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Pedestrian Traffic Operations in Urban Networks

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Abstract

The pedestrian mode is an important component of urban networks, and greatly affects the performance of sidewalks and crosswalks, as well as the entire network traffic operations by interacting with other traffic modes (automobile, bicycle, transit). There have been many studies concerning different aspects of pedestrian behavior, such as pedestrian walking speed, delay, gap acceptance, signal compliance, route choice, etc. The Highway Capacity Manual (HCM) first included the pedestrian mode in 1994. The HCM 2010 provides several methodologies for evaluating the pedestrian level of service (LOS) of different urban street facilities. However, it does not comprehensively address pedestrian operations and does not consider some recent important findings such as pedestrian-vehicle interactions at crosswalks, pedestrian signal compliance rate, pedestrian jaywalking behavior, etc. This paper provides an overview of the literature on pedestrian operations in urban networks, identifies the important aspects of pedestrian operation analysis and provides several recommendations for enhancing the analysis of pedestrian facilities in the HCM on the basis of a summary of available U.S. and international literature. The following topics are discussed: pedestrian movement models, pedestrian crossing behavior, pedestrian-vehicle interactions. Pedestrian travel time estimation at the path level is proposed as an integrated approach for pedestrian operation analysis.

Keywords: Pedestrian, Operation, Urban network, HCM

1 Introduction

The pedestrian mode is an important component of urban networks, and greatly affects the performance of the sidewalks and crosswalks, as well as the entire network traffic operations by

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interacting with other traffic modes (automobile, bicycle, transit). A schematic of a pedestrian trip in an urban network is shown in Figure 1. The trip consists of walking portions which do not have interactions with vehicles, and crossing portions which do. Given an origin-destination, pedestrians have multiple route alternatives and may encounter different traffic conditions along their path. Pedestrian trip travel time represents the total time a pedestrian spends from an origin to a destination within a network.

There have been many studies concerning different aspects of pedestrian behaviors, such as pedestrian walking speed, pedestrian delay, gap acceptance, signal compliance, route choice, etc. The Highway Capacity Manual (HCM) included the pedestrian mode in the HCM 1994 (update to the HCM 1985). The most current edition (HCM 2010) provides several methodologies for evaluating the pedestrian level of service (LOS) of different urban street facilities (i.e., signalized/unsignalized intersections, urban segments). The LOS score for the entire urban street facility is determined as a regression function of pedestrian LOS at intersections, at links and the roadway crossing difficulty, which greatly depend on pedestrian delay at each location, pedestrian speed and available space respectively. However, the HCM 2010 does not fully cover the entire pedestrian trip and it is missing some important findings in recent studies, including research on pedestrian-vehicle interactions, jaywalking behavior outside the crosswalks, pedestrian route choice and crossing location selection.

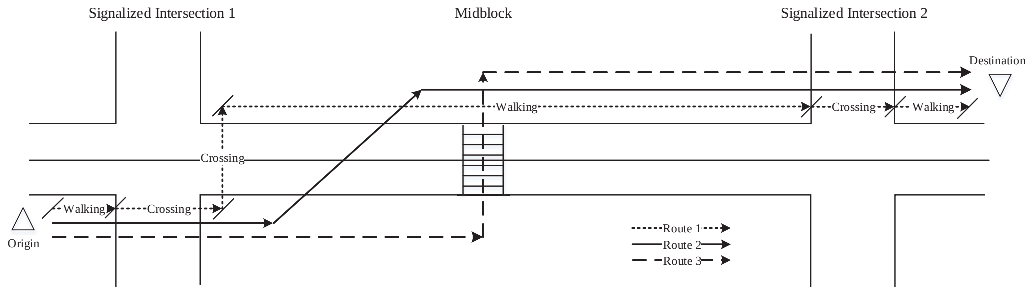

Figure 1 Schematic of a Pedestrian Trip in an Urban Network

Pedestrian behavior in urban networks was described by Hoogendoorn and Bovy (2004) as a hierarchical structure with: strategic level (departure time choice); tactical level (activity scheduling and route choice); and operational level (road crossing and interactions). The tactical decision interacts with the operational level when, for example, pedestrian travel route may change due to available crossing facilities, and pedestrian crossing location may affect the pedestrian overall travel time. This structure explains the relationship among these three levels and emphasizes the necessity for an integrated method for pedestrian operation analysis. However, most existing studies ignore these mutual impacts, and pedestrian travel time is typically analyzed only at the intersection level. Thus, in order to approximate the pedestrian perspective, it is necessary to develop a pedestrian travel time model that considers the entire trip.

The objective of this paper is to provide an overview of research related to pedestrian operations in urban networks, and to provide recommendations for evaluating pedestrian facilities in the HCM on the basis of a summary of available U.S. and international literature. Pedestrian travel time estimation at the path level is proposed as an integrated approach to approximate the pedestrian perspective in pedestrian operation analysis.

The next section provides an overview of previous studies on pedestrian traffic operations, including pedestrian movement, pedestrian crossing behavior, pedestrian-vehicle interactions, and pedestrian travel time. Conclusions are provided at the end of the paper along with recommendations for the HCM.

2 Literature Review

This section provides an overview of available U.S. and international studies on some important perspectives of pedestrian operations in urban networks. Pedestrian movement models, pedestrian-vehicle interactions and pedestrian travel time are discussed.

2.1 Pedestrian Movement

Pedestrian walking speed and available space are the major elements of pedestrian movement along urban segments, and are key performance measures for pedestrian movement operation evaluation. There have been many studies analyzing average pedestrian speeds under different circumstances (Dewar, 1992; Fitzpatrick et al., 2007; MUTCD, 2009; Schroeder et al., 2014). Pedestrian movement in urban networks has been modeled by various simulation methods, including macroscopic and microscopic models, and time-based or event-based simulation techniques. This paper only discusses the pedestrian movement models limited to traffic operations; evacuation models are outside the scope of this paper.

2.1.1 Pedestrian Movement Operation Evaluation

Pedestrian speed and available space are widely-used performance measures for evaluating pedestrian movement in urban networks. The HCM 2010 uses the walking speed and available space along sidewalks to estimate pedestrian LOS at road links. Link LOS further determines the overall LOS performance of urban pedestrian facilities.

For road segments, there are different estimation methods for pedestrian speed and the corresponding available space. The HCM (2010) (Chapter 17 and 23) estimates the average pedestrian speed as a function of pedestrian flow rate and effective width at urban segments (roadway and intersection) and off-street facilities (walkways and stairways), as follows:

$$S_p = \left(1 - 0.00078 v_p^2\right) S_{pf} \tag{1}$$

where v_p is pedestrian flow rate per unit width (p/ft/min); S_{pf} is pedestrian free flow speed (ft/s).

The HCM 2010 assumes equal demand distribution in the two directions without accounting for the impacts of unequal distributions and opposing/conflicting pedestrians. The unit width refers to the effective width, which is the total walkway width minus the width of fixed objects (trees, buildings) and shy distances (the buffer distance between pedestrians and obstacles, such as curbs). For shy distance, Stucki (2003) used 1.5 ft from walls, 1.14 ft from fences, and 1 ft from small obstacles (such as street lights and trees). Hoogendoorn and Daamen (2005) used 1.5 ft for the case of pedestrian inside bottlenecks. A distance of 1.5 to 2.0 ft is used in the HCM 2010. But no reliable and robust methods to estimate shy distance have been provided in the existing studies that would be applicable in different walkway conditions (Pushkarev and Zupan, 1975; Hoogendoorn and Daamen, 2005; Bloomberg and Burden, 2006). A study by the New York Department of City Planning (Bloomberg and Burden, 2006) indicated that the HCM model (Equation (1)) was too insensitive to changes in pedestrian volume and sidewalk width. Direction traveled, pedestrian characteristics and pedestrian density on the sidewalk should be considered as other contributing factors.

For street crossing, the Traffic Engineering Handbook (Dewar, 1992) suggested a speed of 3.0 to 3.25 ft/s would be more appropriate to use for signal timing. A crossing speed of 3.5 ft/s was suggested for the general population by Fitzpatrick et al. (2007). The Manual on Uniform Traffic Control Devices (MUTCD, 2009) suggested 4 ft/s as pedestrian crossing speed for signal timing. The HCM (2010) uses 4.0 ft/s as uniform pedestrian crossing speed in all traffic/geometry/treatment conditions at signal intersection crosswalks. A speed of 5.05 ft/s (or even higher) at midblock crossings among young populations was found within a campus environment (Zheng et al., 2015a). Pedestrian crossing speed is affected by many factors. Some research indicates that crossing speed is a function of internal factors such as pedestrian age, and gender, as well as external factors such as pedestrian volume, grade, width, and environment (Coffin and Morrall, 1995; Knoblauch et al., 1996). Fruin (1971) found that the speed in both directions tended to be equal when there were no dominant flows, while in other cases, the stronger flow tended to weaken others. Blue and Adler (2000) confirmed the impacts of cross-directional pedestrian flow on speed reduction. Zheng et al. (2015a) investigated the crossing speed of jaywalkers and compared it with permissible crossings at crosswalks. They found that there was no significant difference between the average speeds, but the speed variability of jaywalkers was much higher than that for permissible crossings.

2.1.2 Pedestrian Movement Modeling

Macroscopic models for pedestrian movement have been mostly developed based on fundamental traffic flow theory and queueing theory (Hughes, 2002; Daamen et al., 2005; Huang et al., 2009; Xia et al., 2009). Hughes (2002) proposed a continuum theory to understand the mechanics of pedestrian flow in large crowds. The pedestrian crowd behaved rationally and aimed to achieve the immediate goal in minimum time. Daamen et al. (2005) calibrated the fundamental traffic flow diagrams for pedestrian flow operations in congestion and provided a method to estimate the fundamental diagram from observations. Xia et al. (2009) developed a macroscopic model for pedestrian flow at a walking facility. They assumed the pedestrian chose a route based on the memory of the shortest path and tried to avoid high densities.

Micro-simulation of pedestrian movement behavior has been a major focus in pedestrian operations. In these, each pedestrian is considered individually. Antonini et al. (2006) tested two logit models to simulate pedestrian movement at a metro station entrance by considering pedestrian speed, direction angle and other surrounding pedestrians. Cellular Automata (CA) models and Social Forces (SF) models are two typical approaches to simulate pedestrian movement in urban networks microscopically.

CA Method

CA models, which effectively capture collective behaviors, have been widely used for pedestrian simulation (Davidich and Köster, 2012). In a CA model, the entire area of interest is covered by cells. Each cell is occupied by one pedestrian. The interactions a pedestrian may come across (e.g., nearby pedestrians, targets and obstacles) are calculated into scores. In moving toward their destination, pedestrians would choose the neighboring cell with the lowest score. Gipps and Marksjö (1985) first proposed CA modeling in pedestrian simulation. Blue and Adler (2001) applied CA modeling and simulated several pedestrian movement behaviors, such as side-stepping, conflict mitigation, and indicated that the flow patterns were consistent with well-established fundamental properties. Dijkstra et al. (2001) developed a multi-agent CA model of pedestrian movement as a tool to better explain how a design would influence user behaviors. Burstedde et al. (2001) developed a CA model for large systems and showed that the model allowed for faster-than-real-time simulations. However, the CA method does not take into consideration that pedestrians may follow others to cross rather than keep a certain distance with people around and make their own decisions.

SF Method

SF models are commonly used for computer simulations of crowds of interacting pedestrians. Their ability to realistically describe the self-organization of several observed collective effects of pedestrian behavior has been demonstrated (Helbing et al., 2005). Helbing and Molnar (1995) developed the first SF model, which has similar principles as a Benefit Cost Cellular Model. A pedestrian is subjected to several social forces around himself/herself when moving forward to their destination, including motivation to reach their goal, and repulsive forces of other pedestrians and of obstacles. Johansson et al. (2007) applied an evolutionary optimization algorithm for parameter specifications for an SF model. Their proposed model can be applied for large-scale pedestrian simulations of evacuation scenarios and urban environments. SF models are more flexible for modeling different sizes and shapes of obstacles within the walking space, so that complicated scenarios such as evacuations during emergencies can be simulated. A comparison between SF and CA models showed that the SF model took much longer in updating pedestrian positions than the CA model, when simulating the same number of pedestrians (Quinn et al., 2003).

Pedestrian route choice is another important aspect that influences pedestrian operations. However, all the pedestrian movement simulation models mentioned above didn't consider route selection. Their pedestrian travel path was determined by the result of every single simulation step of pedestrian movement. No general travel route preference or pedestrian variability were considered. Asano et al. (2010) proposed a microscopic pedestrian movement model along with a macroscopic tactical model for pedestrian route choice. The model used minimum travel costs as the optimization variable to determine the path to destination. Results showed that a tactical model was helpful in simulating pedestrian movement (validated from field observations).

2.1.3 Discussion

In general, the literature indicates there is consensus about the fact that the pedestrian speed is influenced by many factors –pedestrian volume, available space, age, walkway environment, time of day, trip purpose, etc. However, the HCM 2010 method does not consider most of them, and provides the crossing speed only at signalized intersection crosswalks. Further research at roundabouts, and all-way-stop-controlled intersections are necessary. Moreover, most of the existing studies only focused on the average pedestrian speed and did not well incorporate variabilities in pedestrian behavior.

For pedestrian movement models, most are developed based on traffic flow theory or basic kinematics. Given an Origin-Destination pair, the pedestrian travel path is randomly selected, however, the pedestrian route choice in reality highly depends on pedestrian characteristics and traffic conditions.

2.2 Pedestrian Crossing Behavior and Pedestrian-Vehicle Interactions

Pedestrian-vehicle interactions affect pedestrian traffic operations in urban networks, as well as the pedestrian-related facility performance as they may cause delay and spillback. Pedestrian crossing behaviors and the respective vehicle reactions were observed in the field and studied by a number of researchers (Braun and Rodin, 1978; Coffin and Morrall, 1995; Virkler, 1998a; Sun et al., 2003; Li et al., 2005; Schroeder, 2008; Schroeder and Rouphail, 2010a; Schroeder and Rouphail, 2010b; Guo et al., 2011; Molino et al., 2012; Ni and Li, 2012; Schroeder et al., 2014). Crossing difficulty and crossing options were explored and identified as important factors for multi-modal analysis (Golledge, 1999; Chu et al., 2004; Holland and Hill, 2007; Mitman et al., 2008; Zhou et al., 2009; HCM, 2010; Kneidl and Borrmann, 2011; Zhuang and Wu, 2011; Jim Shurbutt, 2013).

This paper discusses the impact of pedestrian-vehicle interactions on pedestrian operations at signalized intersections, unsignalized intersection and midblocks as well as jaywalking events. Pedestrian delay estimation for each location type is highlighted as a key operational performance measure.

2.2.1 Signalized Intersections

Pedestrian crossing behavior and vehicle interactions at signalized intersections depend on the traffic control features and intersection signal plans. Pedestrians may not directly interact with vehicular traffic where pedestrian volume is high and a protected pedestrian crossing phase is implemented. At some other intersections where right-turn vehicles are allowed to turn during the red, crossing pedestrians may conflict with right turning traffic.

Pedestrian signal compliance rate is another important aspect that affects pedestrian-vehicle interactions as well as pedestrian traffic operations at signalized intersections. It varies with traffic conditions, crossing treatments, signal timing designs and personal characteristics and attitudes (Guo et al., 2011). The HCM (2010) indicates that pedestrian compliance is a function of the expected delay. Dunn and Pretty (1984) found that all pedestrians complied if delay was less than 10 seconds, while no pedestrians complied if the delay exceeded 30 seconds. Huang and Zegeer (2000) indicated that the overwhelming majority of pedestrians preferred the "Pedestrian count-down (PCD) signals" which also had a higher compliance. Lower compliance was more likely to occur at a low-volume minor street approach to a signalized intersection (Stollof et al., 2007).

Pedestrian delay is defined as the wait time due to signal effects and conflicts with turning vehicles or pedestrians at crosswalks. The HCM (2010) only considers signal effects, and it assumes random pedestrian arrival rate, fixed pedestrian timing, no pedestrian conflicts, and 100% pedestrian compliance. The delay model used in the HCM 2010 is as follows:

$$delay = \left(C - g_{walk}\right)^2 \Big/ 2C \tag{2}$$

where C is cycle length (s); g_{walk} is effective walk time (s), depending on crossing treatment type.

This model is a theoretical function of cycle length and pedestrian phase duration. It is not applicable for pedestrian crossing in groups such as two-stage crossings or under high pedestrian volume condition. A New York City study (Bloomberg and Burden, 2006) indicated that 3 seconds as a start-up time was necessary to be added at signalized intersections with high pedestrian volume. Other pedestrian delay models adjusted the pedestrian compliance rate and pedestrian arrival pattern. Virkler (1998a) added a portion of pedestrian clearance interval to actual green time in the case of pedestrian crossings during the clearance period. Braun and Rodin (1978) and Li et al. (2005) both added a parameter in their models to estimate the delay reduction due to non-compliance. Li et al. (2005) found the magnitude of this parameter was affected by conflicting vehicle flow and the percentage of no-complying pedestrians when there was an acceptable gap. Wang and Tian (2010) developed a delay model for signalized intersections with a median. Assuming 100% pedestrian compliance and uniform arrival rates during the first-stage, the delay model consisted of delay from the first-stage crossing, delay from the second-stage crossing beginning with the "Walk" sign, and delay from the second-stage crossing beginning with the "Don't-Walk" sign. Each of them related to the "Walk" duration and the red interval duration of the first stage. Li et al. (2005) introduced another parameter in the delay model to capture the observed pedestrian non-uniform arrival pattern. The models reviewed here improved the delay accuracy relative to the HCM 2010 methods by adjusting the assumptions to be better aligned with field conditions.

2.2.2 Unsignalized Intersections and Midblock Crossings

Pedestrians have more direct interactions with vehicles at unsignalized intersections and midblock crossings. Generally, pedestrians are more likely to cross the street at designated facilities (Dunn and Pretty, 1984; Sun et al., 2003; Zheng et al., 2015a).

The pedestrian street crossing behavior can be regarded as a pedestrian gap acceptance problem, where the vehicle-pedestrian gap is a good indicator that captures the interaction distance between the approaching vehicle and waiting pedestrian. The HCM 2010 assumes pedestrians are consistent and homogeneous, i.e., all pedestrians would always seize the gap if it is greater than the critical value (which may not be completely true in reality). Other studies have proposed distributions for critical gaps, such as log-normal (Troutbeck, 1992), or random distribution (Robertson et al., 1994). This probability-based method considers heterogeneity in the pedestrian population and can be used to analyze pedestrian operations by pedestrian groups. But these models ignore the pedestrian-vehicle interactions that influence the variability of critical gaps. Recent studies conducted field observations and indicated that pedestrian characteristics (age, assertiveness, volume, location), traffic characteristics (platoon, gap size), vehicle characteristics (speed and distance), geometry characteristics (crossing treatments) all influence the pedestrian gap acceptance as well as the pedestrian operations at unsignalized intersections or midblock crossings (Sun et al., 2003; Schroeder, 2008; Schroeder and Rouphail, 2010a; Wang et al., 2010; Avineri et al., 2012). However, there exist other factors in pedestrian-vehicle interactions that have not been considered, such as the maximum pedestrian wait time, vehicle wait time, etc.

Driver yield behavior has been commonly observed when interacting with street-crossing pedestrians and may significantly affect the interactions as well as pedestrian operations at unsignalized intersections /midblock crossings (Sun et al., 2003; Schroeder, 2008; Salamati et al., 2013; Schroeder et al., 2014). The yield rate varies under different conditions. For example, it was found that the drivers were more likely to yield with low vehicle travelling speed (Schroeder and Rouphail, 2010a; Salamati et al., 2011), travelling in a platoon (Schroeder et al., 2014), and within an environment with higher pedestrian activities (Schroeder and Rouphail, 2010b; Zheng et al., 2015a). The behavior of the vehicle in front might also have an impact on the following vehicles (Schroeder, 2008; Schroeder and Rouphail, 2010a). However, most of the previous pedestrian delay studies ignored the driver yielding behavior (Adams, 1936; Mayne, 1954; Weiss and Maradudin, 1962; Troutbeck and Brilon, 1997); for those which considered the yielding possibility, they still ignored it if the vehicle was travelling in a platoon, and assumed pedestrians need to wait for an entire vehicle group to cross (Guo et al., 2004; Wei et al., 2013).

Pedestrian delay models for crossing at unsignalized intersections/midblock crossings were first developed by Adams (1936) and have been expanded/modified by various researchers (Tanner, 1951; Mayne, 1954; Underwood, 1961; Troutbeck, 1986). The early models adopted simple vehicle headway distributions and ignored vehicle yield behaviors. Recent pedestrian delay studies focused on calibrating and modifying the previous models for different traffic scenarios (Guo et al., 2004; Schroeder and Rouphail, 2010b; Vasconcelos et al., 2012), such as two-stage crossing, platooned traffic caused by signals, etc. The HCM (2010) improved Adams' model (1936) by adding the assumption of constant vehicle yield rate. Findings from observational studies have considered additional elements, such as platooned traffic (Sisiopiku and Akin, 2003; Schroeder et al., 2014), driver yielding behavior (Sun et al., 2003; Schroeder, 2008), pedestrian yield recognition (Schroeder, 2008; Schroeder et al., 2014), and they are not currently considered in the pedestrian delay model. Thus, these existing models may not perform well in estimating pedestrian delay in cases of high-level pedestrian activities, such as in major city CBD areas, campus areas, etc. Other researchers explored this problem by considering it as a stochastic process (Weiss and Maradudin, 1962; Heidemann and Wegmann, 1997; Zheng and Elefteriadou, 2015). Zheng and Elefteriadou (2015) proposed a theoretical model for estimating the pedestrian delay at unsignalized intersections in urban networks using Renewal Theory. The traffic platoon pattern and driver yielding behavior were considered. The applicability and accuracy of this model were validated by field data and simulation testing. A generalized model was also developed in their study which could be easily expanded and applied to other traffic conditions by fitting in reasonable assumptions (Zheng and Elefteriadou, 2015). Their delay model, with fully adopting the HCM 2010 assumptions (constant yield rate and Poisson vehicle arrival) is as follows and can be used when the traffic pattern and driver behavior satisfy the HCM assumptions:

$$delay = \left(\frac{1}{\gamma}(1-y) - \left(\tau + \frac{1}{\gamma} \right)(1-y)e^{-\tau\gamma} \right) \Big/ \left(y - ye^{-\tau\gamma} + e^{-\tau\gamma} \right) \tag{3}$$

where γ is vehicle volume (veh/sec); y is driver yield rate; τ is pedestrian critical gap (sec).

2.2.3 Pedestrian Jaywalking Behavior (Outside of Crosswalks)

Pedestrian crossing outside of a marked or unmarked crosswalk (i.e. jaywalking), is one of those pedestrian behaviors that affect safety and operations. Pedestrian jaywalking behavior is commonly observed in the field, especially within an environment with high levels of pedestrian activities (Zheng et al., 2015b). Unlike permissible crossings at crosswalks, jaywalking events are not often anticipated by drivers, which may result in lower driver reaction time, different vehicle dynamics, as well as different pedestrian operations (Zheng et al., 2015a; Zheng et al., 2015b). To date, limited quantitative and behavioral research has been conducted to investigate this interaction or simulate it microscopically. Zheng et al. (2015a) explored pedestrian jaywalking behavior (gap acceptance and speeds) and the corresponding driver reactions (yielding behavior). It was found that jaywalkers were less likely to accept driver's yielding behaviors, resulting in a lower yield utilization rate than permissive crossings at crosswalks. Pedestrian jaywalking behavior may highly affect the pedestrian route selection as well as the pedestrian trip travel time (discussed in section 2.3).

There has been one published study identified pedestrian delay during jaywalking events. Zheng et al. (2015a) observed the average jaywalker delay in Gainesville, Florida was 0.87 seconds, while the average pedestrian delay during permissive crossings was 3.65 seconds. Based on the findings of this research, a pedestrian jaywalking delay model can be developed based on the generalized model from Zheng and Elefteriadou (2015) by adjusting the assumptions of driver yielding and pedestrian gap acceptance/rejection behavior.

2.2.4 Discussion

In general, most research on pedestrian crossing behavior and pedestrian-vehicle interactions conducted observational studies and provided quantitative as well as qualitative information. Pedestrian crossing at most urban street facilities were discussed (except roundabouts and all-way-stop-controlled intersections). However, the existing studies seldom examined the possible impacts of multiple crossing alternatives on pedestrian crossing behavior, or how the crossing behavior and pedestrian-vehicle interactions affected the pedestrian route choice as well as overall travel time at the path level.

2.3 Pedestrian Travel Time Estimation Model

Generally, pedestrian travel time along urban segments can be a good performance measure, since it captures the pedestrian perspective and considers the time spent along the travel path including crossing at intersections, walking along the links and interacting with other road users (Figure 1). Moreover, as identified in section 2.1 and 2.2, previous pedestrian research usually separates pedestrian walking and crossing behaviors when analyzing pedestrian traffic operations in urban networks. However these may often be interrelated, and thus it is necessary to link the pedestrian movement and crossing behaviors with consideration of pedestrian-vehicle interactions. Travel time estimation can offer an integrated way to analyze pedestrian operations along the travel path and evaluate facility performance. There have been several studies focusing on pedestrian travel time prediction/estimation at a path level. Rahman et al. (2013) applied queuing theory to model pedestrian movement and estimated pedestrian travel time only at roadway links without considering pedestrian crossings. Virkler (1998b) proposed a method to predict travel time along a given pedestrian route as a summation of total walking and queueing time. That study did not consider variabilities in pedestrian behavior and traffic conditions, and it was shown that the model accuracy was reduced for coordinated signal systems.

2.3.1 Discussion

Travel time at the path level is a quantitative measure that includes pedestrian movement, crossing and pedestrian-vehicle interactions. Only a few studies analyzed this and these did not consider the possible vehicle interactions and the variabilities in pedestrian behavior. Therefore, to obtain a comprehensive model for pedestrian operations evaluation purposes, we propose developing a method to estimate pedestrian travel time at the path level. Such a model can also be used for predicting the travel time before the trip.

A data-driven methodology is proposed. Recording pedestrians as they travel along their paths (an adaptation of the floating-car method) with GPS recording the real-time location and travel speed is suggested as an approach to collect data. Data may include pedestrian travel time at each component of the path, pedestrian crossing location (signal intersections, unsignalized/midblock crossing, or jaywalking), pedestrian individual characteristics (gender, age), roadway characteristics (shoulder width, number of lanes, crossing facilities, signals), and traffic conditions (traffic volume, average travel speed). Distributions of overall pedestrian travel time as well as walking time and delay time at each location can be obtained. The relationship/dependence between pedestrian movement and crossing behavior, pedestrian route choice and crossing facilities can thus be examined. Furthermore, the pedestrian crossing location selection and route alternative selection can be modeled using data from field observations.

3 Conclusions and Recommendations

This paper identifies the important aspects of pedestrian operation analysis in urban networks. Pedestrian movement models, crossing behaviors and pedestrian-vehicle interactions, as well as pedestrian travel time are all discussed on the basis of available US and international studies. Pedestrian delay models for different locations are highlighted as it is a key performance measure and contributes to overall pedestrian travel time at the path level. Pedestrian travel time represents the total time a pedestrian needs for travelling from origin to destination, encountering different traffic conditions, and interacting with other road users. Pedestrian travel time estimation is proposed as an integrated approach to evaluate facility performance and pedestrian operations in urban networks.

The HCM 2010 does not currently consider some important findings from recent pedestrian studies. Based on our review of the literature we recommend the following HCM enhancements:

Pedestrian Delay Estimation

- At signalized intersections, the pedestrian delay model is not applicable for pedestrian platooning under high pedestrian volume condition. A few seconds can be added according to Bloomberg and Burden (2006). Additional research on adjusting pedestrian compliance rate and arrival pattern assumptions into pedestrian delay model in the HCM 2010 is needed.
- At unsignalized intersections/midblocks, the pedestrian delay model does not capture the driver yielding variabilities and traffic platoons. The proposed model by Zheng and Elefteriadou (2015) is recommended for analyzing pedestrian delay in urban networks. Equation (3) is recommended when fully adopting the current HCM 2010 assumptions (constant driver yield rate and Poisson vehicle arrival).

Pedestrian-Vehicle Interactions

- The assumptions for driver yielding rate and pedestrian critical gap should be adjusted with locally measured values or default values for inclusion parameters. The driver yielding probability and pedestrian gap acceptance models developed by Schroeder et al. (2014) can be used.
- Jaywalking behavior is ignored in the HCM 2010, while it is frequently observed in urban networks with high pedestrian volumes. The quantitative relationship between jaywalkers and vehicles developed by Zheng et al. (2015a) should be considered and can be incorporated into pedestrian delay as well as travel time estimation.

Pedestrian Travel Time Estimation

- Pedestrian walking and crossing are separated when analyzing pedestrian traffic operations in urban networks. Travel time estimation along urban segments is recommended for evaluating the urban facility performance as a direct and comprehensive approach, since it covers all the influencing factors identified in the HCM 2010 (i.e., speed, space, crossing difficulty, delay at intersections) as well as the impact of crossing/route alternatives along pedestrian travel paths.

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