (2005). Continuous spatial data can be found in studies using Cartesian coordinate system, like Helbing et al. (1995) or in flow analyses. The former marks space and location in a grid and may be too rough to observe any local congestions or the performance of the design. Therefore, continuous data is preferred in the present study.

Agents, the environment and rules are the three components of the ABPM simulator (Epstein and Axtell, 1995). An agent of a pedestrian is coded by giving it human dimensions and behavioral characteristics, such as walking speed, body depth, shoulder width and personal space (Fruin, 1971). The range of these characteristics is large. Measures also vary across social factors and culture, and thus behavior characteristics should be surveyed to ensure they fit the local environment (Hall, 1966).

Environment in an ABPM refers to the artificial world for space and facilities. Recently, bottlenecks, room and channel have been simulated to observe the effects of geometrical form (e.g., funnel), behavioral characteristics (e.g., visual perception) and collective behavior (e.g., lane formation) (Helbing et al., 2001; Turner and Penn, 2002; Isobe et al., 2004). It was found that the geometrical form of the design significantly affects a system's performance. This finding indicates that congestion can be improved.

The behavior of agents is governed by a set of rules or a strategy. Maximizing utility and minimizing cost are often applied to analyze route choice (Antonini et al., 2006; Hoogendoorn and Bovy, 2005). Other objectives like minimum energy expenditure or keeping a desired speed, can be developed as strategies (Hsu and Tsai, 2010). Rules and strategies must be designed to fit the environment, because agents act for specific purposes. In this study, pedestrians pass each other in corridors by changing direction in order to bypass slow-walking pedestrians. This strategy can maximize spaciousness and it is discussed in the next section.

Applying an ABPM for a pedestrian corridor design is rarely found in the literature. The most relevant issue is the analysis by Helbing et al. (Helbing et al., 2005). They applied their "social force model" to the analysis of improving walkways, bottlenecks and intersections. They found that a series of columnar objects, e.g., a railing or a row of trees, in the middle of a road can stabilize a lane or a tunnel where impatient pedestrians try to overtake one another but are obstructed by the opposite stream. They also found that a funnel-shaped design can improve a pushy crowd. However, they did not offer any suggestions for dealing with the substantial difference in mobility, nor did they take the effect of reducing the effective width of the corridor into account.

2.7 Summary

In this chapter, I have reviewed the literature of WTW. This thesis integrated the statements from the published studies to make the rigorous definition to illustrate its relationship with street amenities. The previous studies mostly agree that better SA can enhance WTW within a range, but we need empirical evidences to conduct the following analyses. That is because only when the linearity between SA and WTW is ensured, the analyses and prediction can be conducted with Pandolf et al. and discrete choice models I used.

The characteristics of ABM are also reviewed to aid the following study. I first highlighted the advantage of ABM for the dynamic characteristics of pedestrians. The components of ABM generally include rule, scale and parameters. The third is important for the following ABM simulations, because the corridor is designed to reflect a population aging society. By these parameters, the following simulations can be conducted close to the real world. This idea may not be new; in particular ABM recently receives much attention. However, its application for space design by comparing the mobility performances may be a new creation.

CHAPTER 3 ESTIMATING WALKING DISTANCE

To achieve the goals outlined in the previous sections, there are some methodologies designed in the following. The estimated walking distances are also shown to aid to practice.

3.1 Energy expenditure

Walking primarily costs the pedestrian time and physical effort (Pushkarev and Zupan, 1975), and a typical measurement of physical effort is energy expenditure (EE) (McArdle et al., 2007). Let's introduce a "work" type equation, (1), to illustrate the process of EE:

$$e_w = m \cdot g \cdot \int v(t)\mu(\mathbf{r})dt \tag{1}$$

where a pedestrian with a body weight *m*, walks with a speed function $v(t)$ on a sidewalk where the friction value at position $\mathbf{r}$ is $\mu(\mathbf{r})$ and *g* is the gravitational acceleration(9.8m/s^2). If a pedestrian has been walking for a period of time *t*, the total amount of energy s/he consumed is about e_w. If street environments can be categorized by street types, then equation (1) can be rewritten as:

$$e_w = \sum_{p=1}^{P} m \cdot g \cdot \mu_p \cdot s_p \tag{2}$$

where a route involves *P* types of streets, and s_p is the walking distance of a pedestrian walking at a constant velocity *v* for a period of time *t* on a type *p* street; and μ_p is the friction on a type *p* street. If we sum the energy consumption for each type of street, then we get the total energy consumption e_w. It is evident that there is a trade-off for the pedestrian between *s* and μ under a given EE, as shown in Figure 3.

Pandolf et al. (1977) illustrated a WEE model from a physiological perspective:

$$W = 1.5m + 2(m+l)(l/m)^2 + n \cdot (m+l)(1.5v^2 + 0.35v \cdot G) \tag{3}$$

where *W* is the metabolic rate or energy expenditure per second (J/s, watts) ; *m* is the body weight (kg); *l* is the load carried (kg); *v* is the velocity (m/s); *G* is the grade (%); and *n* is the terrain factor or friction. To determine the total amount of WEE, the metabolic rate needs to be multiplied by the walking time *t*:

$$e_w = W \cdot t \tag{4}$$

where the unit of e_w is in joule(J). Hall et al. (2004) compared the published energy expenditure models, and found that the prediction of Pandolf et al.'s model (1977) is very close to the actual value of the walking energy expenditure.

It is worthwhile to note that Pandolf et al. (1977) used two factors to reflect the environmental effects on WEE: terrain factor and grade. The terrain factor was originally defined as an additional WEE where pedestrians had to overcome the friction of the road surface, similar to friction μ in our equation (1). Several studies conducted experiments to establish a set of terrain factor values (n) based on the type of road surface, including blacktop (1), dirt road (1.1), light brush (1.2), heavy vegetation (1.5), swampy bog (1.8), loose sand (2.1) (Pandolf, et al., 1976; Soule and Goldman, 1972).

However, these values do not consider the effect of psychological perception, and the observed value ($\tilde{n}$) measured from real streets may not be equal to the theoretical value that were tested under controlled conditions ($\tilde{n} \neq n$). Thus, the terrain factor ($\hat{n}$) needs to be redefined and adjusted to reflect the actual characteristics of the real street space.

Thus, for the adjustment process we first take the terrain factor as an inverse function of equation (5):

$$\tilde{n} = f(W, m, l, v, G) \tag{5}$$

A vector of variables $\boldsymbol{x}$ contributes to the variance of the terrain factor, except the variables in equation (5). These additional effects of the street's amenities can be aggregated as parameter δ for adjusting the theoretical value n to be the observed value ($\tilde{n} = \delta \cdot n$). The adjusting parameter can then be written as:

$$\delta = \Omega(x_1, x_2, \ldots, x_M) + \varepsilon \tag{6}$$

where $\Omega(\boldsymbol{x})$ is a function consisting of a vector of street factors that significantly affect the WEE, M is the number of factors, and ε is the error term. In the walking spaces in urban areas, the road surface tends to be homogeneous, such as concrete, asphalt, brick etc. According to the previous definition, its theoretical value is similar to that of a treadmill or blacktop ($n \approx 1$). So the observed value can be shown as:

$$\tilde{n} = \delta \cdot 1 = \Omega(\boldsymbol{x}) + \varepsilon \tag{7}$$

The adjusted terrain factor can be estimated through $\Omega(\boldsymbol{x})$ ($\hat{n} = \Omega(\boldsymbol{x})$). Then equation (3) can be rewritten as:

$$W = 1.5m + 2(m+l)(l/m)^2 + \Omega(\boldsymbol{x}) \cdot (m+l)(1.5v^2 + 0.35v \cdot G) \tag{8}$$

and we can then use the modified model from Pandolf et al. (1977) to perform the following analyses.

In addition, this research introduces the "iso-energy curves" concept to enhance the WEE application. We have described a scenario where people are used to a certain amount of

WEE. In reality, WEE varies greatly and depends on many factors, including trip purpose. A greater WEE, as shown in Figure 5 using Pandolf et al.'s (1977) model, implies that the pedestrians must expend more effort during walking. This may be unfavorable for some activities, like commuting.

For those activities, the levels of WEE can be applied to represent the levels of disutility for a pedestrian. A similar concept can be found in the level-of-service (LOS) for pedestrian walkways (Fruin, 1971). WEE results in a degree of 'tiredness' which can be seen as another measure for walking LOS. Thus we termed the set of WEE curves as "iso-energy curves" to illustrate the WEE-based method for evaluating WTW in the following discussions.

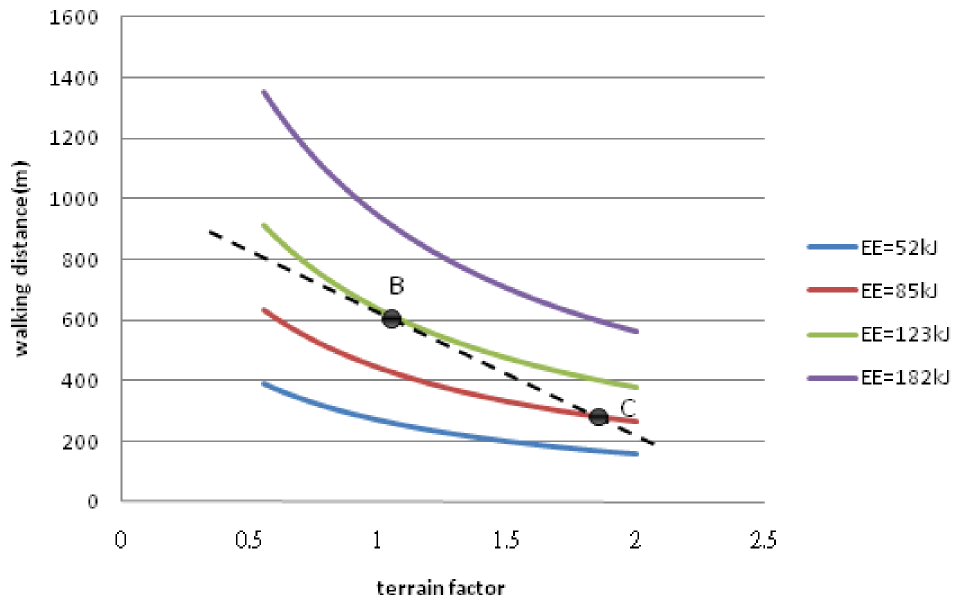

Figure 5 Relationship between terrain factor and walking distance. These iso-energy curves and the constraint line (line B-C) can be used to analyze route choice behavior.

3.2 Energy expenditure experiment

For the following energy expenditure analyses, the predictive function $\Omega(x)$ needs to be established. Thus this research designed an experiment and would recruit 30 participants, 15 men and 15 women, to conduct experiments on seven distinct types of streets. In order to determine the effect of timing (day or evening) and to enlarge the sample size, the subjects would be asked to walk up and down each street, once during the daytime and once in the evening (after dark). Thus, a total of 840 samples would be collected to perform a regression analysis. It was a compromise necessitated by the limited budget.

Streets of seven main types in Hsinchu City, Taiwan would be investigated in this experiment, including arterial roads, boulevards, residential streets, mixed-use streets, commercial parkways, downtown streets, and alleys (Marshall, 2005). The locations of those streets are shown in Figure 6.

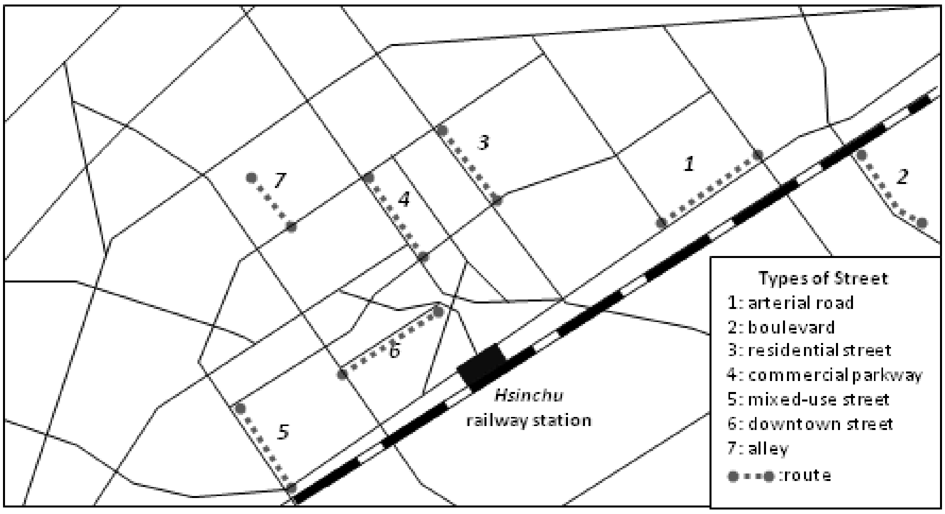

Figure 6 These seven experiment sites were chosen to represent the main street types in Taiwan.

The street spaces are shown in Table 3.1. There are five street elements representing the attributes of these streets in Table 3, including right of way (ROW), width (WD), planting (PL), lighting (LG) and land use.

As to the instrument, this research would use a Polar RS300Xsd heart rate monitor consisting of a watch-style computer, a chest strap, and a speed-distance transmitter to record the wearer's energy expenditure. Before testing, the Polar RS300Xsd asks for the participant's characteristics (birthday, body weight, height and gender) to be inputted, and to test the participant's fitness to determine the max. oxygen consumption ($\dot{V}O_{2\max}$) and max. heart rate (fH), which are then used as the individual parameters. $\dot{V}O_{2\max}$ is the maximum capacity of the body to contain and utilize oxygen during incremental exercises.

This capacity reflects the physical fitness of the individual and accounts for a significant portion of the variation in metabolic rate (Poehlman et al., 1990). The device also records the walking speed, walking time, and walking distance, all of which are required to analyze the terrain factor value through equation (8).

Table 2 Spatial characteristics of the experiment sites.

Experiment sites	Types of street	Main walking space	Width(m)	Right of way	Land use	Planting	Lighting (Lux)
1	Arterial road	Shoulder	2	Shared	Mixed-use	Shrubs	6
2	Boulevard	Sidewalk	5	Exclusive	Mixed-use	Trees	8
3	Residential street	Sidewalk	2.5	Exclusive	Residential	Trees	6
4	Commercial parkway	Sidewalk	3	Exclusive	Commercial	Trees	12
5	Mixed- use street	Arcade	2	Shared	Mixed-use	Shrubs	9
6	Downtown street	Arcade	1.5	Exclusive	Commercial	Potted plants	14
7	Alley	Lane	4	Shared	Residential	Potted plants	4

Note: Width, right of way, land use, planting and lighting are independent variables of regression analysis. Their codes are shown in Table 5.

Prior to the tests, each participant would be informed as to the purpose of the experiment and received training in the operation of the Polar RS300Xsd. Then the subjects tested their personal $\dot{V}O_{2\max}$ value as the parameter for the device to compute the WEE while avoiding any distractions. Heavy physical exertion, smoking and consuming a large meal prior to the test are also avoided. The participants refrained from frequently visiting those streets prior to the test in order to avoid becoming too familiar with those sites, which could then result in a lower stimulus.

During walking, the participants would be asked to maintain as much possible a constant walking speed in order to reduce the inaccuracy resulting from using the mean walking speed as the input velocity *v*. In addition, the subjects would be asked to rest for ten minutes before their next test to avoid the effect of the previous walk influencing their metabolic rate in the next test. All experiments would be carried out in dry weather.

Table 3 Summary of independent variables.

Variable	Data Scale	Value (Unit)	Description
Physiological factors			
Gender (GE)	categorical	Male=1 Female=0	To reflect the physiological difference between male and female
$\dot{V}O_{2\max}$	continuous	(Milliliters oxygen/ kilogram/ minute)	To indicate the difference in physical fitness between the subjects
Design factors			
Right of way(ROW)	ordinal	Shared=1 Exclusive=0	To indicate pedestrians walking under disturbance or not.
Width(WD)	continuous	(m)	Degree of space offering pedestrians unobstructed walking
Planting(PL)	ordinal	Potted plants=1 Shrubs=2 Trees=3	The level of street planting coded as a ordinal variable indicating more green area, more pleasant surrounding
Lighting(LG)	continuous	(Lux)	Facility to indicate a safe walking environment after dark
Land use factors			
Commercial(CM)	categorical	Commercial=1 Mixed-use=0	Land use with various commercial activities as the main attraction for the pedestrians
Mixed- use(MU)	categorical	Commercial=0 Mixed-use=1	A popular pattern of land use in Taiwan mixing retail outlets, residential, service and other functions
Residential(RS)	—	Commercial=0 Mixed-use=0	Land use with low intensity and simple function for residential use only
Environment factors			
Evening(NI)	categorical	Evening=1 Day=0	To differentiate walking in daytime or evening
Temperature	continuous	(℃)	A degree of comfort in the open air; the range is from 18℃ to 28℃

Note: Land use is indicated by means of dummy variable, thus RS is absence of the independent variables.

The questionnaire consists of basic personal data, origin-destination pair survey, and the street characteristics along the routes. For the personal basic data, each respondent would be asked to provide personal basic data including age, gender, body weight (kg), and the load they carried (kg). The load carried would be recorded by the respondent checking the six enumerating types of carried items marked with weight, such as a notebook (2kg). Each of the respondents described their daily commuting trip using an origin-destination pair table, as shown in Table 4.

Table 4 Example of O-D pair table.

Links of trip	Origin	Destination	Mode of transportation	Walking distance(m)	Duration(min)	Street type	Slope(%)
Ⅰ	A	B	1	200	5	5	0
Ⅱ	B	C	2	—	10	—	—
Ⅲ	C	D	3	—	13	—	—
Ⅳ	D	E	1	450	8	7	0

Note: Mode of transportation, 1. walking, 2. bus, 3. rapid transit, 4. bicycle, 5. motorcycle.

Each respondent then identify all places they visited during their trip on a map (such as origin, transit stop, and destination) and then link them as a route. A commuting route might involve several links divided by mode of transport or street type, but the walking link is the only item of concern in this research. The participants would be asked to just write down the walking time for each link, and then I measure each walking distance. Walking velocity would be obtained by dividing each walking distance by the walking time. To compute the adjusted terrain factor value through equation (8), each respondent would mark down how they felt about the right of way, lighting, and planting (see Table 3) by check-marking the items which are shown complete with a sample photograph. For example, the respondents indicate the lighting level from a picture, and then the corresponding Lux number would be used as the input value.

It is unrealistic to assume that respondents can or will spend time on measuring $\dot{V}O_{2\max}$ through a device during the interview. Fortunately, Shvartz and Reibold(1990) provides an age-based method to check the $\dot{V}O_{2\max}$ value after the participant provides the information on their age and gender and how long s/he participates on a regular basis in sports per week.

This allows us to apply equation (8) to calculate the estimated metabolic rate and multiply it with the walking time in each street type. I then summed them using equation (4), and then estimate the walking energy expenditure for each commuting trip:

$$e_w = \sum_{k=1}^{K} w_k \cdot t_k \tag{9}$$

where K denotes the number of street types; w_k denotes the metabolic rate while walking on a type k street, and t_k denotes the walking time on a type k street.

3.3 Results

Then a regression analysis was performed using SPSS 12.0 to establish the predictive model $\Omega(\boldsymbol{x})$. The summary of the values for the observed terrain factors for the seven street sites are shown in Table 3.4. The regression analysis included two steps: the first step was to examine the statistical insignificance among the candidate variables. After deleting the insignificant variables, the second step in designing the predictive model was performed. As shown in Table 5, there is a difference in the ranking of the mean observed values between daytime and evening. In addition, each site shows substantial variation, implying that individual characteristics and timing may contribute at least in part to the effects. Thus, in addition to the five street factors, gender, $\dot{V}O_{2\max}$, timing and temperature are also involved in step 1.

It must be noted that the coding method determined the final number of variables used in regression analysis. For example, we treated land use as a categorical (nominal) variable and coded it as a dummy variable, and it is therefore examined for two types of land use. Planting is assumed to be an ordinal variable because there is wide agreement that a greener area is more pleasing to pedestrians. A more detailed explanation of those variables is discussed in Table 6. A total of 10 candidate variables are used in the first step of the regression analysis.

Other coding methods such as effect coding are worth considering, but they must be designed to fit the surveyed pedestrian environment. For example, when using effect coding, the question is usually termed as “good, fair, poor”, and the codes may then be set as “+1, 0, -1”. However, this is more suitable for psychological measurement. Regarding planting (PL) in this research, green areas are available in most of our surveyed streets, so the question design actually focuses on how green the street is. Coding potted plant as -1 seems to be unsuitable.

Table 6 shows that two personal physiological factors, gender (GE) and $\dot{V}O_{2\max}$, are statistically significant. This suggests that the value of the terrain factor will significantly vary with gender and $\dot{V}O_{2\max}$. A negative sign for the gender variable indicates that, when all other factors are equal, women expend more energy than men. It is probable that women generally have smaller muscle mass and produce less power, thus they put greater effort into the same movement. Kerr et al. (2001) found a similar phenomenon in stair-climbing: after placing motivating messages on the stair risers, men are significantly more willing to use stairs than women. Their finding confirms the effect of gender on WTW. $\dot{V}O_{2\max}$ proves to be strongly significant, suggesting that physical fitness is a determining factor for energy expenditure, and that $\dot{V}O_{2\max}$ reflects individual physical fitness rather than age.

Right of way (ROW) was found to be statistically significant, but the width of the walking space was not. These findings suggest that the range of walking space width (WD) from 1.5 to 5 m does not significantly affect the terrain factor. This is probably due to the fact that the testing range of the width of the walking spaces being tested was wide enough for most participants to walk unhindered. On the other hand, the disturbance from vehicles and incompatible activities significantly affected a pedestrian's energy expenditure. Lighting (LG) had a negative sign and was significant, suggesting that good street lighting contributes greatly to the street amenity. It also suggested that heart rate increases significantly at night but declines when the lighting level is higher. Planting (PL) also shows a significant effect on WEE, confirming that the larger the green area, the higher the amenity of the street. Temperature is not statistically significant, possibly because the participants were used to the range of 18~28℃ weather and temperature did not significantly affect energy expenditure.

Walking in the evening (NI) causes a greater terrain factor value than during the daytime. It is possible that individuals must make more effort to understand the environment or are more concerned about personal safety when lighting levels are low. The greater effort results in a higher heart rate. Both land use factors (CM and MU) were not statistically significant, indicating that land use patterns did not lead to a significant difference in energy expenditure between the seven streets in our experiment.

At the second stage, we removed the insignificant variables and developed a terrain factor predictive function. This function was designed because some variables had independent effects while others reflected interactive effects. For example, lighting is used mainly after dark, and therefore the best calibrated predictive function of an adjusted terrain factor is shown as:

$$\hat{n} = 0.036\dot{V}O_{2\max} - 0.528GE + 0.152ROW + 0.408NI - 0.02NI \cdot LG - 0.074PL - 0.386 \quad (10)$$

where the fourth and fifth terms are designed for variables with interactive effects in which *NI* is a dummy variable to reflect walking after dark (*NI*=1) or during daytime (*NI*=0). The multiplication term of lighting-evening means that street lighting reduces friction after dark by enhancing visibility, but it only operates when walking during the evening. The variance inflation factor (VIF) is a statistical index that measures how much the variance of an estimated regression coefficient is increased because of collinearity. The values in Table 6 show that the variables in the predictive function do not have significant collinearity (VIF < 10). Since *NI* and *LG* are designed as interactions, compared to a linear function, the VIF for *NI* increases from 1.026 to 5.639 and for *NI* · *LG* it increases from 1.47 to 5.910, respectively.

Table 5 Experiment outcome summary.

	Day		Evening	
Experiment site	$\hat{n}$	tau c	$\hat{n}$	tau c
1(Arterial road)	0.798±0.393	0.230(0.076)	1.130±0.631	0.314(0.034)
2(Boulevard)	0.661±0.342	0.305(0.047)	0.833±0.476	0.345(0.052)
3(Residential street)	0.607±0.311	0.208(0.069)	0.841±0.474	0.510(0.001)
4(Commercial parkway)	0.592±0.283	0.317(0.035)	0.722±0.395	0.238(0.062)
5(Mixed-use street)	0.755±0.367	0.289(0.054)	0.901±0.485	0.328(0.002)
6(Downtown street)	0.738±0.363	0.078(0.605)*	0.938±0.466	0.125(0.500)*
7(Alley)	0.696±0.361	0.355(0.008)	1.067±0.607	0.322(0.026)

Note: The adjusted terrain factor values ($\hat{n}$) are shown as $\text{mean} \pm SD$; tau c is shown as value (p-value) ; * not significant at the 10% level.

To determine the consistency between psychological perception and physiological response, the participants ranked all streets by preference (1~7). We then compared the data of the observed ranking of the terrain factor by means of Kendall's tau c test. As shown in Table 5, most sites show a statistical consistency between psychological and physiological rankings at the 10% significance level, but site 6 does not. This discrepancy may be due to the unexpected effects site 6 had on some of the participants. Site 6 is a downtown street with a variety of activities and actors in a compact arcade, such as street vendors. We may have overlooked the fact that some positive emotions such as excitement also cause a high heart rate. However, this is beyond the scope of this research, and we will leave that to future study.

Table 6 Results of regression analysis.

	Step 1		Step 2		
	Coefficients	Significance	Coefficients	Significance	VIF
GE	-0.537	0.012	-0.528	0.005	1.178
$\dot{V}O_{2\max}$	0.037	0.02	0.036	0.001	1.181
ROW	0.12	0.016	0.152	0.011	1.194
WD(m)	-0.03*	0.131	—	—	—
PL	-0.058	0.032	-0.074	0.006	1.09
LG	-0.029	0.048	—	—	—
CM	0.095*	0.202	—	—	—
MU	0.029*	0.584	—	—	—
NI	0.222	0.004	0.408	0.001	5.639(1.026)
Temperature	-0.006*	0.314	—	—	—
Constant	0.031*	0.877	-0.386	0.032	—
NI×LG	—	—	-0.02	0.015	5.910(1.47)
Adjusted R^2	0.722		0.721		

Note: Step 1 is performed to examine statistical significance of the variables, * removed when not significant at the 5% level; step 2 is performed to design the regression model.

3.4 WEE distribution

After developing an adjusted terrain factor model we conducted a small sampling to observe the WEEs and their aggregate characteristics. Walking distances were estimated to aid planning by means of statistical distribution.

I conducted a trip behavior survey of commuters from the urban area of Taipei to collect data for calculating their WEE. The survey was conducted around several rapid-transit stations using face-to-face interviews between March 1 and June 30, 2010. By applying stratified sampling, the data from a total of 385 commuters from 12 districts in Taipei city were collected. This sampling fraction was based on the percentage of employment in each districts (Beitou 3%, Da-an 16%, Zhongshan 20%, Zhongzheng 17%, Xinyi 8%, Shilin 4%, Songshan 12%, Nangang 3%, Wanhua 2%, Datong 5%, Neihu 8%, Wenshan 2%) (Taipei City Government, 2009).

The questionnaire consists of basic personal data, origin-destination pair survey, and the street characteristics along the routes. For the personal basic data, each respondent was asked to provide personal basic data including age, gender, body weight (kg), and the load they carried (kg). The load carried was recorded by the respondent checking the six enumerating types of carried items marked with weight, such as a notebook (2kg). Each of the respondents described their daily commuting trip using an origin-destination pair table, as shown in Table 4.

Each respondent then identified all places they visited during their trip on a map (such as origin, transit stop, and destination) and then linked them as a route. A commuting route might involve several links divided by mode of transport or street type, but the walking link was the only item of concern in this research. The participants were asked to write down just the walking time for each link, and then we measured each walking distance. Walking velocity was obtained by dividing each walking distance by the walking time. To compute the adjusted terrain factor value through equation (9), each respondent marked down how they felt about the right of way, lighting, and planting (see Table 3) by check-marking the items which were shown, complete with a sample photograph. For example, the respondents indicated the lighting level from a picture, and then the corresponding Lux number was used as the input value.

It is unrealistic to assume that respondents can or will spend time on measuring $\dot{V}O_{2\max}$ through a device during the interview. Fortunately, Shvartz and Reibold (1990) provide an age-based method to check the $\dot{V}O_{2\max}$ value after the participant provides the information on their age and gender and how long s/he participates in sports per week on a regular basis. This allowed us to apply equation (3.9) to calculate the estimated metabolic rate and multiply it with the walking time in each street type. We then summed them using equation (11), and then estimated the walking energy expenditure for each commuting trip:

$$e_w = \sum_{k=1}^{K} w_k \cdot t_k \tag{11}$$

where K denotes the number of street types; w_k denotes the metabolic rate while walking on a type k street, and t_k denotes the walking time on a type k street.

A summary of the sample is shown in Table 7 and the total walking energy expenditure is plotted as a histogram in Figure 7. From the right-skewed distribution it is evident that commuters tend to pick an effort-saving route. Time (or distance)-saving has been demonstrated to be a characteristic of WTW with right-skewed distribution (Pushkarev and Zupan, 1975; Seneviratne, 1985). This characteristic is obvious since the available time of most commuters is constrained, and as such, maximum walking distance is rarely attained. This survey developed a deeper understanding of commuting trips by including effort-saving characteristics which take the effect of PEQ into account.

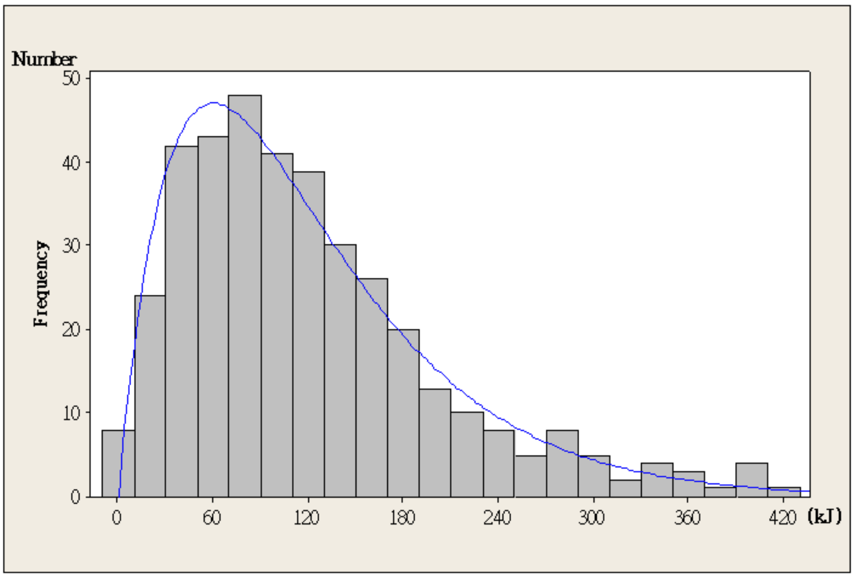

Figure 7 The statistical distribution of the observed WEEs shows right-skewed.

To estimate a specific distribution for the WEEs, this study assumed three distribution functions: Gamma, Normal and Exponential, to perform the goodness of fit with the Chi-squared test. The results show that only the Gamma distribution is a suitable model for representing the e_w distribution ($0.979<\chi^2_{(0.95;\ df=8)}=15.5$), denoted as:

$$e_w \sim \mathrm{Gamma}(\alpha = 2.1137, \lambda = 56.977) \tag{12}$$

where α is a shape parameter, and λ is a scale parameter.

Table 7 Individual and trip characteristics of the commuters.

Characteristics	Mean	SD	Minimum	Maximum	Skewness[a]	Kurtosis[b]
Age	29.15	8.23	16	63	1.50	2.56
Weight(kg)	60.03	11.16	39	98	0.62	-0.42
Load carried(kg)	0.33	0.61	0.00	5.00	3.55	17.43
Velocity(m/s)	1.44	0.40	0.55	2.00	-0.34	-0.91
$\dot{V}O_{2\max}$ (mL/kg/min)	37.43	5.37	24	49	-0.02	-0.38
Slop(%)	0.01	0.04	-0.05	0.50	6.08	54.23
Total walking distance(m)	704.90	498.40	50	4230	2.39	10.36
Total walking time(min)	11.65	7.90	1.00	52.50	1.52	3.81
Percentage of walking time (%)	51.40	37.06	5	100	0.35	-1.58
WEE(kJ)	120.43	82.84	3	410	1.19	1.35

Note:

a. Skewness value approaches zero when data are symmetrical; the value is greater than 0, when data are right skewed; if the distribution's tail points to the left, it shows a negative skewness value.

b. A perfect normal distribution shows a kurtosis value of 0; a distribution with a sharper than normal peak shows a positive kurtosis value; a flatter than normal peak indicates a negative kurtosis value.

3.5 Walking distance estimates

The expected value, the center of gravity of a probability distribution, represents a reasonable point estimation for our right-skewed distribution. In a Gamma distribution, the expected value is $\alpha\lambda$, and thus the expected value of e_w is approximately equal to 120 kJ. Using equations (3) and (9), we derived the expected walking distance as about 505~1113m ($\hat{n}$ =1.35~0.35) with sample means (60 kg weight, 0.33 kg carried, 1.44 m/s walking speed). This range of walking distance seems to be greater than the traditional distance of about 402 m (a quarter mile), but covers the average walking distance of about 525 m (1,720 ft) observed by Pushkarev and Zupan (1975). The two estimates were found to be less than our average (704.9 m). It is possible that the earlier walking distance of a quarter mile was an estimate of the willingness to walk on a local trip, such as from home to a local service center (Perry, 1929). To date, trip length extends as a result of the urban sprawl (Meyer, 1995), and many commuters must travel from the suburbs to downtown because their spheres of activities are not restricted to a local neighborhood or community.

In addition, this distance can be broken down by classifying the WEEs into levels. Assume that a greater WEE yields a lower utility for commuters because most of them need to conserve energy for the coming work. We classified the cumulative distribution of WEE (e_w) into five levels of percentiles. The first level is set below the 20th percentile of WEE, and represents the lowest level of feeling tired among the five levels, and the walking distance derived means that 80% of the commuters will accept it. Second, the space characteristics in Table 3 and the sample means of the individual characteristics are used as the inputs for equation (9) to calculate the adjusted terrain factor ($\hat{n}$). As a result, the walking distances by men and women can be derived for the seven types of streets (see Table 8).

These distances offer planners a new accessibility-evaluating tool for considering space and individual characteristics. For example, commuters require easy and ample access to a transit station, or a convenience store which should be located close by so that the vast majority of their consumers can quickly do some emergency shopping. In these cases, level A or B distances are suitable. Distances at the same or similar level of WEE can be regulated by street amenities, and the planner can find the most similar street in Table 3 and use its corresponding distance in Table 8 as the acceptable distance. If the facility is gender-specific, such as dormitories or washroom facilities, the planner can find male and female measures in Table 8 to aid in choosing the location, or to evaluate the service area.

Table 8 Estimates of walking distance by street type and gender.

Level	Cumulative probability (%)	WEE (kJ)	Street type	Walking distance (male)	Walking distance (female)
A	$P \le 20\%$	$E \le 52$	Alley	$S \le 243$	$S \le 256$
			Arterial road	$S \le 263$	$S \le 274$
			Mixed-use street	$S \le 276$	$S \le 284$
			Residential street	$S \le 317$	$S \le 317$
			Downtown street	$S \le 321$	$S \le 320$
			Boulevard	$S \le 329$	$S \le 326$
			Commercial parkway	$S \le 356$	$S \le 346$
B	$20\% < P \le 40\%$	$52 < E \le 85$	Alley	$243 < S \le 397$	$256 < S \le 418$
			Arterial road	$263 < S \le 431$	$274 < S \le 447$
			Mixed-use street	$276 < S \le 451$	$284 < S \le 464$
			Residential street	$317 < S \le 519$	$317 < S \le 518$
			Downtown street	$321 < S \le 524$	$320 < S \le 523$
			Boulevard	$329 < S \le 538$	$326 < S \le 533$
			Commercial parkway	$356 < S \le 582$	$346 < S \le 566$
C	$40\% < P \le 60\%$	$85 < E \le 123$	Alley	$397 < S \le 574$	$418 < S \le 605$
			Arterial road	$431 < S \le 623$	$447 < S \le 647$
			Mixed-use street	$451 < S \le 652$	$464 < S \le 672$
			Residential street	$519 < S \le 750$	$518 < S \le 750$
			Downtown street	$524 < S \le 759$	$523 < S \le 757$
			Boulevard	$538 < S \le 778$	$533 < S \le 772$
			Commercial parkway	$582 < S \le 842$	$566 < S \le 820$

Table 8 (continued).

Level	Cumulative probability (%)	WEE (kJ)	Street type	Walking distance (male)	Walking distance (female)
D	$60\% < P \leq 80\%$	$123 < E \leq 182$	Alley	$574 < S \leq 849$	$605 < S \leq 895$
			Arterial road	$623 < S \leq 922$	$647 < S \leq 957$
			Mixed-use street	$652 < S \leq 956$	$672 < S \leq 994$
			Residential street	$750 < S \leq 1110$	$750 < S \leq 1110$
			Downtown street	$759 < S \leq 1122$	$757 < S \leq 1120$
			Boulevard	$778 < S \leq 1152$	$772 < S \leq 1142$
			Commercial parkway	$842 < S \leq 1245$	$820 < S \leq 1213$
E	$P > 80\%$	$E > 182$	Alley	$S > 849$	$S > 895$
			Arterial road	$S > 922$	$S > 957$
			Mixed-use street	$S > 965$	$S > 994$
			Residential street	$S > 1110$	$S > 1110$
			Downtown street	$S > 1122$	$S > 1120$
			Boulevard	$S > 1152$	$S > 1142$
			Commercial parkway	$S > 1245$	$S > 1213$

Note: The values of the adjusted terrain factor are calculated using equations (3) and (9), and the inputs for the individual characteristics are our sample means. The inputs for the 7 street types are given in Tables 3 and 5; all distances are assumed walked on a continuous uniform street; the means of the female sample include 53 kg weight, 0.3 kg carried load, 35 $\dot{V}O_{2\max}$, 1.44m/s walking speed, 0.01% slope, and values of adjusted terrain factor are: alley: 1.28, arterial road: 1.166, mixed-use street: 1.106, residential street: 0.94, downtown street: 0.928, boulevard: 0.9, commercial parkway: 0.82; means of male sample include 68 kg weight, 0.35 kg carried load, 41 $\dot{V}O_{2\max}$, 1.45m/s walking speed, 0.01% slope, and values of adjusted terrain factor are: alley: 0.968, arterial road : 0.854, mixed-use street: 0.794, residential street: 0.628, downtown street: 0.616, boulevard: 0.588, commercial parkway: 0.508.

CHAPTER 4 EVALUATING STREET IMPROVEMENT

In this chapter, I explore psychological effect of street amenities on WTW. A route choice experiment is designed to observe these effects. I also show suggestions to planning practice when designing project.

4.1 Modeling walking route choice

To estimate psychological WTW for street improvement, this thesis analyzed behavior from people's route choice. The route choice data included *revealed* and *stated* preferences. RP is an approach to measure the real decision-making behavior, but it may be limited insofar the situation we tested entailed more than status. This usually happens when a project is intended to implement a great range of improvements that fall outside of respondents' experiences. The revealed preference method may suffer from colinearity among attributes. I therefore simultaneously surveyed SP data in which alternatives were designed as hypothetical routes with an orthogonal matrix to widen the test range of each attribute.

In a walking route choice, a choice set C_i consists of several alternative routes linking a specific origin-destination, and is defined by a pedestrian *i* who takes SA and walking time into account to choose a route with the maximum utility from his/her choice set. Given the nature of walking behaviors, it seems reasonable that pedestrians will tend to maximize contact with SA involving safety, comfort, convenience and attractiveness, but minimize walking time or distance (Mitra-Sarka, 1994; Untermann, 1984). Pedestrians' utility function can be expressed as:

$$U_{io} = V_{io}(X,T) + \varepsilon_{io} = \beta_1 + \beta_2 \cdot x_{io2} + \cdots + \beta_q \cdot x_{ioq} + \alpha \cdot T_{io} + \varepsilon_{io} \quad (13)$$

where U_{io} is the random utility of alternative route *o* for pedestrian *i*; V_{io} is the systematic component of pedestrians' utility that could be rationally measured and modeled, and ε_{io} is the random component of utility. The systematic utility V_{io} is a function of SA attributes X_{io} and walking time T_{io}; x_{ioq} is denoted as SA attribute *q* of alternative route *o* of pedestrian *i*. There are seven physical attributes to represent SA: right of way, lighting, planting, street furniture, pavement, retailing, and fountains. Although other attributes have been mentioned in previous studies, it is those selected that form a basic street space and significantly affect users' behavior (Alexander, 1974; Appleyard and Lintell, 1972; Booth, 1983; Fukahori and Kubota, 2003; Gehl, 2001; Harris and Dines, 1997). Walking time is the measure of WTW since a pedestrian can definitely recognize the length of time required for a trip and evaluate whether he/she accepts this amount of effort. Community planning literature usually sets a walking distance as a quarter mile, and walking time as five minutes (Perry, 1929). Either walking distance or time can be seen as the continuous type of WTW. The discrete measure is the walking frequency that people decide to walk, or not to walk, in a given space (Gehl, 2001; Untermann 1984). The former is more suitable for this study to analyze route choice, because here a pedestrian is a decision maker, implying that he/she already decided to walk.

If route choice is also associated with the decision maker's socio-economic characteristics, equation (13) can be rewritten as equation (14):

$$U_{io} = V_{io}(X,Z,T) + \varepsilon_{io} = \beta \cdot X_{io} + (\gamma \cdot Z_o) \cdot T_{io} + \varepsilon_{io} \tag{14}$$

where Z_o is a vector of individual characteristics of pedestrian *i*, γ is a vector of the parameters of the covariates (individual characteristics multiplied by walking time) (Johnson et al., 2000). When the random component in equations (13) and (14) is defined as Type 1 extreme value error structure, known as Gumbel distribution, the choice probability model can be formulated as a multinomial logit model (MNL) (Ben-Akiva and Lerman, 1985):

$$P(V_{io} + \varepsilon_{io} \geq V_{io'} + \varepsilon_{io'}, \quad \forall o, o' \in C_i) = \frac{\exp(\theta \cdot V_{io})}{\sum_{o \in C_i} \exp(\theta \cdot V_{io'})} \tag{15}$$

where o and o' are alternatives that belong to pedestrian i's choice set C_i, and θ is the scale factor which is usually set as 1, because it cannot be independently identified. A route may involve several links of various street types where SA varies. In this case, the value of x_{ioq} in a route is calculated by taking the average of its links weighted by link length.

The IIA needed to be examined before using MNL. Figure 8 illustrates a typical example of IIA violation where a pedestrian has three alternative routes, in which only Route C is completely independent from Routes A and B, since they have the same links from two ends (with the exception of the links within the dashed square).

Random-parameters logit model (RPL), also referred to as a mixed logit model, does not exhibit the restrictive forecasting patterns of MNL (Revelt and Train, 1998), and is used here. Thus, equation (15) is modified as equation (16):

$$P(C_i = o) = \frac{\exp\left[\theta \cdot V_{io}\left(\beta^*\right)\right]}{\sum_{o \in C_i} \exp\left[\theta \cdot V_{io'}\left(\beta^*\right)\right]} \quad (16)$$

where $\beta^* = \beta + \eta_i$, and η_i is the subject-specific stochastic component for each β.

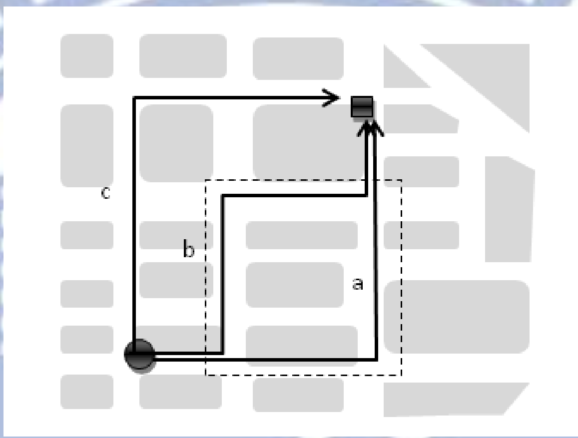

Figure 8 An example of IIA violation in a pedestrian's route choice.

Referring to welfare measurement (Freeman, 1993), equation (17) estimates the change in WTW for the improved SA:

$$CV = -\frac{1}{\alpha}\left\{\ln\left(\sum_{o \in C_i} \exp\left(V_i^0\right)\right) - \ln\left(\sum_{o \in C_i} \exp\left(V_i^*\right)\right)\right\} \quad (17)$$

where CV is compensating variation, α is the marginal utility of walking time, V_i^0 is the initial state, and V_i^* is the level of utility in the subsequent state.

An additional issue is whether RP and SP data can be combined into a joint model. This can enlarge the sample size to assist insignificant variables to enrich data variation and improve the correlations between attributes in RP data. Swait and Louviere (1993) proposed a procedure for joint estimation through log-likelihood value testing, after rescaling the relative scale factor. This would be performed in the next step of this research.

4.2 Route choice experiment

Psychological measure is different from the physiological one (WEE). Walking time is more suited to a self-reporting survey, because respondents can recognize time spent, but not distance traveled. Thus, I denote walking time as the measure of WTW. A higher WTW is considered as an effect of improved amenities from improvement projects. To systematically describe alternative routes, each attribute of SA is represented with two or three levels, as shown in Table 9.

Table 9 Attributes and levels of SA.

Attribute	Level	Description
Right of Way(ROW)	Shared(S)[a] Exclusive(E)	Whether pedestrian is disturbed by vehicle or other incompatible use.
Lighting(LT)	5 Lux(L1) 10 Lux(L2) 15 Lux(L3)	The degree of lighting that street lamps offer pedestrians to ensure safety after dark.
Planting(PT)	Potted plants(P1) Bushes(P2) Trees(P3)	Three types of planting on street (reflecting green level).
Street Furniture(SF)	Few(FF) Various(FV)	To indicate whether a street offers various facilities to serve more outdoor activities for pedestrians.
Pavement(PV)	Asphalt/concrete(A) Colored brick(C)	Two types of walkway surface; the first is rigid, monolithic, and poor-colored; the second is flexible and colorful.
Retailing(RE)	Few(RF) Various(RV)	To indicate whether the street offers retail services, such as food stands, kiosks, or a grocery stop.
Fountain(WA)	None(NO) Available(AV)	To indicate if there is a static or flowing waterscape on street.
Walking Time(WT)	Minute; the self-reporting as RP data, and three levels: 5, 10, or 15 min as SP data.	Measure of WTW, also implying travel cost.

Notes:

a. Levels of each attribute are coded using effects codes. The base level is assigned -1 to represent the lowest level of amenity. For 2-level attributes, the values are assigned -1 and 1; for 3-level attributes, the values are assigned -1, 0, and 1.

Definitions of levels and questions was revised by a 14-person focus group consisting of four students, six researchers, and four residents, interested in our study, to ensure that questions are designed to give participants clear information consistent with what the study wants to ask. It is also important for them to make questions to be user-friendly to help the participants form judgments. For example, right of way for pedestrians is a major determinate of street design (for example, in sidewalks or arcades) to exclude vehicle or incompatible use; after revision, it refers to whether the street protects pedestrians from a conflict between “exclusive” or “shared” use. Lighting provides safety for pedestrians after dark, and there are three Lux levels: 5 Lux, 10 Lux, and 15 Lux, to represent the degree of lighting here. The common types of road planting - potted plants, shrubs, and trees - are used to represent the degree of greenery and enclosure. Street furniture is a set of equipment with various functions for pedestrians, but only includes benches, signs, waste receptacles, and public art, in this instance. The pavement is made from two common types of material: asphalt/concrete and bricks. Street retail usually consists of food stands, kiosks, sidewalk cafés, retail stores, and so forth. In this case, its levels are designated as “few” and “various” to indicate whether the street accommodates a variety of daily need. Lastly, the design of a street fountain will feature flowing water or a static pool; here, we use “none” and “available” to indicate whether there is static or running water on the street.

Five variables - gender, age, weight, income, and education - are considered as individual characteristics. The levels of services (A~F) defined in Fruin (1971) are used to represent the effects of free-flow degree on pedestrians’ utility (see Appendix 1). Stay home or drive vehicle (HO) is the alternative specific constant in the SP questions, used to indicate whether respondents accepted the alternatives designed for walking.

The RP question is designed to record people’s actual route choice behavior. However, a pedestrian chooses one potential walking route from the given O-D pair near his/her origin. If the street conditions of those routes are similar, there would be little variation in the attributes of SA between alternatives. This would prove a disadvantage in our model estimation, since a discrete choice model is operated by detecting the degree of variation between each attribute (Louviere, Hensher, and Swait, 2000). Otherwise, RP data may suffer from colinearity among the attributes of alternative routes (Adamowicz, Louviere, and Williams, 1994). To solve this, the SP question is designed to elicit preferences by using hypothetical questions, whereby alternatives and choices would not be restricted in the status (Louviere et al., 2000). For example, street furniture is rarely placed on a shared

ROW walkway in Taiwan, but the SP question could simulate this situation. In addition, earlier studies found that elicited preferences from multiple sources would predict behavior better than single ones (Huber, Wittink, Fiedler and Miller, 1993; Johnson et al., 2000; McFadden, 1986).

Table 10 List of the individual characteristics and the specific constant.

Characteristic	Level	Description
Gender(GE)	Male(GE=1) Female(GE=0)	Dummy variable to indicate difference between genders
Age	Years	Number of years that a person has lived
Weight(WE)	kg	Total body weight
Income(IC)	NT$/per month	Gross monthly income
Education(ED)	Elementary school(ED=1) Junior high school(ED=2) … Doctor(ED=6)	Level of education
Level of Service(LOS)	Level A(LOS=1) Level B(LOS=2) … Level F(LOS=6)	Degree of free walking according to Fruin (1971) definition
Stay home or drive vehicle(HO)	Yes(HO=1) No(HO=0)	A specific constant for each SP choice set to detect whether respondent accepts the two designed alternatives

The survey trips include work-to-home, home-to-shopping, and home-to-leisure; unlike home-to-work trips, people have more free time and discretion in those trips to decide between walking time (distance) and SA, thus they will not necessarily choose the shortest path. In the first part of the questionnaire, respondents are asked to give checks on the individual characteristics in Table 10 as a warm up task. They then describe their trips by answering RP questions regarding origin, destination, most frequent route, two alternative routes, and road names. A map is also prepared for respondents for when they could not accurately recognize road names or alternative routes. The attributes and levels in Table 9 was designed as a checklist for respondents to describe the SA of each route. If the route involves several links of different street space, the links are described respectively, and the value of x_{ink} is calculated by taking the average of links of the various street types weighted by link length.

The SP question was designed using the fractional factorial method (Louviere et al., 2000). Instead of using full-factorial design to produce a total of $2^5 \times 3^3$ alternatives, this study applies SAS 9.0 software to design the five 2-level and three 3-level attributes into a balanced and orthogonal matrix. As a result, 36 alternatives are generated with D-efficiency 100% (see Table 11), meaning the colinearity was eliminated (Kuhfeld, Tobias, and Garrat, 1994). Note that walking time is regarded as an attribute when designing alternative, because it represent the cost of each route and people should take it into account when choosing the route. It is categorized into three levels: 5 (convenience), 10 (acceptable) and 15(long) min with reference to literature (Pushkarev and Zupan, 1975).

Example				
Street Amenity	Right of way	Exclusive	Shared	Stay home, or drive vehicle
	Lighting	10 Lux	5 Lux	
	Planting	Bushes	Trees	
	Street furniture	Benches and waste receptacles	Few	
	Pavement	Concrete	Colored Bricks	
	Retailing	Few	Various	
	Fountain	Available	Available	
Walking time(min)		5min	10min	0min
I would choose… (☑Check only one)				

Figure 9 An example of a stated preference question

Table 11 List of the designed SP alternatives.

Block	*Set*	*Alternative*	*ROW*	*LT*	PL	*SF*	*PV*	*RE*	*WA*	*WT*
1	1	1	1	3	2	2	1	1	2	3
1	1	2	2	1	1	1	2	2	1	2
1	2	1	1	1	1	2	2	2	2	1
1	2	2	2	2	3	1	1	2	1	2
1	3	1	2	2	3	2	2	2	1	1
1	3	2	1	1	2	1	1	1	2	2
1	4	1	2	3	2	1	1	1	2	1
1	4	2	1	2	1	2	2	2	2	3
1	5	1	2	2	3	2	2	1	2	2
1	5	2	1	3	1	1	1	2	1	3
1	6	1	1	1	3	2	1	1	1	3
1	6	2	2	2	2	1	2	2	2	1
2	1	1	1	1	3	2	1	2	2	1
2	1	2	2	2	1	1	2	1	1	3
2	2	1	2	2	2	2	1	2	2	3
2	2	2	1	3	1	1	2	1	1	1
2	3	1	1	2	3	1	2	1	2	2
2	3	2	2	3	2	2	1	2	1	1
2	4	1	2	1	1	2	1	1	1	2
2	4	2	1	2	2	1	2	2	2	1
2	5	1	1	3	3	1	2	1	2	3
2	5	2	1	2	1	2	1	2	1	2
2	6	1	2	3	1	2	2	1	2	2
2	6	2	1	1	3	1	1	2	2	3
3	1	1	2	3	3	2	2	2	2	2
3	1	2	1	2	1	1	1	1	1	3
3	2	1	2	1	2	2	2	1	1	3
3	2	2	1	3	3	1	1	2	2	2
3	3	1	2	1	1	1	1	1	2	1
3	3	2	1	3	2	2	2	2	1	2
3	4	1	1	2	1	2	1	1	2	2
3	4	2	2	1	3	1	2	2	1	3
3	5	1	2	2	3	2	1	1	2	1
3	5	2	1	1	2	1	2	2	2	2
3	6	1	1	2	2	1	1	1	1	1
3	6	2	2	3	1	2	1	2	2	3

Those alternatives were further blocked into three groups (12 alternatives in each group), so each respondent only need to make six choices (two alternatives in a choice set). Two techniques are used to aid respondents when making judgments; the initial condition with zero travel cost could be used as the reference of other alternatives, and the figure of street space could help respondents to understand what the street looks like, as shown in Figure 9. However, the alternative would violate IIA because it implies that respondents decide not to walk, and it is truly different from the other two alternatives. This is another reason why I used RPL. Finally, the total number of questions were reduced to less than 21, and the SP choice sets were less than 8, as suggested in empirical studies (Kuhfeld, 2005).

4.3 Calibrated results

The collected RP and SP data are coded using effects codes, and estimated using LIMDEP software with a maximum likelihood estimation for equation 15, respectively. Table 12 illustrates the results. It can be reasonably inferred from the results that all attributes of SA are positive, which means an increase in the values of attributes would result in higher utility. The attributes of walking time are negative because more walking time results in lower utility. The values of McFadden's ρ^2, indicating the fraction of an initial log-likelihood value explained by the model, are all greater than 0.2, which means the data has good model fits (Louviere et al., 2000).Right of way, lighting, planting, retailing, fountains, and walking time are significant in RP and SP data, which suggests that the improvement of these five SA attributes result in a higher WTW. Surprisingly, some practices focus on street furniture and pavement design, but the two are not statistically significant at the 5% level (p-value>0.05).

The estimation result of equation 14 shows a greater difference between the RP and SP data than equation 13. The parameters in RP show that age, education, and level of service significantly affect utility, but none show significance in the SP estimation results. Otherwise, RP data has a higher McFadden's ρ^2 (0.427), and the estimation of equation 14 explains more variance (ρ^2 =0.441). This is not the case with respect to the estimation of SP data, with McFadden's ρ^2 unchanged at equations 13 and 14 (ρ^2=0.287). In terms of the decision-making process (see McFadden, 1986), this result means that the SP questions we designed can assist respondents to form their perception of SA. However, all their individual characteristics do not significantly influence decision-making, and are not taken into account by the process of SP. Their preference for one of the two types is probably shaped by different cognitive processes (Swait and Louviere, 1993).

Table 12 Estimation results for utility function.

	Equation 1		Equation 2	
	SP	RP	SP	RP
Street amenity attributes				
ROW	0.333(0.001)[a]	1.083(0.011)	0.329(0.001)	1.216(0.001)
LT	0.153(0.001)	0.536(0.032)	0.154(0.001)	0.582(0.003)
PL	0.088(0.001)	0.404(0.001)	0.087(0.001)	0.423(0.002)
SF	0.017(0.312)*[b]	0.131(0.275)*	0.017(0.298)*	0.138(0.295)*
PV	0.038(0.156)*	0.354(0.056)*	0.038(0.155)*	0.352(0.687)*
RE	0.072(0.009)	0.750(0.011)	0.069(0.012)	0.866(0.018)
WA	0.069(0.022)	0.482(0.026)	0.066(0.030)	0.597(0.001)
WT	-0.095(0.001)	-0.566(0.001)	—	—
Individual characteristics(*WT)				
GE	—	—	0.013(0.378)*	-0.181(0.211)*
AGE	—	—	-0.002(0.290)*	-0.057(0.043)
WE	—	—	-0.001(0.444)*	0.001(0.828)*
IC	—	—	0.008(0.129)*	0.075(0.132)*
ED	—	—	-0.008(0.246)*	0.117(0.046)
LOS	—	—	-0.009(0.158)*	0.139(0.025)
Specific constant				
HO	-2.963(0.001)	—	-2.935(0.001)	—
L(β)	-1564.218	-137.057	-1566.777	-139.625
Mcfadden's ρ^2	0.287	0.427	0.287	0.441

Notes:

a. ( ) is p-value.

b. *means not significant at 5% level.

Referring to welfare measurement (Freeman, 1993), equation 18 estimates the change in WTW for the improved SA:

$$CV = -\frac{1}{\alpha}\left\{\ln\left(\sum_{i\in C_n}\exp\left(V_n^0\right)\right) - \ln\left(\sum_{i\in C_n}\exp\left(V_n^*\right)\right)\right\} \tag{18}$$

where CV is compensating variation, α is the marginal utility of walking time, V_n^0 is the initial state, and V_n^* is the level of utility in the subsequent state. Table 13 illustrates how much WTW would increase after improving one level of a SA attribute. For example, when street lighting is improved from 5 Lux to 10 Lux, people would increase 1.081(RP)/1.54(SP) min in WTW. The case of multiple attributes improvement is illustrated in the next section. It is noted that improvement in pedestrians' right of way would produce the highest WTW, and lighting is also high, implying that pedestrians are mostly concerned about their safety. Since the RP coefficients in equation 14 are estimated for covariates, five scenarios are drawn, as shown in Table 13.

Table 13 WTW estimation (min) for levels of improvement.[a]

Amenity Attribute	Level of Improvement	Equation 1 RP	Equation 1 SP	Equation 2 RP Ⅰ[b]	Equation 2 RP Ⅱ[c]	Equation 2 RP Ⅲ[d]	Equation 2 RP Ⅳ[e]	Equation 2 RP Ⅴ[f]
Right of way	S→E	4.167	7.107	3.178	3.729	4.512	5.412	1.629
Lighting	L1→L2, L2→L3	1.081	1.540	0.782	0.917	1.110	1.331	0.401
	L1→L3	2.163	3.080	1.563	1.834	2.220	2.662	0.802
Planting	P1→P2, P2→P3	0.905	0.946	0.686	0.805	0.974	1.168	0.352
	P1→P3	1.810	1.891	1.372	1.610	1.948	2.337	0.703
Retailing	RF→RV	2.610	1.715	2.106	2.472	2.991	3.587	1.080
Fountain	NO→AV	1.688	1.679	1.425	1.672	2.023	2.427	0.731

Notes:

a. The unit of WTW is minute, and each level of improvement is defined in Table 1.

b. The scenario is that a person is 26.19 years old (mean age of our samples) with a high school diploma, and walks on LOS A street.

c. The scenario is that a person is 26.19 years old with a high school diploma, and walks on LOS B street.

d. The scenario is that a person is 26.19 years old with a high school diploma, and walks on LOS C street.

e. The scenario is that a person is 26.19 years old with a college degree, and walks on LOS C street.

f. The scenario is that a person is 50 years old with a college degree, and walks on LOS C street.

As LOS changes from A to C, those WTWs increase, meaning that improvement for more crowded streets would yield a higher benefit. When the scenario in Table 13 goes from Ⅲ to Ⅳ in education - i.e. from high school to college - then WTWs will increase, meaning the same improvement for users with a higher education degree would receive higher utility. However, when the scenario in Table 13 varies from Ⅳ to Ⅴ in age range - from 26.19 to 50 - WTWs decline. This suggests older users would benefit less than their younger counterparts from the same level of amenity; in other words, the elderly require a better-designed environment before they are able to reach the same utility of younger users.

An additional issue is whether RP and SP data can be combined into a joint model. This can enlarge the sample size to assist insignificant variables to enrich data variation and improve the correlations between attributes in RP data. Swait and Louviere (1993) proposed a procedure for joint estimation through log-likelihood value testing, after rescaling the relative scale factor. Since estimation in equation 14 obviously shows different results between RP and SP, we tested Swait and Louviere's (1993) H_{1A} hypothesis by using the estimated equation 13. Results show that our maximum log-likelihood occurs at 0.73 relative scale factor (see Figure 10). I rescale the value of scale factor of SP data relative to RP data to find the maximum log-likelihood value of the joint model. Figure 9 indicates the optimal value lies in 0.73.

The chi-squared statistic value for Swait and Louviere's (1993) H_{1A} test is:

$$-2\left[\left(L^{RP}+L^{SP}\right)-L^{Joint}\right]=-2\cdot\left[(-147-1668)-1915\right]=200>\chi^2_{(0.05,DF=8)}=15.5$$

This result rejects the hypothesis of preference equality across data sources; even significant variables are similar at equation 1, but the coefficients are totally different.

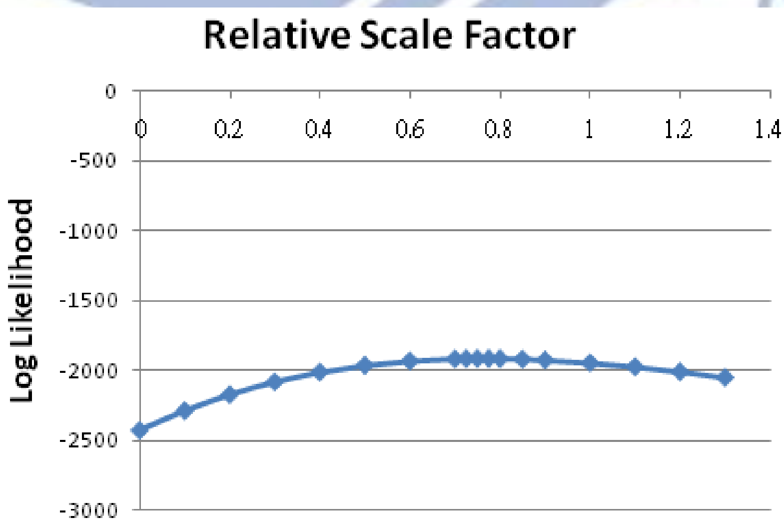

Figure 10 Plot of relative scale factor and log-likelihood.

4.4 Model application

Caogong Canal Regeneration in Kaohsiung City[2], Taiwan, is a project renowned for its ecological and leisure function (Sustainable Public Infrastructure, 2009). This project aims to remove illegal occupancy and build a greening walkway along Caogong Canal beside Fongshan Station to enhance WTW and transit ridership, as shown in Figure 11. It was formally completed on December 28, 2009.

As expected, this project now attracts more users than before. This change is probably the result of two sources: one is the pedestrians shifting from other routes, and the other is more people staying longer to undertake outdoor activities, such as sit-to-talk. To test this hypothesis, we interviewed 82 pedestrians from August 1 to October 30, 2010. The survey trips included school-to-home, leisure-to-home, home-to-leisure, and work-to-home. Although their O-D pairs may not be the same, the trips must involve a link between the main gate of Fongshan Stadium and Fongshan Station.

Figure 11 Caogong Canal before (left) and after (right) improvement.

Table 14 and Figure 12 illustrate three alternative routes of the choice set defined between the two nodes; where Route A is passing a downtown street with many food stands, Route B is passing a square with an attractive lighting design and sidewalk café, and Route C is the route of the project, a full greening sidewalk.

Respondents were asked to answer questions about the routes they walk before and after the improvement of the three routes, as well as in regard to walking time. However, some were unsure of their walking time, so we referred to Henderson (1971) and Willis, Gjersoe, Havard, Kerridge, and Kukla (2004), to set walking speed as a normal distribution with 1.44 m/s means speed and 0.244 standard deviation to predict the walking time (Hsu and Tsai, 2010). The estimated equation 4.1 of SP and equation 4.2 of RP with better model fit were used to make aggregate forecasts of the theoretical distribution (Ben-Akiva and Lerman, 1985). The number of pedestrians after improvement was the observed frequency distribution, and Table 15 illustrates the results of a chi-square test for discrepancies between the observed and predicted number of pedestrians on the three routes.

Table 14 Spatial characteristics of the three alternative routes in Caogong Canal Regeneration.

Characteristic	Route A	Route B	Improved Route C	Original Route C
Right of way	Shared	Exclusive	Exclusive	Shared
Lighting	12Lux	8Lux	8Lux	6Lux
Planting	Potted plants	Trees, shrubs	Trees, shrubs, grass	Potted plants
Street furniture	None	Sculpture, sign, bench	Bench, public art, billboard	None
Pavement	Asphalt	Brick	Brick	Asphalt
Retailing	Various retailing	Sidewalk café	None	None
Fountain	None	Fountain	Canal	None
Distance(m)[a]	600	500	450	450

Notes:

a. Distance is from the gate of stadium to Fongshan Station.

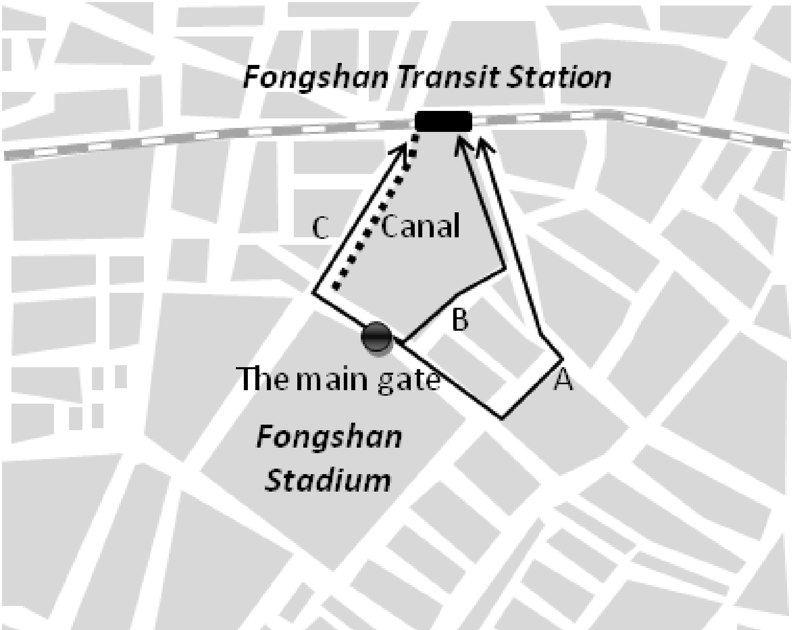

Figure 12 The three alternative routes between the main gate of Fongshan Stadium and Fongshan Station.

Respondents were then asked, "How much longer do you spend on the street than on your previous visits - watching people, sitting down to talk et cetera? Please give an estimate on the time interval.” We arranged their answers by statistical frequency, and conducted a chi-squared goodness of fit test to determine a fit distribution function. Distribution was right-skewed, and the results suggest a Gamma distribution (6.3858< $\chi^2_{(\alpha=0.05, df=5)} = 11.07$).

The expected value of the Gamma distribution is 7.5798 min $(\alpha = 4.4394, \lambda = 1.7074)$, meaning that the improved Route C would attract people to spend more time engaging in outdoor activities, and the point estimation is 7.5798 min. The increase of WTW can be forecast by applying the estimated equation 4.1 and equation 5, then:

$$WTW_{SP} = -\frac{1}{-0.095}\left\{\begin{array}{l}\ln\left[e^{0.333\times(-1)+0.153\times(-1)+0.088\times(-1)+0.072\times(-1)+0.069\times(-1)}\right] \\ -\ln\left[e^{0.333\times1+0.153\times0+0.088\times1+0.072\times(-1)+0.069\times1}\right]\end{array}\right\} = 11.926\,\text{min}$$

,

and that of the RP model is 7.905 min. The latter is closer to the expected value. The RP model is appropriately developed by eliciting revealed preferences, so the increase of WTW is close to the actual behavior in this case.

Furthermore, according to the construction estimation report of the Great Fongshan River Restoration Plan, commissioned by the Kaohsiung City Government, we summarize the cost of each level of improvement by selecting essential items, as shown in Table 15.

Table 15 Results of chi-square test for discrepancy between the observed and predicted number of pedestrians on the three alternative routes in Caogong Canal Regeneration.

	Before	After	SP Prediction[a]	RP Prediction[b]
Route A	12	7	3	8
Route B	29	25	35	22
Route C	9	18	12	20
χ^2			0.0004	0.7010
$\chi^2_{(\alpha=0.05, df=2)}$				5.99

Notes:

a. SP prediction is derived from equation 1.

b. RP prediction is derived from equation 2.

The results show that the discrepancy is not statistically significant ($\chi_{SP}^2 = 0.0004 < 5.99$, $\chi_{RP}^2 = 0.701 < 5.99$), which suggests our models can be used to predict the route choice within an acceptable level of bias.

Planners removed the illegal occupation along the canal to create a priority walkway to improve right of way from shared to exclusive. According to the administrative regulations of the Kaohsiung City Government, compensation must be paid for migration allowance and property subsidies, which are, surprisingly, approximately NT$ 3,000,000 per 100m. If this cost is assigned to right of way improvement, it accounts for 87% of this item. The polluted canal is improved as a clean stream, and the clean water is purchased from the nearby river. Even so, the cost of cleaning and circling by machines is still necessary, which accounts for 45% of fountain improvement costs.

Table 16 Improvement cost ranking of Caogong Canal Regeneration.

Street amenity	Content	Cost (NT$1000/per100m)	Rank of cost	Rank of RP WTW	Rank of SP WTW
Right of way	Compensation[a], construction	3,946(S→E)	1	1	1
Lighting	Lamp, power fee for 3 years, pipeline	573(L1→L2)	5	6	6
		776(L2→L3)			
		803(L1→L3)	4	3	2
Planting	Plants, planting maintenance for 3 years	115(P1→P2)	7	7	7
		129(P2→P3)			
		148(P1→P3)	6	4	3
Retailing	Kiosk, air conditioning, maintenance for 3 years	1,514(RF→RV)	3	2	4
Fountain	Cleaner and circulation system, maintenance for 3 years	1,523(NO→AV)	2	5	5
Pavement	Colored bricks	702	-	-	-
Street furniture	Bench, public art, billboard	285	-	-	-

Notes:

a. Assume there are ten households per 100m, four people per household.

Improvement for retailing is not included in this project, so we assume it is to build four kiosks and calculate the cost by adding the cost of each essential facility. Since Kaohsiung's climate is hot and humid, air conditioning and refrigeration equipment must be used to store foods; these facilities account for 53% of the cost of improving retailing. Lighting costs less as it only operates after dark. Planting has the lowest cost due to the modest cost of maintenance and operation.

Table 16 illustrates some practical suggestions. First, improvement for right of way would significantly enhance WTW; however, its expense places it in the highest cost ranking. For other projects, planners should try different methods to reach the same effect, such as transportation management.

The increase of WTW for the improved planting shows the lowest order in RP/SP and cost ranking, suggesting that the improvement is suitable when a budget is extremely limited. Only the ranks of lighting from L1 to L3 and planting from P1 to P3 are better than their costs; however, 15 Lux mostly exists in arterial roads and downtown commercial districts. It may not be a welcome residential zone due to excessive lighting and the unsustainability of low utilization after midnight.

CHAPTER 5 DESIGNING CORRIDOR FOR HIGH MOBOLITY DIFFERENCE

In this chapter, walking mobility is studied to response aging population. To aid to planning practice, I explore how to design pedestrian corridor to reduce the local congestions due to mobility difference. There are six common types of corridor examined by comparing their level of service in the designed flow.

5.1 Agent-based modeling

The designed agent-based model is based on Helbing et al. (2000). Helbing have built a framework of dynamic walking behavior with reference to molecular dynamic and other physics theory. However, few studies follow them, because the models and simulators are too difficult to be applied for planning practice. Thus, I simplify their models and design a C simulator. Truly, walking behavior is also simplified in my models, but the technique of experiment design can improve it. Verification would also be shown in the following.

Based on the principles concluded in the above reviews, I can define the pedestrian's coordinate system and formulate the passing behaviors to examine which type of corridor can raise passing speed.

Since a corridor is plane space, the position of the pedestrians can be marked with a Cartesian coordinate plane and time: $\mathbf{r}_i = (x_i, y_i, t)$ (Helbing et al., 2000; Helbing, 1991). Pedestrian i walks from $\mathbf{r}_i^0$ and plans to arrive $\mathbf{r}_i^*$ at time T_i^E at his desired velocity $\vec{v}_i^0(t) = \frac{\mathbf{r}_i^* - \mathbf{r}_i^0}{T_i - t}$, the normalized direction vector is $\vec{e}_i = \frac{\mathbf{r}_i^* - \mathbf{r}_i^0}{\left\|\mathbf{r}_i^* - \mathbf{r}_i^0\right\|}$, and $\vec{v}_i^0 = v_i \cdot \vec{e}_i$. If pedestrian i is located at $\mathbf{r}_i^t$, then his/her position in the next second is: $\mathbf{r}_i^{t+1} = \mathbf{r}_i^t + v_i \cdot \vec{e}_i$.

Pedestrians prefer to walk in a straight line ($\vec{e} = \langle 0,1 \rangle$), because this minimizes time cost by avoiding an y-axis offset.

If they encounter others that are traveling at low speed in a high density flow, they will change direction to keep their desired speed and personal space. When the distance between pedestrian i and the other is less than his/her radius of personal space, a "potential energy" is created as a result of that pedestrian's tendency to keep a "personal space" to avoid contact with others. Pedestrian behavioral studies found that the range of personal space can be set at 40~50 cm (Bailenson et al., 2003; Gerin-Lajoie et al., 2008). The potential energy can be represented as:

$$u_{ij} = \begin{cases} A\exp\left[\left(r_i + r_j - d_{ij}\right)/B\right] & d_{ij} < r_i + r_j \\ 0 & d_{ij} \geq r_i + r_j \end{cases} \tag{19}$$

where r_i denotes the radius of pedestrian *i*'s personal space, and $d_{ij} = \left\| \mathbf{r}_i - \mathbf{r}_j \right\|$ denotes the distance between the pedestrian *i* and *j*'s center; A and B are empirical constants that have been suggested as $A = 2000$ and $B = 0.08$ in Helbing et al. (2000). When $d_{ij} < r_{ij} = r_i + r_j$, pedestrian i and j produce a potential energy u_{ij} that forces them apart, and exponentially increases the difference between "comfortable distance" and the real distance .

In addition, pedestrians will avoid colliding with objects or walls. The uncomfortable feel can be represented as equation (20):

$$u_{iw} = \begin{cases} A\exp\left[\left(r_i - d_{iw}\right)/B\right] & d_{iw} < r_i \\ 0 & d_{iw} \geq r_i \end{cases} \tag{20}$$

where if pedestrian i is too close to object (or wall) w ($d_{iw} < r_i$), s/he produces a potential energy u_{iw} which increases with the exponentially increasing difference between the radius of his/her personal space and the real distance. Equation (21) denotes that when pedestrian i moves in direction k, the extent of the crowdedness can be represented with the summation of the potential energy of set C. Set C includes all pedestrians or facilities (λ) that intrude into pedestrian i's personal space:

$$EPO_{ik} = \sum_{\lambda \in C} u_{i\lambda}, \quad C = \left\{\lambda : d_{ij} < r_{ij},\ j \in \text{pedestrians};\ d_{iw} < r_i,\ w \in \text{objects}\right\}. \tag{21}$$

To avoid collision, pedestrian i has the maximum acceptable potential energy EPO^* when s/he touches another person or an object, as shown in equation (22):

$$EPO^* = \begin{cases} u_{ij}\left(r_{ij},\ d_{ij} = r_i^* + r_j^*\right) & j \in \text{pedestrians} \\ u_{iw}\left(r_i,\ d_{iw} = r_i^*\right) & w \in \text{objects} \end{cases}, \tag{22}$$

r_i^* denotes pedestrian i's body circle radius, which is used as a way to reduce the complexity of the body ellipse (Fruin, 1971).

We consider five directions: zero degree to straight line ($k=1$), right-leaning 22.5 degrees ($k=2$), right-leaning 45 degrees ($k=3$), left-leaning 22.5 degrees ($k=4$) and left-leaning 45 degrees ($k=5$). I did not consider any directions over 45 degrees to the straight line since the offset in the y-axis is less than the one in the x-axis is rarely found in normal walking behaviors.

The basic rules for choosing a direction are shown in equation (23):

$$\vec{e}_i = \begin{cases} 1 & \text{if} \quad 0 \le EPO_1 < EPO^* \\ k & \text{else if} \quad EPO_k = \min(EPO_2, \ldots, EPO_k) < EPO^* \\ \text{random}(2,4) & \text{else if} \quad EPO_2 \approx \ldots \approx EPO_k < EPO^* \\ v_i = 0 & \text{else} \quad EPO_1, \ldots, EPO_k \ge EPO^* \end{cases} . \tag{23}$$

If walking in the desired direction ($k=1$) by pedestrian i will not result in a collision with anyone, the pedestrian will choose that path. This is called "straight-line preferred," because walking in the direction costs the minimum passing time. If not, s/he will choose the more spacious direction from right or left-leaning 22.5 degrees to right-leaning 45 degrees to search the directions that will not result in a collision. If walking in the desired direction will result in a collision and all the other possible directions produce a similar potential energy without collision, then pedestrian i will randomly choose one among the rest of the directions. If a collision will happens when moving into any of these directions ($EPO_1,\ldots,EPO_k \ge EPO^*$), then pedestrian i will stop ($v_i \to 0$) and wait for dispersal of the obstacles.

5.2 Agent-based simulations design

This section describes how we performed the experiment. Fruin (1971) proposed LOS standards in flow rate. Because the performance of mobility is mean passing speed, I have to convert flow rate to speed and to design an experiment as shown in the following: A pedestrian corridor in the Main Station of Taipei's Rapid Transit system, measuring 50 m in length and 6.4 m in width was chosen as the experimental site because the various flow rates could aid in observing the different pedestrian behaviors and help in collecting a sample. The survey was held from June 18th to 29th, 2011. The radius of the personal area was set at 0.5±0.15 m (mean±standard deviation) for young pedestrians and 0.7±0.15 m for the elderly, and the body radius was set at 0.25±0.1 m for everybody. Although this is slightly different from the literature, it fitted the local environment.

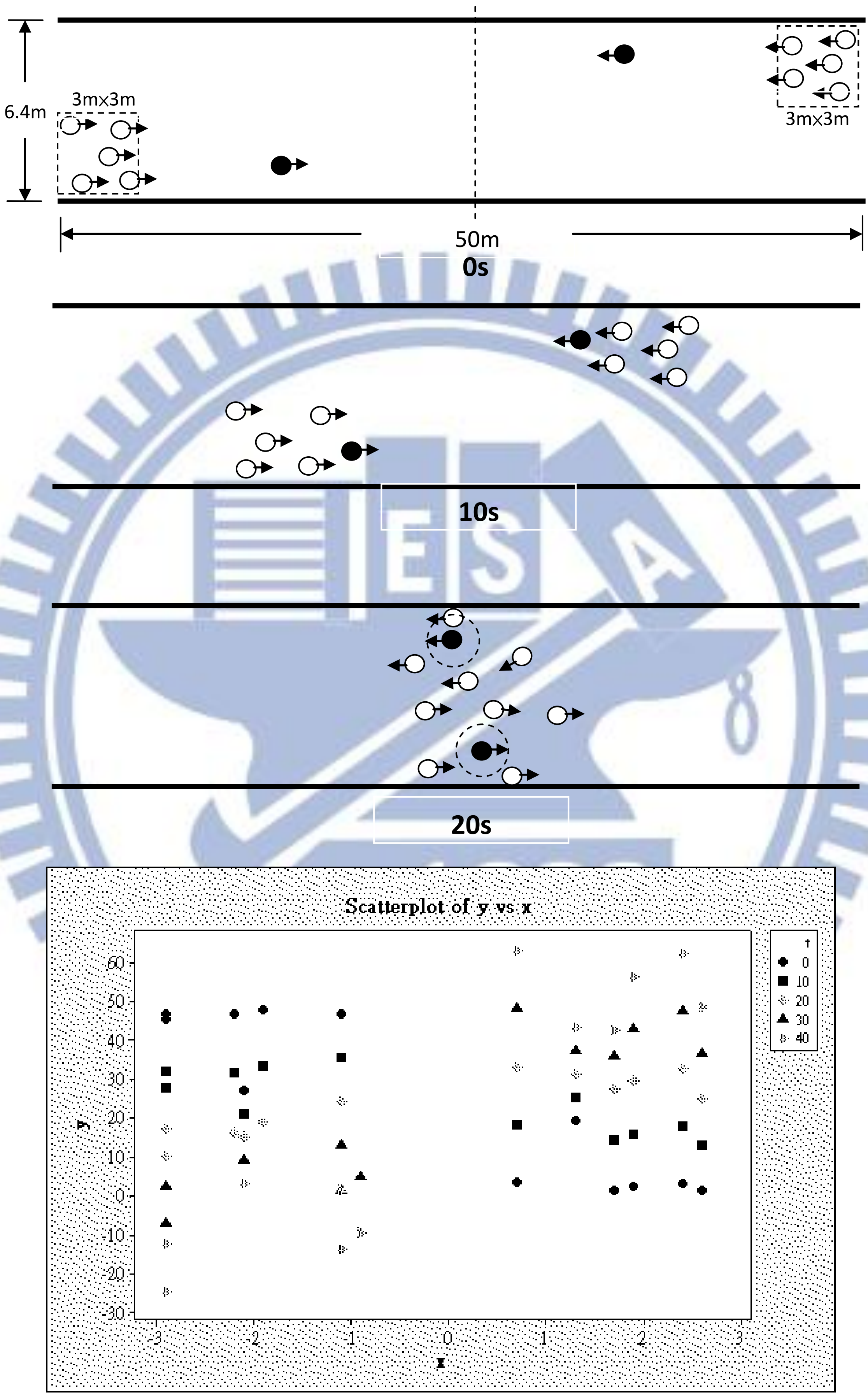

Figure 13 The location of 10 agents at each 10s.

The process of the experiment was as follows. First, given the width of corridor, the number of pedestrians for each flow rate were calculated using the flow equation, as shown in Table 17.

Table 17 Percentage of elderly in the pedestrian flow

LOS	Flow rate (p/min/ft)	Width (ft)	Passing midpoint time (min)	Number of pedestrians(p)	Number of elderly			
					5%	10%	15%	20%
A	<5	21	0.33	26	1	3	4	5
B	5~7	21	0.37	44	2	4	7	9
C	7~10	21	0.38	68	3	7	10	14
D	10~15	21	0.38	106	5	11	16	21
E	15~23	21	0.40	170	9	17	26	34
F	>23	21	0.42	260	13	26	39	52

We assumed that there were two crowds of young commuters. One crowd occupied the bottom right area measuring 3 m × 3 m and they were moving upward. Another crowd occupied the upper left area and were moving downward, as shown in Figure 13. In front of each of these 2 groups, some elderly people were walking in the corridor. When these 2 groups of younger commuters encountered the elderly pedestrians, they passed them with the pattern of equation (23). This passing interval was then selected to calculate the mean passing speed as being from 10 seconds to 30 seconds for most agents to pass the center line of the corridor.

To show the results as LOS, some advanced techniques were employed to set the initial values to fit Fruin's observations. The mean desired speed of the elderly was set as the control variable of 0.6 m/s. From our observation local congestion tends to occur when the walking speed is down to about 0.6 m/s, happens. The mean desired speed tends to vary substantially in the literature as well as from our observations. We tested two values: 1.31 m/s and 1.44m/s to observe which one fitted Fruin's standards. Since the flow volumes were provided, the mean passing speed was employed as the performance indicator. For one pedestrian, the mean passing speed is $\overline{\upsilon}_i = \left(y_i^t - y_i^0\right)/\Delta t$ where y_i^t is pedestrian i 's y-axis coordinate at second t; if there are N pedestrians in the corridor, then the mean passing speed is $\bar{V} = \left(\sum_{i=1}^{N} \bar{\upsilon}_i\right) / N$. In real world, people may keep a mean passing speed by accelerating. In this case, mean passing speed cannot reflect the effect of local congestion. However, this study would not suffer from this problem, because each agent walks in a constant speed. This way can make results reflect the effects of corridor design by simplifying some details of walking behavior.

Table 18 Changes of LOS as the percentage of elderly increases

LOS	Mean speed (m/s)	Percentage of elderly				
		0%	5%	10%	15%	20%
A	>1.29	A(1.36)	A(1.32/1.34)[a]	C(1.24/1.32)	D(1.21/1.33)	D(1.18/1.32)
B	1.27~1.29	A(1.34)	B(1.28/1.31)	C(1.23/1.30)	D(1.18/1.28)	E(1.14/1.28)
C	1.21~1.27	B(1.29)	C(1.24/1.26)	D(1.20/1.26)	D(1.16/1.26)	E(1.09/1.22)
D	1.14~1.21	C(1.24)	D(1.18/1.21)	E(1.09/1.13)	E(1.09/1.18)	E(1.07/1.17)
E	0.76~1.14	D(1.15)	E(1.07/1.09)	E(1.04/1.09)	E(1.01/1.08)	E(0.98/1.08)
F	<0.76	E(1.02)	E(0.94/0.96)	E(0.92/0.95)	E(0.90/0.95)	E(0.88/0.95)

Note. a“LOS (α/β)” means that LOS is estimated using speed α. Speed α is the mean speed of all pedestrians, and speed β is the mean speed of the young. To be an unbiased estimator, each result used the mean of thirty runs of simulation.

As shown in Table 18, a flow containing 5% elderly pedestrians and 95% young pedestrians walking at a mean desired speed of 1.44 m/s can fit Fruin’s observations. The mean passing speed of the younger pedestrians tends to decrease as the percentage of elderly pedestrians increases. This trend is not perfectly linear, probably due to the interactions among pedestrians (e.g., counter flow) and the fact that the desired speed may lead to some unexpected effect. In addition, the extreme high density flow (LOS F) cannot be successfully represented. Possible incidents of pushing and shoving were not modeled here, because they are out of the scope of this study. We therefore did not analyze them in the following steps.

To systematically compare the performance of these alternatives, we developed a simulator(see the Appendix 2). The simulator was coded using Visual C++ 6.0 and was based on the program examples in Rapaport (2004) and Sadus (1999). As shown in Figure 14, the main program includes loops of run, seconds, agents and potential direction. Time step counts with seconds are used as a counter in the looping of the simulator. The duration of the movement is 40 seconds. The functions include generators of agent characteristics that create a population of pedestrians and give them origin, desired speed, radius of body and personal space and direction.

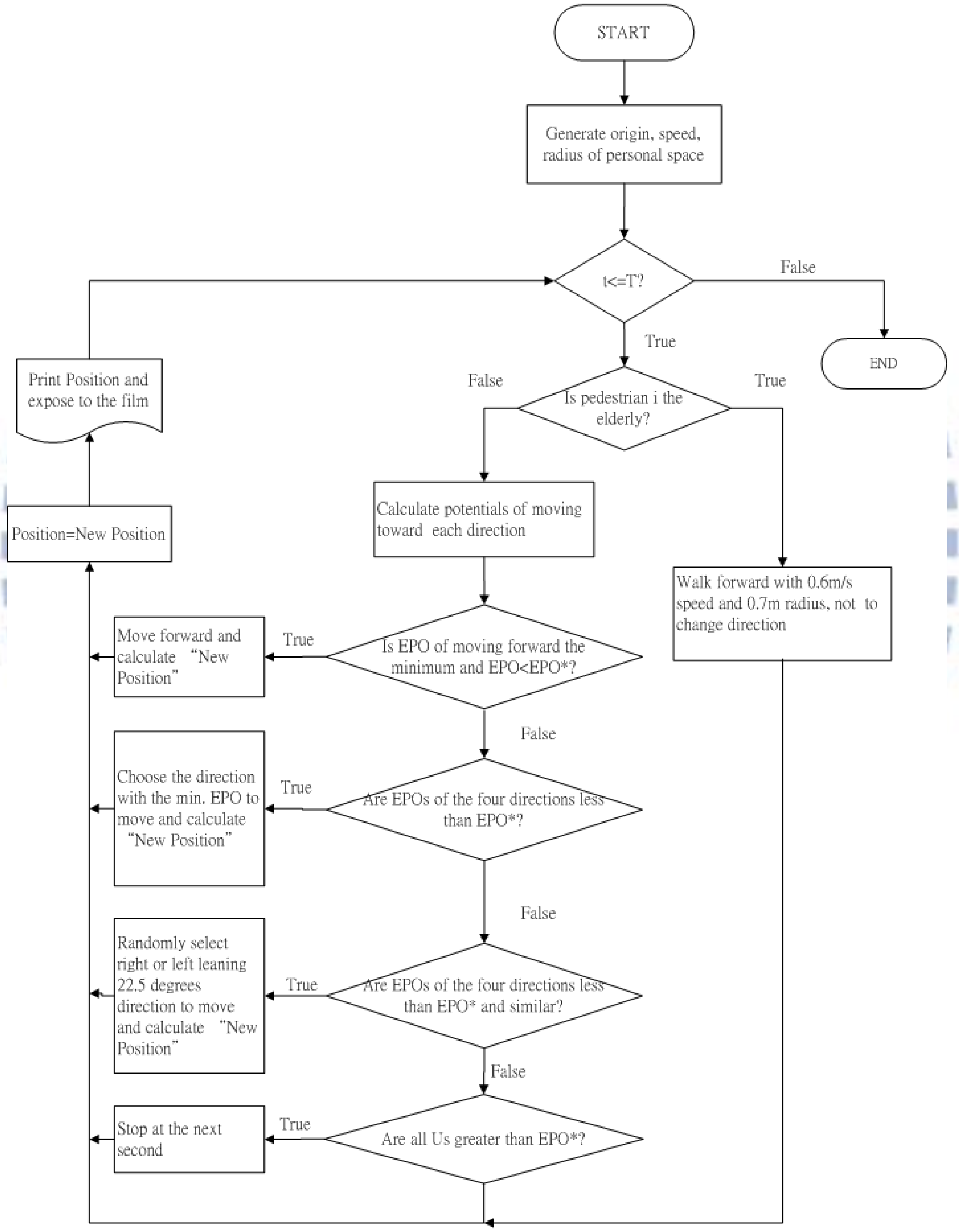

Figure 14 Simulation flow.

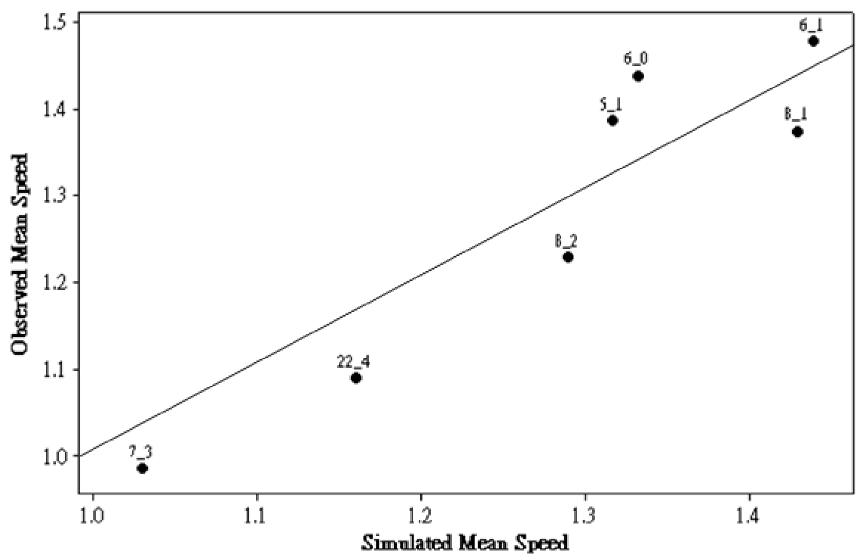

Figure 15 Verification of our models. The data labels illustrate the number of elderly in a flow. For example, "5_1" means a 5-people flow consisting of one elderly person.

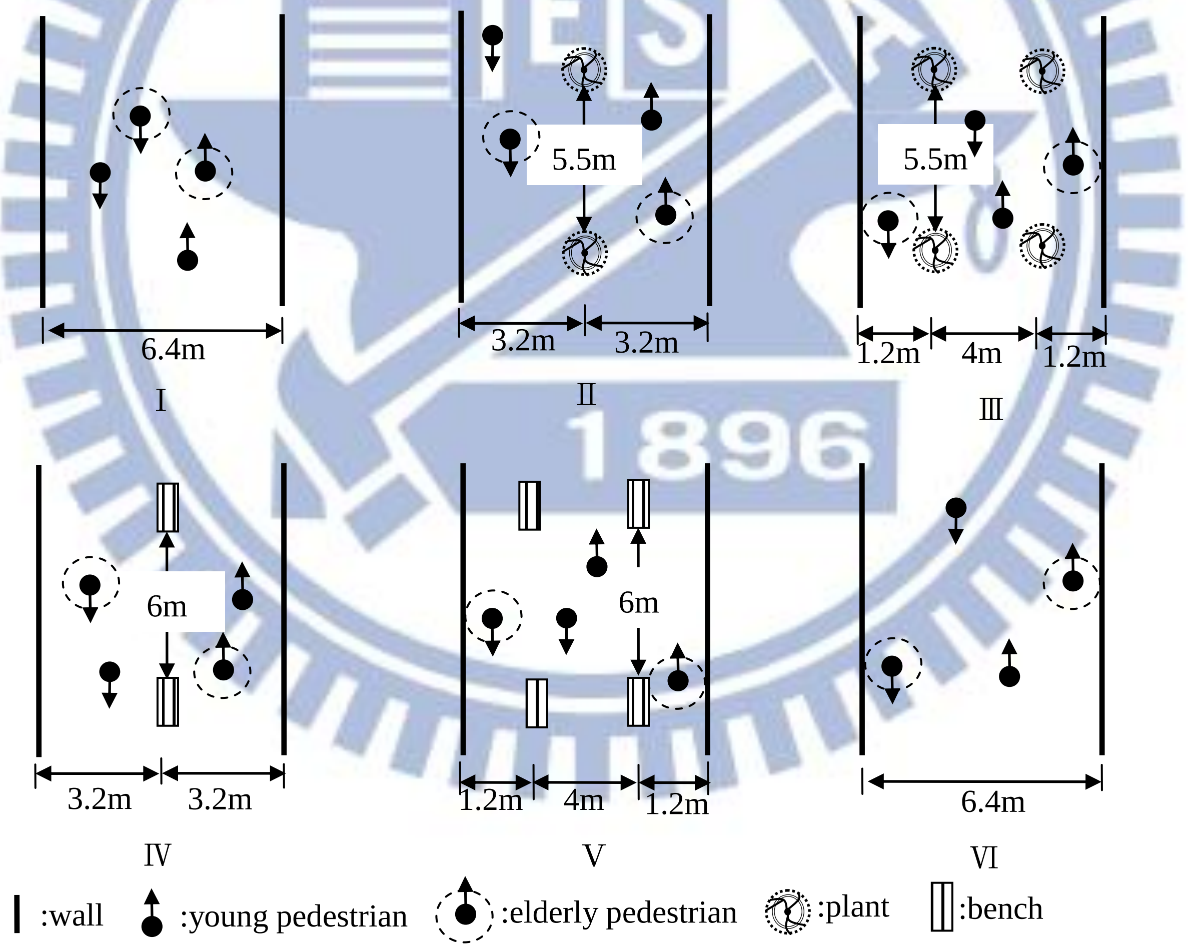

Figure 16 Configuration of six types of corridor design.

Then, to ensure that the above process and models were correct we verified them by comparing our observations and simulations. Data such as arrival time, passing time and offset during in the corridor were extracted from the video recorded from the observational survey. The results are shown in Figure 15. The line illustrates when the observed mean speed is equal to the simulated one. It is easy to see that there is still a bias in each test, although it does stray far from the equal line. The six types of corridor design are shown in Figure 16. Based on traffic-calming techniques, I used separation of pedestrians of different mobility to provide priority and safety for the elderly.

Table 19 Characteristics of the six alternatives.

	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
Type of separation	No separation, open space	Separation by direction	Separation by mobility	Separation by direction	Separation by mobility	Non-physical separation by direction
Facility Number	0	8×1	8×2	6×1	6×2	0
Min. Effective width	6.4 m	5.9 m	5.4 m	5.97 m	5.54 m	6.4 m
Occupied area	0%	0.49%	0.98%	1.01%	2.02%	0%
Function	Passing	Passing, aesthetics	Passing, aesthetics	Passing, rest	Passing, rest	Passing

Note. The corridor is 50 m long by 6.4 m wide (about 164 ft. by 21 ft.). The younger pedestrians walk at 1.44±0.23m/s (about 4.72±0.76 ft/s), have a 0.5±0.1m radius of personal area (about 1.64±0.33 ft.), and 0.25 m radius of body (about 0.82 ft.). The older pedestrians walk at 0.6 m/s (about 1.97 ft/s), have 0.7 m radius of personal area(about 2.3 ft.), and 0.25 m radius of body.

The similar design can be easily found in urban bus lane that segregation is used on dense networks of city streets with numerous parallel lanes by consolidating all the bus routes onto bus-only lanes. As shown in Figure 15, many types of separation are permeable and allow pedestrians to overtake other pedestrians. Alternative Ⅰ is a totally open corridor like most urban walking spaces. Alternative Ⅱ has been suggested by Helbing et al. (2005) for separating opposite directions. Alternative Ⅳ is a similar design but uses benches as a series of obstacles. A priority design for the safety of the elderly can be found in Alternative Ⅲ and Alternative Ⅴ that allow the elderly walking in the sub-corridors to avoid possible collisions with other commuters.

In these 2 designs, planting boxes and benches act as barriers to separate different directions and speeds. Alternative Ⅵ shows a special type of separation by promoting the young to use the central lane and the elderly walking beside the wall. This idea can also be found in the escalators of the rapid transit stations in Taipei City where people spontaneously stand on the right-hand side to leave the left-hand side as a passing strip. Additional characteristics of the six types of corridor design are shown in Table 19. Alternative Ⅵ does not change the effective width, but the self-regulated separation formed by the pedestrians is easily violated.

5.3 Results

The simulations were performed with the assumption that 20% of the pedestrians were elderly, as per the estimation of the Taiwan Council for Economic Planning and Development for 2025 (2011), and the mean speed standards we used are from Burden (2011). The speed-flow relationships obey the basic rules of traffic flow, as each alternative decreases as the flow rate increases. In other words, our models are rational and the following simulation was successful performed.

Table 20 Simulation results when the pedestrian flow contains 20% elderly

Speed Range Of LOS (m/s)	Type of corridor design					
	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
A	D[a]	D	D	D	D	C
(>1.29)	(1.18/1.33)	(1.19/1.34)	(1.20/1.35)	(1.16/1.30)	(1.18/1.32)	(1.21/1.36)
B	E	D	D	E	D	D
(1.29~1.27)	(1.14/1.27)	(1.16/1.30)	(1.17/1.32)	(1.12/1.25)	(1.15/1.29)	(1.16/1.30)
C	E	E	E	E	E	E
(1.27~1.21)	(1.09/1.23)	(1.12/1.25)	(1.14/1.28)	(1.08/1.20)	(1.12/1.25)	(1.12/1.25)
D	E	E	E	E	E	E
(1.21~1.143)	(1.07/1.18)	(1.08/1.20)	(1.10/1.22)	(1.04/1.14)	(1.07/1.19)	(1.09/1.21)
E	E	E	E	E	E	E
(1.143~0.76)	(0.98/1.08)	(1.00/1.10)	(1.02/1.13)	(0.96/1.06)	(1.00/1.10)	(1.01/1.11)

Note. a“LOS (α/β)” means that the LOS is estimated using speed α. Speed α is the mean speed of all pedestrians, and speed β is the mean speed of the younger pedestrians. To be an unbiased estimator, each result uses the mean of thirty runs of simulation.

Table 20 shows that when the percentage of elderly is up to 20%, the LOS of an open corridor (Alternative Ⅰ) will go down sharply from A to D and the original LOS B will go down to E. The original levels of service C, D and E will also go down to or remain at E. It is possible that the difference in mobility causes local congestion and reduces the mean passing speed. So, how can we improve local congestion through the design of the corridor? As shown in Table 20, when the percentage of elderly pedestrians is up to 20%, an uneven flow will reduce the LOS of the corridor from B to E, while Alternatives Ⅱ, Ⅲ, Ⅴ and Ⅵ can raise the LOS from E to D. However, when the flow rate is very low and the percentage of elderly is up to 20% the LOS of the corridor goes down from A to D, and only Alternative Ⅵ can raise the LOS to C.

When I examine the simulation in detail, we find that the geometrical form of the obstacles is partially responsible for the effects. When I compared groups Ⅱ-Ⅳ and Ⅲ-Ⅴ, I found that the alternatives using circular planting boxes have a higher performance than the ones using rectangular benches. As to the number of columns: I found that using two lines of columnar obstacles for the creation of two priority lanes for the elderly has a higher performance than using one. This result surprised us since it reduced the effective width. It is possible that the positive effect of reducing the difference in speed is greater than the negative effect of reducing effective width.

Table 20 shows both the mean passing speed of all pedestrians, and that of the younger ones to show how fast different commuters can traverse a corridor. The mean speed of the younger pedestrians is 1.44 m/s but covers a wide range of speeds, and can be substantially lower than the mean speed. Therefore, it is possible that local congestion and interactions among pedestrians (e.g., counter flow) leads to some temporary delays. However, Alternative Ⅲ can improve the mean passing speed of the younger pedestrians. This means that if the main objective is to improve the passing time of the commuters, planners can choose Alternative Ⅲ.

It is worth noting that Alternative Ⅵ which does not use physical separation also has a relatively higher performance. Alternative Ⅵ can reduce the impact of the difference in mobility among the pedestrians when the flow rate is less than 7(p/min/ft). This suggests that according to Fruin’s definitions, this alternative can meet most of the design requirements for transportation terminals, public buildings, or open spaces. An even flow rate is greater than 7 p/min/ft. It is also non-inferior among the six alternatives. In fact, it is the best when there are less than 5 p/min/ft.

I also noticed that although Alternative Ⅰ never shows the highest performance among the six types, it is non-inferior at many levels of flow rate. This might explain why most cases have an open design. Uncertainty is always a challenge for planners. Unless they are sure of the behavior of the users, they will rather take the conservative approach to avoid creating a wrong design. Based on our finding, they can promote a “regulation” to effectively improve performance, like shown in Alternative Ⅵ, where the younger pedestrians are advised to use the central lane allowing the slower elderly pedestrians to walk along the left-hand side of the wall.

CHAPTER 6 DISSCUSSIONS

The above analyzes and findings give us some implications for practice, application and methodology as shown in the following discussions.

6.1 Implications for practice and applications

I have observed an amount of walking energy expenditure and plotted them as a histogram to estimate a specific distribution for the WEEs. The above surveys could enrich the traditional walking distance with more content and a wider application. The surveyed WEEs show a right-skewed distribution, suggesting that when people walk when commuting they do so with a focus on saving effort. This characteristic is actually quite easily determined, since walking distances have been demonstrated to be right-skewed distributions and WEE is associated with walking time. However, WEE cannot be estimated if we do not model the effects of the pedestrian environment. As a result, effort-saving cannot be demonstrated without evidence of the right-skewed distribution of WEE.

It should be worthwhile to explore applying iso-energy in planning. For example, in a community, a local walking path system offers a pedestrian a set of alternative routes within an O-D pair. Each alternative route can be plotted as a point in Figure 4, which presents a bundle of distances and street amenities. We can then draw the energy curve by linking each point that consumes the same WEE. After repeating this process for all alternative routes per the levels of WEE, a set of curves similar to Figure 4 can be created. Let us assume the outer energy curve gives the pedestrian a lower utility. There is a constraint line BC for a pedestrian commuting from home to the transit station. To pursue a less energy-consuming route, the pedestrian would choose point C instead of point B. However, this idea needs more future study, as pedestrians may get used to their daily walk on specific routes regardless whether that route maximizes utility.

The energy-based approach supports considering more individual characteristics for setting walking distance. A new trend in planning theory is to change the current top-down planning perspective to a bottom-up one (Batty, 2001). Our proposed WEE approach improved the traditional aggregate walking distance by taking more individual characteristics into consideration (such as speed, body weight, gender, etc.) and by classifying the WEEs into levels based on the surveyed WEE data. In addition, energy reflects physical effort, and using WEE as a walking ability is suitable for enhancing the rational duration during agent-based simulation.

In addition to physical WTW, the psychological WTW was further estimated for a higher level of SA that can aid street improvement evaluation. The above analyses and findings should interest planners for several reasons. Sometimes a project site is very small or narrow, so planners may have few alternatives because it is only permissible to improve or rebuild one or two street facilities. Even so, they still hope the chosen alternative will prove effective. Referring to Table 12, planners can choose a set of SA attributes as targets to enhance WTW. There is scope for our results to be further developed as a criterion to evaluate the degree of achieving WTW enhancement.

These findings can improve the traditional land use theory. First, the proposed WEE approach could enrich the current planning theory in policy implications on land use patterns. “Concentric” is a general land use pattern for neighborhood or community planning where the levels of distance are set as radiuses of circles surrounding a service center (Banai, 1998). The bid-rent theory, inspired by the von Thünen model, supports the concentric pattern with a space economics analysis (Alonso, 1960). However, the circular area drawn using a constant distance does not take into account the effects of PEQ. For example, walking distance should be shorter in blocks without a walkway where pedestrian-vehicle conflict frequently happens. According to this research, a service area should be larger in an area with better PEQ but smaller in one with worse PEQ. Consequently, the concentric land use pattern should be modified into a contour pattern, as shown in Figure 17.

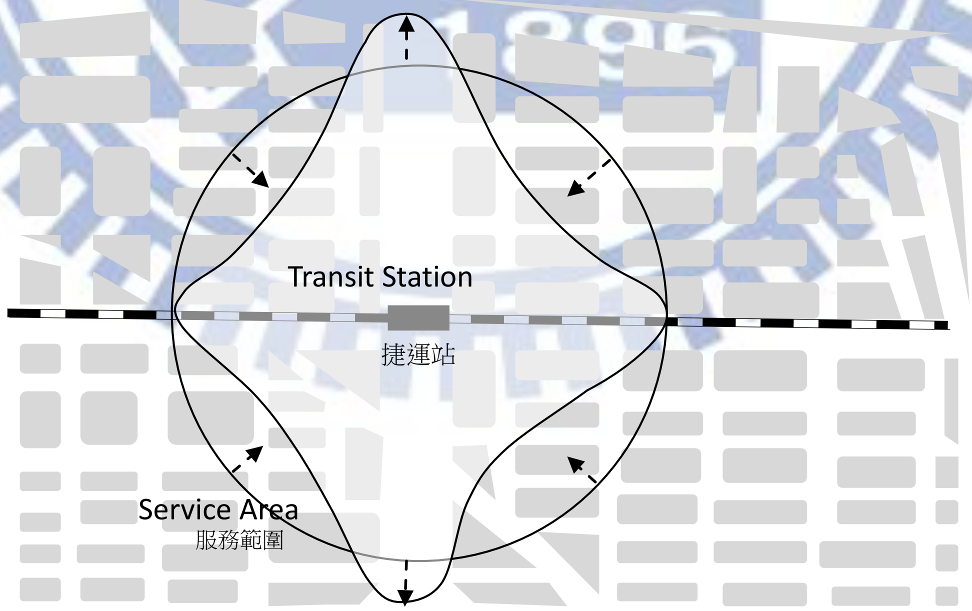

Figure 17 The service area with cosideration of WEE

Not only the shape, service area can also be broadened in the better environment. In our estimation, an improved street would increase pedestrians' utility to the point where they can spend more time to maintain the same level of utility. The increase in walking time implies that people would walk slowly or extend his/her distance. For example, street retailing is improved to provide pedestrians with a variety of stores (RF→RV), and this yields a 1.715(SP)/2.61(RP) min increment in WTW (Δt). When walking speed is set as 1.44m/s (υ), the change in distance is equivalent to 148(SP)/226(RP) m ($\Delta s = \upsilon \cdot \Delta t$). For a TOD planning, the result implies that the street improvement around a transit station would broaden its service area, as shown in Figure 18.

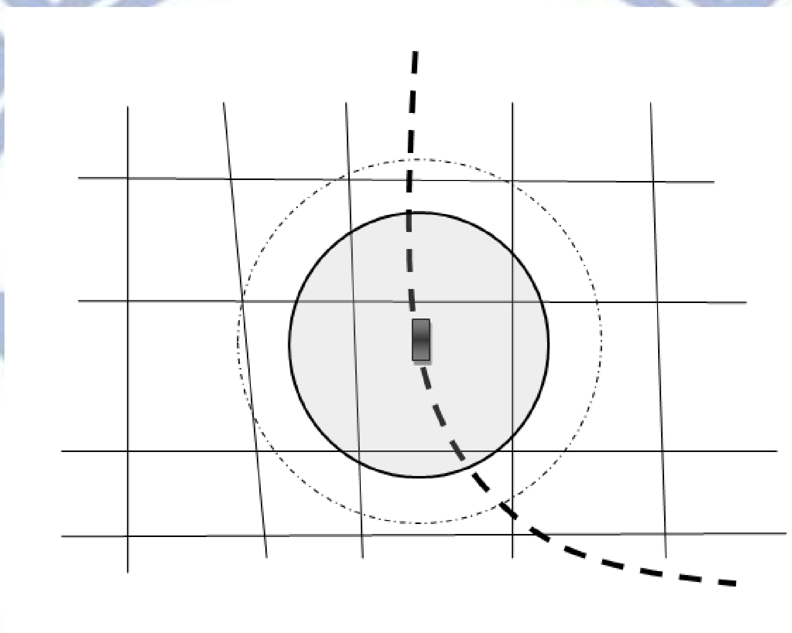

Figure 18 Street improvement around a transit station would broaden the walking accessible area.

6.2 Implications for methodology

This study applied two utility function types to determine the difference between the RP and SP models. The results show little discrepancy in the significant variables in equation 13, in contrast to equation 14, which considers individual characteristics, meaning that the participants do not take individual characteristics into account in the process of SP. Based on this finding, it should be noted that if a street improvement project is planned for a specific group, such as the elderly, planners should not be solely reliant on SP data, but should collect both SP and RP data to examine users' behavioral intentions.

As shown earlier, the result of the test conducted by Swait and Louviere (1993) rejects the estimation of an increase of WTW using a joint model. This result may not only occur in this study. Previous studies have explored the possibilities of combining various procedures and conditions (Huang, Haab, and Whitehead, 1997; Swait and Louviere, 1993), or sought another combing technique (Earnhart, 2002). However, reasons for and implications of this result are worth to be explored, which provide future research the direction to improve the preference equality or to explain the discrepancy between the SP and RP models.

In agent-based experiment, I found that there is a limitation when I analyzed the flow rate greater than 23 p/min/ft. As shown in Table 18, when the number of elderly pedestrians exceeds 5%, the mean speed is 1.44m/s and when the flow rate is less than 23 p/min/ft, the simulation can well fit Fruin's standards. However, it failed when the flow rate was greater than 23 p/min/ft; even when the elderly increased to 20%. It is likely that the nature of the extreme high density flow is best represented with the models of Helbing et al. (Helbing et al., 1995; Helbing wt al., 2000). In fact, people in highly congested flows may frequently end up touching each other. Although pushing might not happen, more detailed motion modeling than ours will be required to represent this situation. I designed direction-choosing and stopping as a bypass movement of agents, but readers will find that Helbing et al. used several forces, e.g., sliding friction force, to describe jammed pedestrians. Thus, extreme high density flows are out of the scope of this study.

Because the corridor is assumed only to serve as a passing corridor, the psychological effect of corridor design is not taken into account. Planting boxes and benches were the elements used to separate the counter flow or the difference in mobility between pedestrians, but in the real world they act both as a barrier and an amenity. Planting boxes provide greenery and raises the aesthetics of the corridor environment. Some pedestrians may avoid them by some distance but some may be attracted to them and slow down to admire them. Benches are usually placed on the side of a walkway to provide a means to take a rest. It also attracts pedestrians to remain in the area longer. However, this research assumed that the corridor serves mainly as a passing corridor, and that pedestrians tend not to stay for the facilities and amenities. This type of corridor exists mainly in bus, train and rapid transit terminals, and is not suitable for a corridor with different uses.

For uneven flows, the description of the LOS should be redefined to fit the real feel and need of the pedestrians. For example, when the flow rate is 10~15 p/min/ft, all the observed LOS were at level E. According to the original definitions of Fruin, this means that virtually all pedestrians would have their normal walking speeds restricted. However, the LOS of the younger pedestrians was higher, up to D (1.21~1.143 m/s). I did not use Fruin's original description to describe this situation, because the younger pedestrians may not be of the opinion that there is insufficient area available to maintain their buffer zone and desired speed. They may have a mindset that the only thing they need is a frequent change of direction or adjustment of gait if they wish to bypass slower-moving pedestrians. Thus it is suggested that the description of LOS be redefined to reflect the characteristics of uneven flow.

CHAPTER 7 CONCLUSIONS AND SUGGESTIONS

The conclusion and limitations of the thesis are shown in the following. Finally, I make some suggestions for future studies.

7.1 Conclusions

First, I am not the first to propose the WEE idea, but I am the first to apply it for planning. Pushkarev and Zupan (1975) have pointed in this direction by reviewing many relevant studies in applied physiology, and Hoogendoorn and Bovy (2005) involved energy consumption in their studies on travel cost. However, their ideas have not been further followed and carried out in planning. Fortunely, the adjusted Pandolf et al. (1977) model allowed us to represent the relationship between walking distance and pedestrian environment systematically. However, since the terrain factor needed to be redefined for the urban street space I conducted an experiment in seven streets and established a predictive function through regression analysis. The trend of commuting WEE in the urban area of Taipei shows a right-skewed distribution which was fitted as a Gamma distribution function. Compared to the traditional distance of a quarter mile (about 402 m), the expected walking distance in our study ranges between 505 and 1113 m (n=1.35~0.35). The levels of walking distance in Table 8 served as a guide to evaluate the classes of walking distance while taking into consideration the gender of the pedestrian and the street amenities. A contour type of land-use pattern is suggested to improve the traditional concentric pattern used in the evaluation of the service area. An opportunity to analyze route choice is shown in the Iso-energy curves concept, and WEE is suggested as a behavior parameter for agent-based modeling and simulation.

Second, I extend the application for discrete choice model from marketing research to pedestrian research to aid planners' street improvement practices. There are still some issues I have to address when approaching this goal. Walking time is defined as the measure of willingness to walk; in this way, I control randomness and nonlinearity in pedestrian behavior by focusing on the linear relationship between SA and WTW (Batty, 2001). I survey route choices with self-reporting O-D pairs to enrich the variation of RP data, and design a set of SP questions using a balanced and orthogonal matrix to reduce colinearity between alternatives. Third, the route is defined as an alternative, featuring changes to the level of SA attributes (defined as street improvement). A discrete choice model has already been applied to economic valuation and pedestrian-related studies (Audirac, 1999; Englin and Cameron, 1996), and their modeling frequently defines destination sites as alternatives, and environmental resources as attributes. That approach is unsuitable for our research, since it disregards the effects of street (road) amenities, which are very important to pedestrians.

Third, I propose a practical agent-based model for pedestrian environment design. This issue is addressed to respond aging population in following decades (Lacomba and Lagos, 2006). Application of ABM grows up in recent decades, but studies designing an agent-based pedestrian experiment with fine-scale data to show ex-post results are still few. Additionally, even researchers have aimed at improving the traditional methodologies to accommodate more objectives, e.g., safety, environmental aesthetics, by new rating, calibrating or modeling (Miller, Bigelow and Garber, 2000; Landis, Vattikuti, Ottenberg, McLeod and Guttenplan, 2001; Sisiopiku, Byrd and Chittoor, 2007), but I believe that dynamic studies solving local congestions in opinion of Fruin's LOS are rarely found. In particular, I found separation by promoting the young using the central lane and the elderly walking on priority lanes beside wall can be an acceptable solution. Because it showed non-inferior results among the six alternatives but did not reduce effective width. Finally, although permeable obstacle has been demonstrated useful for stabilizing flow and make them more fluid (Helbing, Buzna, Johansson and Werner, 2005), why is it rarely adopted in most corridors of Taiwan? Our results suggest that because it is conservative design that does not reduces effective width.

7.2 Contributions

This thesis makes contributions not only for practice but also for theory. This thesis is the first time linking physiology to planning theory that Pushkarev and Zupan (1975) have promoted but no research realizes it so far. Walking distance is also redefined from single value to the intervals according to the levels of WEE. This improves traditional neighborhood unit development (TND), where walking distance determines town size, by taking individual characteristics into account. Researchers may criticize the thesis because the results still lack to reflect pedestrians' subjective preferences. However, if planners and decision-makers need standards or planning tools to tell them what should be obeyed, the thesis truly provides them the improved ones.

The thesis may not be the first time using marketing research methodology for planning, but a systematic process of route choice experiment from alternative design to model calibration is rigorously designed. To raise the accuracy, I showed the respondents the designed figure of each candidate alternative to help them make judgment. This study applies SAS 9.0

software to design the five 2-level and three 3-level attributes into a balanced and orthogonal matrix. Pictures are not adopted here, because information is difficult to be controlled to meet the designed alternatives. RP question was designed as self-reporting O-D pairs and the SP question was designed using a fractional factorial method to enhance data variation in model-calibration. To avoid violation of the irrelevance of independent alternatives (IIA), random-parameters logit were applied to build route choice model.

Helbing's agent-based models can represent pedestrian flow close to real world; however, in contrast to traditional route choice model, his models are too complicated to apply. That is probably why rare researchers follow his work. The thesis retains the essence of his models, including coordinate, potential and direction-choice, to simulate walking behaviors in corridor when population aging. In particular, a line of round objects, such as potted plants, and rectangular ones, such as benches, have been tested and compared with mean passing speed. It should be the first time conducting the comparison and applying for space design to reduce local congestions among ABM studies.

7.3 Limitations

Like many studies, the thesis only can focus on linear relationship between WTW and SA. The attributes of SA considered only include what can be classified into levels. The other factors, e.g., culture, have not been explored. Interactions between SA factors, e.g. the mixed effect of planting and lighting, were not examined here and each topic only surveyed one kind of trip purpose.

In addition, the limitation becomes apparent when I consider both data variation and the ability of respondents to form judgments. One difficulty of this research was to simplify a complex street space as a perceptible message for respondents. To reduce complexity when making judgments, levels of attributes were set as 2 or 3; however, this would limit estimation in detecting the degree of variation between each attribute. To solve this problem, we did not survey the specific O-D pairs, but rather accepted open answers based on participants' status. Participants needed to record the detail of their trip using links, which made answering more difficult and probably reduced people's willingness to participate (thereby limiting the sample size).

As shown in Table 5, most sites show a statistical consistency between psychological and physiological rankings at the 10% significance level, but site 6 does not. This discrepancy may be due to the unexpected effects by site 6 on some of the participants. Site 6 is a downtown street with a variety of activities and actors in a compact arcade; random events (such as street vendors) combined with the spatial characteristics of the street probably lead to disparate responses and preferences among the participants. In other words, the uncontrolled events and the interactive effects on site 6 caused some subjects a high heart rate, even though these events might not have been “negative” for them. This speculation needs more studies to explore and validate, but it is beyond the scope of this research.

When I explored which type of pedestrian corridor design can improve the congestions resulting from high mobility difference, some unexpected results occurred. I first simulated the pedestrian flows by varying the elderly percentage from 5% to 20% to observe how LOS was worsen. The results suggest that when the number of elderly in a group of pedestrians exceeds 20%, the LOS of that corridor will decrease sharply. However, once flow rate is greater than Fruin’s LOS C, corridor design cannot significantly improve level of service.

As shown in Table 17, the flows at a mean desired speed of 1.44 m/s can fit Fruin’s observations. The mean passing speed of the younger pedestrians tends to decrease as the percentage of elderly pedestrians increases. This trend is not perfectly linear, probably due to the interactions among pedestrians (e.g., counter flow) and the fact that the desired speed may lead to some unexpected effect. In addition, the extreme high density flow (LOS F) cannot be successfully represented. Possible incidents of pushing and shoving were not modeled here, because they are out of the scope of this study. We therefore did not analyze them in the following steps.

7.4 Suggestions

The following are some suggestions for future studies. First, the WEE distribution for other trip purposes is worth investigating. In this research, the WEE distribution for commuting trips to and from work was shown, but for other trip purposes, such as shopping trips, the distribution is unknown. Future study could apply our approach to survey WEEs, and fit them as a feasible distribution function to represent the WEE properties. Second, future experiments could explore the consistency between psychological perception and physiological response. Our experiment shows that a higher PEQ will slow down the heart rate during walking. Positive attributes of a street (such as comfort, safety and other pleasant feelings) have been validated as the sources for lowering the heart rate compared to the negative effects (such as danger, discomfort and darkness etc.). However, the consistency testing between the psychological and physiological responses showed us that there may also be some positive experiences which were not pre-considered in the design of my experiment, and which could also contribute to a higher heart rate, such as excitement, expectation, anticipation, pleasant surprises and others.

I also suggest extending the WEE approach application to other facility planning. For example, for the path system of our national parks, like climbing and hiking, where service facilities need to offer visitors rest facilities to restore their energy. Such facility location planning still focuses on forecasting a feasible walking distance to meet acceptable WEE, even though more variables need to be considered.

There are some factors contributing to street amenities but left for future study. Closed-circuit television (CCTV) can be the one. Recently, CCTV plays a role of walking safety at night; even people criticize this because of the loss of privacy of the people under surveillance. It really provides safety at night, in particular, for women. However, comparing to lighting, CCTV is difficult to design into the alternatives of route set, because respondents are difficult to recognize it from the figure, unless they have been notified.

Some street amenities may not be associated with physical objects but still worth to be explored. Climate probably differentiates users' preference for street amenity attributes. Kaohsiung City is typically subtropical, and the hot and wet weather quickly make pedestrians feel tired and uncomfortable. Pedestrians probably need a fountain to cool down. They might also be inclined to purchase a beverage or food from a retail kiosk to recharge their energy levels. The high values of these two options are shown on the WTW estimation. In addition, street furniture and the pavement could be examined in another study by designing more levels. Most of our survey sites were urban streets with well-maintained pavements, and street furniture that already met most respondents' requirements, so higher levels of such attributes were not desired.

More behaviors can be involved for a corridor with various land use. The corridor was assumed only for passing. However, more and more corridors are planned with various land uses, e.g., shopping. Thus the related activities would be generated, e.g., stay-and-watch. In this case, crosswalk would happen more than the one I assumed, because pedestrians may want to visit the stores on the two sides. Psychological effect or preference for design can be considerate in model. As the earlier stated, the shopping behavior goes increasing in corridor planning. The developers would expect some spaces designed to retain people. In this case, effect of corridor design would not only include geometrical form and effective width, but also more amenities, e.g., lighting, pavement. So the effect of using bench, e.g., Alternative Ⅴ, should be reexamined, because it serves people's rest needs. Finally, the interaction between pedestrians and designs can be taken into account in future. A pedestrian environment is usually designed changeable (or flexible) to face any possible behavior. Thus, the type of corridor can be changed on performance by using moveable unit, e.g., potted plant. Performance can be improved in real case. However, walking behaviors here are assumed determined and rational. In future, the feedback can be designed in the ABM to reflect the change of pedestrian flow.

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APPENDIX 1

LOS	Volume(f) min pr/ft	pr/m	Average Area(a) ft^2/pr	m^2/pr	Description
A	7 or less	23 or less	35 or more	3.3 or more	Threshold of free flow. Convenient passing, conflicts avoidable.
B	7-10	23-33	25-35	2.3-3.3	Minor conflicts, passing and speed restrictions
C	10-15	33-49	15-25	1.4-2.3	Crowded but fluid movement, passing restricted, cross and reverse flows difficult.
D	15-20	49-66	10-15	0.9-1.4	Significant conflicts, passing and speed restrictions, intermittent shuffling.
E	20-25	66-82	5-10	0.5-0.9	Shuffling walk: reverse, passing and cross flows very difficult; intermittent stopping.
F	Flow variable up to maximum		5 or less	0.5 or less	Critical density, flow sporadic, frequent stops, contacts with others.

Source: http://ntl.bts.gov/DOCS/11877/Chapter_8.html

APPENDIX 2

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <math.h>
#define PED 12        /* amount of ped,符合 Fruin 的 LOS D~E */
#define DURA 40       /* simulation duration */
#define DIRECT 5      /* 方向總數 */
#define BORDER 2      /* 牆個數 */
#define A_W 2000   /* 牆的 A 參數 */
#define A_P 2000   /* 行人間的 A 參數 */
#define B_W 0.08   /* 牆的 B 參數 */
#define B_P 0.08      /* 行人間的 B 參數*/
int i,j;    /* counter of ped */
int t;        /* counter of time */
int k;     /* counter of direction */
struct R{
    float x, y;
};                  /* 時間－空間陣列 */
R ri[PED];       /* 行人 i 於時間 t 之位置陣列 */
```

```
const float I[DIRECT]={0, 0.4472, 0.7071,-0.7071, -0.4472}; /* 0:直行，1:小角度右，2:45 度右，3:45 度左，4:小角度左 */
const float J[DIRECT]={1, 0.8944, 0.7071, 0.7071, 0.8944}; /* 共有五個方向之 the normalized direction*/
float riCut[PED];                /* 每個行人有一個安全距離，包含個人身體寬度 */
float rijCut[PED][PED-1];
float v_0[PED];                  /* 行人初始速度 */
float PedVel(void);              /* 隨機產生速度函數，老年人用指定的 */
float PedDistance(int i, int j); /* 計算兩個行人間距離函數 */
float rCut(void);                /* 隨機產生安全半徑之函數 */
float PerDis(int i, int j);      /* 行人間不會造成不安之保持間距函數 */
R PedOrig(void);                 /* 隨機產生起點位置 */
int main(){
  float total[DIRECT], wal[DIRECT];      /* 總潛能，牆的潛能 */
  float potent[PED-1];           /* 與周邊行人的潛能 */
  float U[DIRECT];               /* 往方向 w 移動將產生多少潛能 */
  float rX, rY, d;               /* 與他人在 X 軸上之差，在 Y 軸上之差，距離 */
  float UM;
  float v;                   /* 真實步行速度 */
  int w;                     /* 第幾個方向 */
  R t_ri;                    /* 測試位置 */
  R N_ri[PED];                   /* 新的位置 */
  R W[BORDER];                   /* 牆的位置 */
  FILE *pFile;
  pFile = fopen("outcome.txt","w");
  srand(time(NULL));
  PedVel();
  rCut();
  PedOrig();
  ri[3].y=(rand()%130)*0.1+7;
  ri[8].y=(rand()%130)*0.1+27;
  W[1].x=3.2;     /* 右牆的 X 軸 */
  W[2].x=-3.2;    /* 左牆的 X 軸 */
fprintf(pFile, "%2s %3s %6s %6s %7s %7s %3s %13s %13s
%13s%13s\n","t","i","x","y","v_0[i]","v","w","total","wal","U","UM");
  for(t=0; t<=DURA; t++){
    for(i=1; i<=PED; i++){
      if(i==3){
        v=0.6;
```

```
  riCut[i]=0.70;
  w=0;      /* 老人速度、方向皆一致*/
  U[w]=0;
}
else if(i==8){
  v=-0.6;
  riCut[i]=0.70;
  w=0;      /* 老人速度、方向皆一致*/
  U[w]=0;
}
else {
  UM=A_P*exp((riCut[i]+0.45-0.5)/B_P); /* 潛能最大值 */
  for(k=0; k<DIRECT; k++){      /* 每人都以現在的位置去預想往那個方向前進*/
    t_ri.x=ri[i].x+I[k]*v_0[i];
    t_ri.y=ri[i].y+J[k]*v_0[i];
      if(t_ri.x >= W[1].x){    /* 前進位置不得超出右邊界 3.2 */
        t_ri.x=2.95;
      }
      if(t_ri.x <= W[2].x){    /* 前進位置不得超出左邊界-3.2*/
        t_ri.x=-2.95;
      }

      if((W[1].x-t_ri.x)>riCut[i] && (t_ri.x-W[2].x)>riCut[i]){ /* 計算與邊界的 potential*/
        wal[k]=0;
      }
      else if(riCut[i]>(W[1].x-t_ri.x)>0.25){
        wal[k]=A_W*exp((riCut[i]-fabs(W[1].x-t_ri.x))/B_W);
      }
      else if(riCut[i]>(t_ri.x-W[2].x)>0.25){
        wal[k]=A_W*exp((riCut[i]-fabs(W[2].x-t_ri.x))/B_W);
      }
      else{
        wal[k]=UM;
      }
      total[k]=0;  /* initializing total */
      for(j=1; j!=i && j<=PED; j++){
        rX=t_ri.x-ri[j].x;
        rY=t_ri.y-ri[j].y;
```

```
    d=sqrt(pow(rX, 2)+pow(rY, 2));
    if(d>PerDis(i, j)){
      potent[j]=0;
    }
    else if(PerDis(i, j)>d>0.5){
      potent[j]=A_P*exp((PerDis(i, j)-d)/B_P);
    }
    else{
      potent[j]=UM;
    }
    total[k]+=potent[j];
  }/*end for j*/
  U[k]=total[k]+wal[k];
}/*end for k */

if (U[0]==0 || U[0]<UM){
  w=0;
  v=v_0[i];
}/* 當前方沒有人的時候直走，若距離在 0.45 公尺以上者且是所有最小的也是直走 */
else if( (U[4]< U[1] && U[2] && U[3]) && (U[4]<UM) ){
  w=4;
  v=v_0[i];
}
else if( (U[3]< U[1] && U[2] && U[4]) && (U[3]<UM) ){
  w=3;
  v=v_0[i];
}
else if( (U[1]< U[2] && U[4] && U[3]) && (U[1]<UM) ){
  w=1;
  v=v_0[i];
}
else if( (U[2]< U[0] && U[4] && U[3] && U[1]) && (U[2]<UM) ){
  w=2;
  v=v_0[i];
}
else if( (U[0] && U[1] && U[2] && U[3] && U[4]) > UM ){
  v=0;
}
```

```
        else if( 0.8*UM < U[1] && U[2] && U[3] && U[4] < UM ){
          w=rand()%2*3+1;
          v=v_0[i];
        }
        else if( 0.6*UM < U[1] && U[2] && U[3] && U[4] < 0.79*UM ){
          w=rand()%2*3+1;
          v=v_0[i];
        }
        else if( 0.4*UM < U[1] && U[2] && U[3] && U[4] < 0.59*UM ){
          w=rand()%2*3+1;
          v=v_0[i];
        }
        else if( 0.2*UM < U[1] && U[2] && U[3] && U[4] < 0.39*UM ){
          w=rand()%2*3+1;
          v=v_0[i];
        }
        else if( U[1] && U[2] && U[3] && U[4] < 0.19*UM ){
          w=rand()%2*3+1;
          v=v_0[i];
        }
        else{
          w=0;
          v=B*v_0[i];
        }
      }/* end else */

      N_ri[i].x=ri[i].x+I[w]*v; /* offset of x */
      N_ri[i].y=ri[i].y+J[w]*v; /* offset of y */
      ri[i].x=N_ri[i].x;
      ri[i].y=N_ri[i].y;
      fprintf (pFile, "%2d %3d %6.1f %6.1f %7.2f %7.2f %3d %13.1f %13.1f %13.1f %13.1f\n", t, i, ri[i].x,
ri[i].y, v_0[i], v, w, total[w], wal[w], U[w], UM);
    }/*end for i */
  }/*end for t */
  fclose (pFile);
  return 0;
}
/*---初始位置產生器---*/
```

```
R PedOrig(void){
  for(i=1; i<=PED; i++){
    if(i<=floor(0.5*PED)){
      ri[i].x=(rand()%30)*0.1; /* x 軸位置初始值 */
      ri[i].y=(rand()%30)*0.1; /* y 軸位置初始值 */
    }
    else{
      ri[i].x=(rand()%30)*0.1*(-1);
      ri[i].y=(rand()%30)*0.1+47;
    }
  }
  return ri[i];
}
/*----隨機產生速度函數----*/
float PedVel(void){
  double mean_v, std_v, M_PI;
  double u,k;
  mean_v=1.44;
  std_v=0.233;
  M_PI=3.1416;
  for(i=1; i<=floor(0.5*PED) ; i++){
    u = rand() / (double)RAND_MAX;
    k = rand() / (double)RAND_MAX;
    v_0[i] =sqrt(-2 * log(u)) * cos(2 * M_PI * k) *std_v+mean_v;
  }
  for(i=floor(0.5*PED)+1; i<=PED ; i++){
    u = rand() / (double)RAND_MAX;
    k = rand() / (double)RAND_MAX;
    v_0[i] =-1*(sqrt(-2 * log(u)) * cos(2 * M_PI * k) *std_v+mean_v);
  }
  return v_0[i];
}/* end viod */
/*----i-j 距離函數----*/
float PedDistance(int i, int j){
  float rXij, rYij, dij;
  rXij=ri[i].x-ri[j].x;
  rYij=ri[i].y-ri[j].y;
  dij=sqrt(pow(rXij, 2)+pow(rYij, 2));
```

```
  return dij;
}
/*----個人領域空間---- */
float rCut(void){
  for(i=1; i<=PED; i++){
    riCut[i]=(rand()%50)*0.01+0.25;
  }
  return riCut[i];
}
/*----i-j 之安全間距間----*/
float PerDis(int i, int j){
  return riCut[i]+riCut[j];
}
```

VITA

姓　　名：蔡耀慶

地　　址：高雄市鳳山區大東二路 142 巷 7 號

現　　職：新竹市政府交通處工程師

E – mail　：ching4212@gmail.com

行動電話：0921-025671

學歷

- 國立交通大學運輸科技與管理學系 博士
- 國立台北大學都市計劃研究所 碩士
- 中國文化大學景觀學系 學士

著作

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