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Weighted Regression Method for the Study of Pedestrian Flow Characteristics in Dhaka, Bangladesh

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Abstract

The proper estimation of pedestrian speed-flow-density relationships is of vital importance, because such relationships play an important role in developing useful tools for analysing and improving pedestrian facilities in terms of efficiency and safety. One of the major problems with previous macroscopic studies of pedestrian flow characteristics is that the relationships were established based on a model with specification errors that had been estimated by ordinary least squares (OLS). Thus, the validity of the relationships and conclusions drawn from those studies is open to question and should be examined further. In this study, pedestrian speed-flow-density relationships in Dhaka, Bangladesh, are estimated using a weighted regression method. The flows and speeds generated by the derived flow-density and speed-flow relationships based on the weighted regression method and the OLS method, separately, are compared with empirical values. The root mean square error is used as an evaluation criterion. In addition, the pedestrian characteristics of Dhaka are compared with those of other studies. The results indicate the existence of a probable bias in previous studies and an improvement in predictive power with the use of the weighted regression method. Pedestrian flows on the sidewalks in Dhaka have some particular characteristics that are not similar to the uninterrupted pedestrian flows in other countries. Since the weighted regression estimation techniques can mitigate a part of the OLS bias, such techniques could be incorporated in simulation packages to predict pedestrian flows and speeds as well as to design and analyse the capacity of a pedestrian facility precisely. The study also recommends refraining from the direct adoption of foreign design and parameters for pedestrian facilities in Dhaka.

Keywords: pedestrian flow, ordinary least squares (OLS), weighted regression method

1. Introduction

Although walking is not usually considered a transportation mode, every human trip begins or finishes with walking. The pedestrian mode has received recognition as a vital building block at every age of urbanization. Ancient cities were developed in such a way as to make it possible for every citizen facility to be within walking distance for their dwellers. The pedestrian was the primary consideration for Roman and Hebrew planners (Benepe, 1965). Even in the mechanized world of today, short trips and intermodal transportation in cities depend on the vital means of locomotion, walking, which is impossible to duplicate. In addition, the constantly increasing air pollution, urbanization, and urban population, along with the constraints on the increment of vehicles on the road, have served to popularize the natural mode of transportation. In least developing countries, however, the scarcity of transportation, poor traffic management, and less ability to bear transportation fares compel a significant portion of urban inhabitants to walk long distances. Thus, pedestrianization has become an integral part of sustainable modern urban design, where pollution-free, convenient, safe, and comfortable pedestrian facilities are ensured. To build a walking-friendly urbanization, which should be matched with the equilibrium of pedestrian demand and the capacity of pedestrian facilities, proper evaluation of local pedestrian flow characteristics and travelling behaviour is very essential. Research on pedestrian movements and flow characteristics began in the 1960s, mostly in developed countries. However, they are limited compared with research that focuses on vehicle traffic flow.

Pedestrian flows are the outcome of many complex and stochastic phenomena. However, at least a partial attempt to realize the flow characteristics and travelling behaviour is always imperative for the design of optimal land use in pedestrian facilities. A number of physiological, psychological, and environmental factors make a significant contribution to the free flow movements of a pedestrian. These factors include age, gender, the baggage-carrying capacity of a pedestrian and the walkability of a facility (Rahman, Ghani, Kamil, & Mustafa, 2012), the gradient or roughness of surface (Older, 1968), time of day (Hoel, 1968), the intention, intelligence, and physical fitness of a pedestrian (Robertson, Hummer, & Nelson, 1994), indoor or outdoor walkway (Lam, Morrall, & Ho, 1995), and type of walking facility (Tanaboriboon & Guyano, 1991). For pedestrian movements on a public walkway facility, the most important factor is the presence or absence of other pedestrians (Older, 1968).

Studies that consider pedestrian movements in the presence of other pedestrians could be broadly categorized into two groups: microscopic level and macroscopic level. A microscopic-level study considers individual units with traffic characteristics such as individual speed and individual interaction (Teknomo, 2002). On the other hand, a macroscopic-level study considers the movements of all pedestrians in a pedestrian facility and aggregates their characteristics to traffic flow. The main concern of macroscopic pedestrian studies is the space allocation for pedestrians that minimizes pedestrian conflicts and the expenditure of human energy and time on the pedestrian facilities. However, consideration of a number of factors that affect the flow of pedestrians is not universal. Normal movement and emergency movement have some different distinguished patterns, and they have different expectations on the required level of facilities (Stanton & Wanless, 1995).

This paper revisits the fundamental diagram of speed-flow-density relationships and evaluates the applicability and effectiveness of the weighted regression method for the study of macroscopic pedestrian flow characteristics in normal movement. Thus, the rest of the paper is organized as follows: The section 2 identifies a study gap of the macroscopic pedestrian studies, which is the prime concern of the current work. The section 3 discusses the weighted regression method and the motivation for its use in macroscopic studies. The selected locations, procedure adopted for data collection, and descriptive statistics of collected data are presented in 4th section. The estimated and the derived relationships under ordinary least squares (OLS) and weighted regression estimation techniques are discussed in 5th section. This section also includes the empirical differences that are observed from the estimation techniques and a discussion on the comparison of pedestrian characteristics in Dhaka with the uninterrupted pedestrian flows in different countries. The findings and suggestions related to the pedestrian module are also discussed in section 5. The paper ends with conclusions and policy recommendations for pedestrian facilities planning.

2. Problem Identification

Macroscopic studies have identified essentially three variables that could describe pedestrian flow characteristics on pedestrian facilities. These variables are speed, flow, and density. The fundamental equation for pedestrian traffic flow is based on these variables and is analogous to fluid flow as follows (Council, 2000; Fruin, 1970)

$$q = vk \tag{1}$$

where q= mean flow rate (ped./m/s)

v= pedestrian mean speed (m/s)

k= pedestrian mean density or concentration (ped./m^2)

This equation implies that for a fixed mean flow rate in a given pedestrian facility, if the pedestrian mean speed increases the mean density decreases or vice-versa. Thus, the curves produced by Equation (1) are akin to the indifference curves or isoquants used in economics theory.

The proper modelling of mean speed is not simple due to the effect of physiological, psychological, and environmental factors and the design complexity of facilities. In addition, the mean values of speed and density suffer from measurement errors. As a result, the specification bias has an effect on the estimation of mean speed and mean density. Therefore, the development of a deterministic relationship, like Equation (1), for foot traffic flows has a limited scope. However, many research efforts (Cheah & Smith, 1994; Cruz & MacGregor, 2007; Mitchell & MacGregor, 2001; Yuhaski & Smith, 1989) have been made to find out the optimal throughput through a walking facility.

A considerable number of researches on macroscopic pedestrian studies (Khisty, 1985; Lam et al., 1995; Laxman, Rastogi, & Chandra, 2010; Liu, Zhou, & He, 2008; Smith, 1995; Tanaboriboon, Hwa, & Chor, 1986) adopted Equation (1) to evaluate site- and region-specific pedestrian traffic flow characteristics. The studies found that useful tools for analysing and improving pedestrian facilities in terms of efficiency and safety could be developed based on the basic relationship of speed-density. From this relationship, using the traffic flow formula in Equation

(1), other fundamental relationships such as speed-flow, flow-density, flow-space, and speed-space could also be derived. On the contrary, to derive the bivariate relationships of speed-flow, flow-density, and others, some researchers have not utilized the conventional practice of using Equation (1) (Chen, Ye, & Jian, 2010; Ye, Chen, Yang, & Wu, 2008). The effect of density on the speed-flow relationship and the effect of speed on the flow-density relationship have not been considered their studies, which is unrealistic from the practical point of view. In addition, it makes difficult the estimation of two corresponding speeds for a unique flow: one for upper the upper stage and another for the lower stage. Among others, Navin and Wheeler (1969) suggest that the average walking speed of pedestrians is affected by many influences, but for the purpose of a capacity analysis only concentration (density) need be considered. Thus, the proper estimation of pedestrian speed and density relationship is of vital importance.

A variety of models have been developed for different pedestrian facilities to determine the relationship between speed and density. Majority of such studies (Fruin, 1970; Lam et al., 1995; Laxman et al., 2010; Navin & Wheeler, 1969; Older, 1968; Polus, Schofer, & Ushpiz, 1983; Sarkar & Janardhan, 2000; Tanaboriboon et al., 1986) suggest a linear relationship, while others suggest a nonlinear relationship or both (Chen et al., 2010; Smith, 1995). Parabolic relationships of speed-flow and flow-density have further been established from the linear relationships of speed-density. In addition, several time intervals are adopted by different researchers to measure traffic flow rate, density, and speed. However, a common feature shared by the current study and prior studies is that, although flow rate can be determined easily, a sample of pedestrians is used for the measurement of mean speed and mean density. Such sample-based measurements as well as the omission of influential factors lead to one of the major problems with previous studies. For the speed-density relationship, a model with specification errors has been estimated by OLS, which renders biased and inconsistent estimates of parameters (Koutsoyiannis, 1977). Therefore, the validity of the relationships and conclusions drawn from such studies is open to question and should be examined further. The predictive power of derived relationships from the estimated speed-density relationship was also not justified in previous studies.

What this study intends to do is to use an appropriate estimation method for speed, flow, and density relationships that will improve the predictive power and mitigate a part of the OLS bias incorporated in previous studies. As little attention has been devoted to studying Bangladeshi pedestrian behaviour and flow characteristics, the pedestrian flow characteristics on sidewalks in Dhaka, Bangladesh, are considered as a case study to calibrate the parameters.

3. Motivation for the Weighted Regression Method

In prior studies on the speed-density relationship, speed was considered a dependent variable and was usually expressed as a linear function of density,

$$v = \alpha - \beta k + e\,,\ a<k<b, \tag{2}$$

where v is the mean pedestrian walking speed, in meter/second; k is the mean density, in pedestrians/meter^2; α, β are the intercept and slope parameters, respectively; a, b are the density limits for a given location, in pedestrians/meter^2; and e is the random error term. Expressing the bivariate relationship with speed as the dependent variable is natural in the sense that density is viewed as one of the factors in which increment of density in a flow leads to interactions between pedestrians and affects walking speed. According to Al-Azzawi and Raeside (2007), the influences on pedestrian speed, in addition to density, can be categorized into individual attributes, the purpose of the journey, the physical nature of the walkway, the nature of the surrounding area, and weather. In their study, four models were developed to explain the reciprocal of pedestrian speed, with R^2 equalling 0.675, 0.686, 0.840, and 0.862, respectively.

In Equation (2), the random error e absorbs primarily stochastic variations in the dependent variable (v) produced by the factors omitted from the equation and possibly errors of measurement in the mean speed. Since a sample of pedestrians is used for the measurement of mean density, like the measurement of mean speed, the mean density (k) in different time intervals is stochastic and includes errors of measurement. When there are errors of measurement in density superimposed on the errors of measurement in speed, we have the following consequences of the use of OLS on a linear relationship between speed and density (Koutsoyiannis, 1977). Firstly, the value of the slope, i.e., the contribution of density to speed, is usually underestimated. Secondly, the bias in the parameter estimates does not tend to decrease as we increase the size of the sample of mean speed and density. Therefore, there is a need to use an appropriate estimation method that could render the estimates of coefficients both unbiased and consistent.

Various solutions have been suggested for the problem of errors in independent variables: inverse least squares, the two-group method, weighted regression, instrumental variables, the maximum likelihood approach, etc. As considered in the capacity analysis, it is assumed that only speed and density mutually determine the flow rate. Therefore, we need an estimation method that could estimate the speed-density relationship in such a way that the total variation in speed is completely explained by the density and an expression for the speed-density relationship would be provided in analytical form. As a result, the estimated coefficients would account for the indirect effects of omitted factors on speed and provide the remedial for the effect of the errors of measurement. The method should also increase the predictive power of the speed-flow and flow-density relationships that are derived from the estimated speed-density relationship. Hence, the weighted regression method can be used to achieve the requirements (Koutsoyiannis, 1977). The method is appropriate in the sense that the increment of density affects pedestrian walking speed, and inversely, the acceleration of speed by the forwarded pedestrians relieves a crowd from congestion. Thus, the bi-directional relationship between speed and density can be validated. Therefore, the weighted regression method for the speed-density relationship may be outlined as follows:

i. Obtain an estimate of β so that $\hat{v} = \hat{\alpha} - \hat{\beta}k$.

ii. Obtain an estimate of β so that $\hat{k} = \hat{\alpha}' - \hat{\beta}'v$, from which we have $\hat{\beta} = 1/\hat{\beta}'$.

iii. Take as the final estimate of β the geometric mean of the above two estimates, that is, $\hat{\hat{\beta}} = \pm\sqrt{\hat{\beta}.1/\hat{\beta}'}$.

Since the sign of the covariance of *k* and *v* is negative, the sign of $\hat{\hat{\beta}}$ is negative. The estimate of the constant intercept $\hat{\hat{\alpha}}$ can be obtained from the formula

$$\hat{\hat{\alpha}} = \overline{v} - \hat{\hat{\beta}}\overline{k} .$$

The implicit assumption that the ratio of the variances of the errors in mean speed and mean density is equal to the ratio of variances of observed speed and density is assumed to be fulfilled. The method seeks to lessen the defect of the dependence of *k* and *e*, which violates one of the basic assumptions of the OLS method.

Evidence by Chen et al. (2010) and Smith (1995), among others, also propose a nonlinear relationship between the speed and density of pedestrian flows. In particular, the response coefficient may differ if the variables are transformed to reciprocal, logarithm, etc. (Al-Azzawi & Raeside, 2007). However, the nonlinear and transformed analyses are beyond the scope of the current study. The main point here is that using a weighted method can lead to less biased and consistent estimates of traffic flows and speeds compared with those currently provided by OLS estimation.

4. Data Collection and Basic Statistics

Dhaka, a mega city of 15 million people with a metropolitan land area of 1,530 km^2, is one of the major cities of South Asia (Association & Corporation, 2010). It is the 28th city among the most densely populated cities in the world. The economic, political, and cultural lives in Bangladesh are centred in the capital city Dhaka. Although Dhaka has the most developed urban infrastructure in the country, it suffers from urban problems such as overpopulation and air pollution. In the last few decades, transport and communications in Dhaka have been modernized, but these efforts are not enough to meet the movements that a highly dense population demands. Due to the shortage of transports, commuters are forced to walk and use alternative facilities. As a result, a lot of pedestrian traffic is usually formed on the sidewalks. Therefore, in this study some sidewalks of Dhaka have been selected to calibrate the traffic parameters.

4.1 Study Locations

Farmgate is one of the major business centres of Dhaka, where a number of government, nongovernmental organizations, and commercial institutions are located. It is one of the main transportation hubs of the city that caters to different types of passengers travelling to other parts of Dhaka as well as to other parts of the country. Pedestrian and vehicle traffic congestion is a common scene in Farmgate, and thus the main sidewalk in front of Commissioner's Market is often crowded. Two over-bridges connect Farmgate to Kazi Nazrul Islam Avenue. At least eight educational institutions are located adjacent to this segment of the avenue (between the two over-bridges). The biggest wholesale market of Dhaka, Kawran Bazar, and the highly crowded market, Sezan Market, are also located on this avenue. Thus, the high density of pedestrians on the sidewalk in front of Tejgaon Govt. Girls' School is a common phenomenon over the day. In addition, the sidewalk of Mirpur Road near the Science Laboratory intersection is used daily by a large number of pedestrians from and to Dhanmondi, which is one of the most planned areas in the city. One location was chosen on each of the sidewalks to study the pedestrian flow characteristics.

Table 1. Details of selected locations on sidewalks

Location No.	Location Description	Length (m)	Width (m)
1	Commissioner's Market Sidewalk, Farmgate	6.60	2.80
2	Kazi Nazrul Islam Avenue (in front of Tejgaon Govt. Girls' School)	7.00	4.20
3	Mirpur Road (Science Lab Signal Right Corner, approaches to Mirpur)	6.00	2.10

Description of the locations, the length and width that were monitored to observe the movements of pedestrians are provided in Table 1. At each study location, pedestrians were assumed to have different trip objectives, and movements were bi-directional, with no entry from or exit to other walkways. Data were collected on typical weekdays under clear and dry weather conditions that cover low to high density of pedestrians in each location. Pedestrian flow characteristics at all selected locations were assumed to be the same.

4.2 Data Collection Procedure

Self-adhesive masking tape was used to prepare longitudinal pedestrian traps, and the effective width remained constant throughout the observed length for a data set. Except for Kazi Nazrul Islam Avenue, the observed locations were occupied by vendors. In these cases the widths were measured by excluding the space occupied by the vendors. In cases where vendors exist, small numbers of 'vendor gazers' were noted and thus were included in the counts of pedestrians as well as in the measurement of densities. However, these numbers were insignificant to have any effect on the general flow. To record the required data on pedestrian average speed, flow, and density, a video recording technique that facilitated a bird's-eye view of the selected dimensions was used. The prevailing conditions were natural, as pedestrians were not aware that their movements were being recorded.

The recorded videos were later converted to digital files, and Adobe Premiere Pro software was used to playback the videos at a film speed of 25 frames/sec. The frame-by-frame videos ensured the accuracy of data reading, even at a high density of pedestrian flows. For credible relationships among flow variables (traffic flow rate, density, and speed) and a reasonable capacity analysis, a 30-second time interval was used to extract the data from recorded videos, as pointed out by Jianhong and Xiaohong (2011).

4.3 Data Extraction

The following methods were used for calculation and data collection on pedestrian flow, density, and speed.

Pedestrian flow: From each video clip of 30-second interval, the total of flow was easily measured by the number of pedestrians in both directions passing a line of sight across the width of the sidewalks. For comparison purposes, that number of pedestrians was then divided by the width of the sidewalk and 30 to express the pedestrian flow rate as the number of pedestrians per meter width of sidewalk per second (ped/m/s).

Pedestrian density: As the volume of pedestrians fluctuates in the 30-second cycle time and approximately 3 to 10 seconds are required for a pedestrian to pass the selected trap lengths, the number of pedestrians in the observed dimensions at the 8^{th}, 15^{th}, and 22^{th} second were counted. Under the low-flow condition, pedestrians at any three instants were considered. The average of these three values was considered as the number of total pedestrians in the selected dimensions corresponding to the flow of the 30-second interval. Pedestrian density was expressed as total pedestrians divided by the area of observed dimensions resulting in pedestrians per square meter (ped/m^2).

Pedestrian speed: A random sample of twelve pedestrians, two from each direction at the 0^{th}, 10^{th}, and 20^{th} second, was selected in each cycle of 30-second interval to estimate the average pedestrian speed. All pedestrians were considered when the total pedestrians travelling the selected trap in the 30-second interval were less than 12 under the low-flow condition. The traverse time of a particular pedestrian to travel the mark-off pedestrian trap length was obtained using Adobe Premiere Pro software. The average of travelling times of selected pedestrians was then used to divide the pedestrian trap length to obtain the pedestrian average speed (space mean speed) corresponding to the flow of the 30-second interval. It was expressed as (m/s).

4.4 Sample Characteristics

Table 2 reports the descriptive statistics of all variables for each test location. The basic information reveals that the average of the mean values of speed (1.29 m/sec.) at Mirpur Road is higher than all others as low densities remained at this location. However, the location at Kazi Nazrul Islam Avenue generated a higher minimum speed compared with other test locations. This indicates that the wider sidewalk facilitated pedestrians to be hurried in their movements. The minimum, maximum, and average values of the speed means at Commissioner's Market Sidewalk, where high densities prevailed, are relatively lower. The higher densities indicate the presence of more pedestrians, which restricts a pedestrian from moving with own chosen speed. However, from the standard deviation and range of the values of mean speed it is observed that a wide variation of mean speeds exists at high densities. Thus, in the presence of obstacles, pedestrian individual capacity for movements may vary with personal attributes.

Table 2. Descriptive statistics

	Speed			Density			Flow		
Location	1	2	3	1	2	3	1	2	3
Minimum	0.76	1.11	1.09	0.34	0.12	0.03	0.44	0.19	0.03
Maximum	1.16	1.42	1.43	1.55	0.49	0.32	1.07	0.49	0.29
Average	1.03	1.24	1.29	0.80	0.29	0.13	0.70	0.33	0.14
Standard Deviation	0.09	0.06	0.07	0.26	0.09	0.06	0.12	0.08	0.06

The minimum, maximum, and average values and the standard deviation of flow rate are higher at Commissioner's Market Sidewalk than at the other locations. This is for the magnitudes of minimum, maximum, average, and standard deviation of the mean densities at this location, which are also higher than at all other locations. In addition, the correlation between the mean values of speed and density are -.85, -.25, and -.20 for Commissioner's Market Sidewalk, Kazi Nazrul Islam Avenue, and Mirpur Road, respectively. Thus, the existence of a strong correlation between speed and density results in more flow of pedestrians.

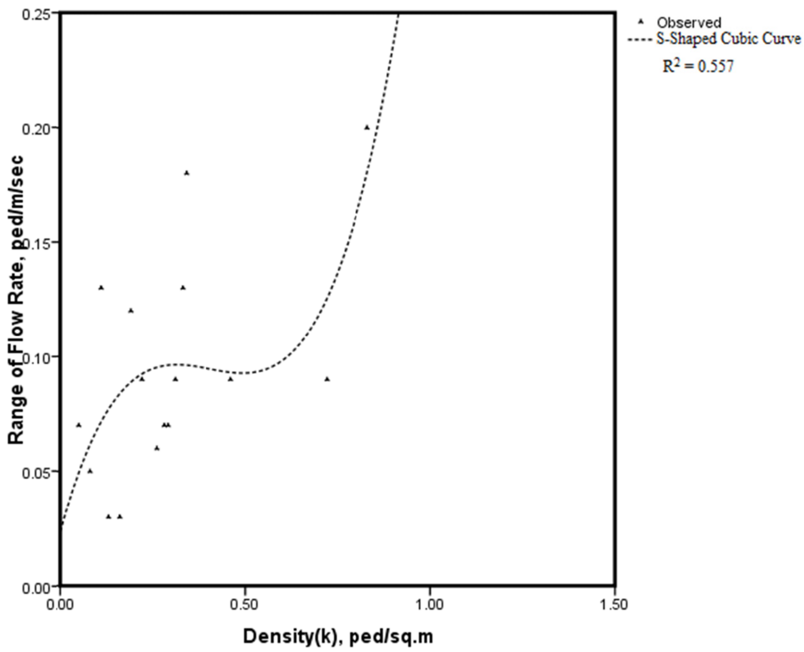

Figure 1. Range of flow rates and density of pedestrians on sidewalks

An inspection was also done on the change in the range of flow rates at various densities. Ascendant density was found to widen the range of the flow rate, and this relationship, as shown in Figure 1, is not concave or convex, but S-shaped cubic ($R^2 = 0.557$). This implies that widening the range of flow rates first increases gradually and then rapidly with densities. The S-shaped cubic curve could be explained with the help of the results from Polus et al. (1983). That study analysed the characteristics of pedestrian flow on sidewalks and found that at low densities (0.6 ped/m^2) speed is only slightly affected by an increase in density. Hence, up to the density of 0.6 ped/m^2, the variation in the range of pedestrian flow is comparatively composed. After the threshold point of low densities, there is a point-of-inflection, and the range of pedestrian flow increases fast at moderate densities (0.6-0.75 ped/m^2) and at high densities (≥0.75 ped/m^2) as well.

5. Empirical Relationships and Discussion

The ranges of densities observed at selected locations were not similar, and no statistically significant relationships between speed, density, flow, and space could be established at a single location. Thus, under the assumption of the same set of attributes followed by pedestrians at each location, data from all locations were pooled to develop appropriate relationships. In addition, an inferential study was carried out on the basis of the single-regime approach.

The relationships for pedestrian traffic flow on sidewalks have been established in accordance with the OLS method and the weighted regression method, as described in 3rd section, and the corresponding comparisons are discussed below.

5.1 Speed-Density Relationship

Figure 2 shows the scatter diagram for the speed-density relationship, where each dot corresponds to the mean speed and the mean density of a sample of pedestrian cohort during the chosen 30-second interval. The best-fitted linear lines to the collected data, generated by OLS and weighted regression techniques, are also depicted in the diagram. The following linear lines are fitted with R^2 equal to 0.79 and 1, respectively.

$$\hat{v} = 1.33 - 0.36k \qquad \text{(by OLS method)} \tag{3}$$

$$t = (164.87)\ (-23.403)$$

$$\hat{v} = 1.36 - 0.41k \qquad \text{(by weighted regression method)} \tag{4}$$

As expected, the rate of decrease of speed with density and the value of the coefficient of determinant R^2 increase from OLS to the weighted regression method. These lines can be used to determine average pedestrian speed in terms of different densities. However, these relationships are not valid under the free flow condition.

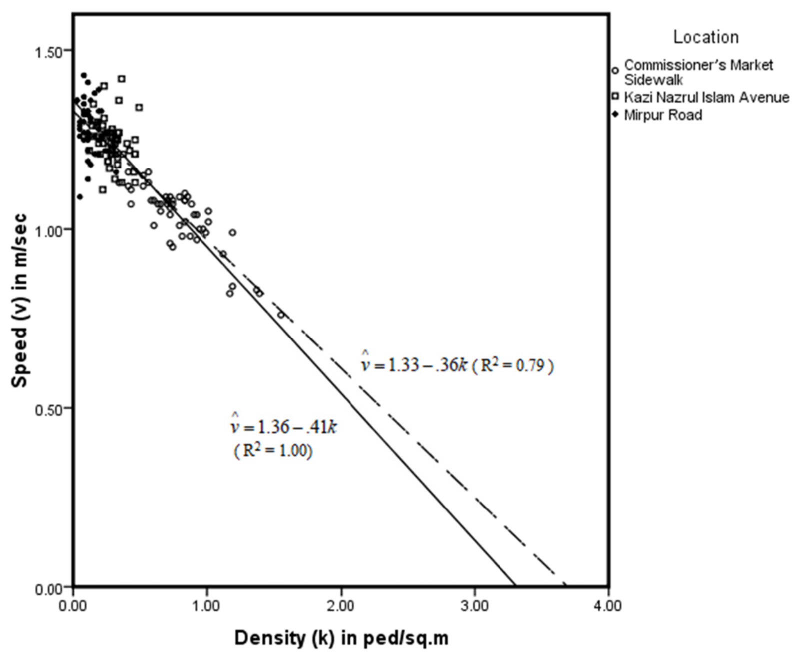

Figure 2. Speed-density relationship for sidewalks in Dhaka

The free flow condition refers to the pedestrian walking condition under which the traffic density and the conflicts between pedestrians are minimal to support a pedestrian in selecting her/his desired normal walking speed. The determination of pedestrian mean speed under the free flow condition (called the free flow speed) is necessary to evaluate the constraints on pedestrian movements that occur at higher levels of concentrations (densities) of traffic (Fruin, 1970). Polus et al. (1983) observed that up to the densities of about 0.6 ped/m^2 no significant deterioration of pedestrian desired speed occurs. According to Ando, Ota, and Oki (1988), however, on level surface the free flow walking condition remains valid up to the density of 0.8 ped/m^2. Hence, the interpretation of interception value of 1.33 of Equation (2) with $k=0$ as mean free-flow walking speed is not acceptable, even though such interpretation has been used in some previous studies (Laxman, et al., 2010; Sarkar & Janardhan, 2000). It is also evidenced from the study of Lam et al. (1995) and from a comparison between the intercept of the current study (1.33) and the value of free flow speed of 1.20 m/sec by Rahman et al. (2012) using the same data set, substituting $k=0$ into Equation 2 to estimate free-flow speed is meaningless. In addition, even with the existence of a single pedestrian, the density can never be zero, i.e, $k=0$. It should also be noted that under the free flow condition, pedestrian speed (free flow speed) is likely to be more sensitive to age, gender, the baggage-carrying capacity of a pedestrian, the walkability of a facility, etc., rather than densities (Rahman et al., 2012; Smith, 1995).

The jam density on the sidewalks in Dhaka as derived using the OLS method is 3.69 ped/m^2. This value is smaller compared with the value of 3.89 ped/m^2 in the British study on shopping streets (Older, 1968), the 3.99 ped/m^2 in the American study at a bus terminal (Fruin, 1970), and the 4.20 ped/m^2 in the Indian study at an intermodal transfer terminal (Sarkar & Janardhan, 2001). However, the value is comparable with and greater than the jam density values in mixed traffic conditions of 3.6 ped/m^2 found by Gerilla, Hokao, and Takeyama (1995), and 3.44 ped/m^2 by Laxman et al. (2010). The lower jam density value can probably be explained by the socio-security conditions in Dhaka. Pedestrians in the capital city are generally unknown to each other, and hence everyone usually tries to avoid the close touch of others for security and safety reasons. In addition, as Bangladesh is a moderate Muslim country, female pedestrians always try to maintain a certain distance to refrain from conflicts with male pedestrians. Thus, pedestrians on sidewalks in Dhaka tend to form less concentration as compared with shoppers and commuters. However, the rate of contribution of density (0.36) to the declining of speed is close to the rates of 0.34, 0.34, and 0.35 found by Older (1968), Fruin (1970), and Sarkar and Janardhan (2001), respectively.

In addition, it should be mentioned that the jam density that has been estimated in this study by the OLS method and the jam densities of the studies as quoted in the above are lower than those of uni-directional flows and emergency evacuation situations (Hankin & Wright, 1958; Pushkarev & Zupan, 1975; Seneviratne & Morrall, 1985; Smith, 1995; Tregenza, 1976). This is because of the two-way flow on sidewalk, shopping streets, bus terminal, etc. Navin and Wheeler (1969) noted that the two-way flow reduces the number of paths and manoeuvring space. It also generates the friction at the interface between opposing streams of traffic, which in turn reduces total flow as well as the jam density.

The jam density derived using the weighted regression method, 3.32 ped/m^2, is less than that derived with the OLS method. This is due to the indirect effects of unobserved factors on speed, which are considered by the weighted regression method. The weighted regression method also provides remedial measurement for the effect of the errors of measurement.

5.2 Flow-Density Relationship

Figure 3 depicts the scatter diagram for the flow-density relationship in conjunction with the fitted curves formulated based on Equations (1), (3), and (4). Each dot corresponds to the flow rate and the mean density of a sample of pedestrian cohort during the chosen 30-second interval. The parabolic curves of the flow-density relationship derived by the OLS and the weighted regression methods are given as follows:

$$\hat{q} = 1.33k - 0.36k^2 \quad \text{(by OLS method)} \quad (5)$$

$$\hat{q} = 1.36k - 0.41k^2 \quad \text{(by weighted regression method)} \quad (6)$$

Since the product of speed and density provides a flow rate and there is an inverse linear relationship between speed and density, an optimum value of products that generates a maximum flow should arise at the middle level of the flow curve. From the parabolic flow curve of Equation (5) and the speed line of Equation (3) derived using the OLS method, it is observed that the maximum flow of 1.23 ped/m/sec occurs at density 1.85 ped/m^2 with speed 0.66 m/sec. Table 3 compares uninterrupted pedestrian characteristics at maximum flow on different walking facilities. The table shows that pedestrian characteristics at maximum flow are comparable on the sidewalks and on the shopping streets. Comparability may exist between bus terminal and intermodal transfer terminal. In addition, a comparison of the sidewalk flow characteristics in this study with that of same facilities in Singapore (Tanaboriboon et al., 1986) reveals that the maxium flow rate (1.48 ped/m/sec) for pedestrian flow in Singapore occurs at density (2.42 ped/m^2) with speed (0.61 m/sec), which are not the same as those in Dhaka. Thus pedestrian uninterrupted flow characteristics are facility-specific as well as region-specific and are not universal. Therefore, the concerned policymakers should refrain from the direct adoption of foreign design and parameters for pedestrian facilities on sidewalks in Dhaka, Bangladesh.

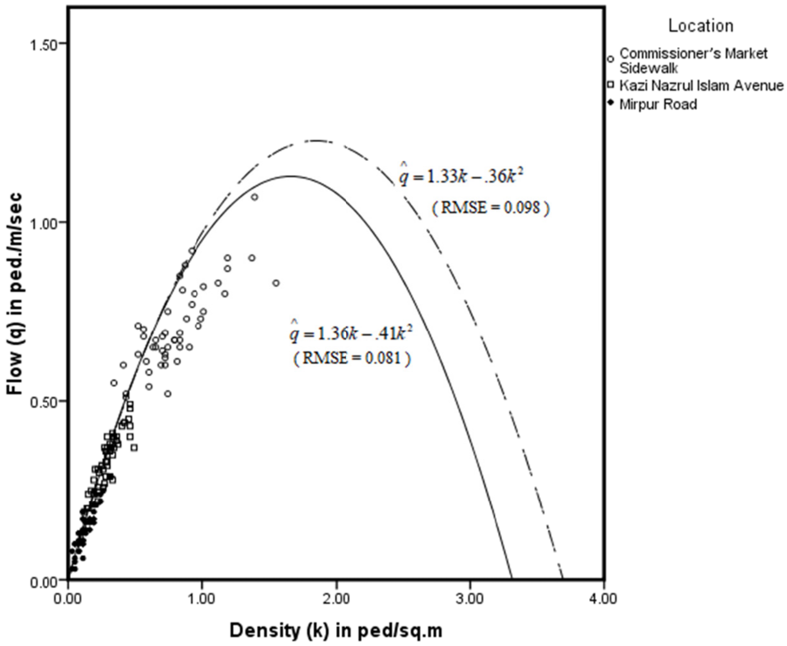

Figure 3. Flow-density relationship for sidewalks in Dhaka

Table 3. Pedestrian characteristics at maximum flow on different walking facilities

	Type of walking facility			
	Sidewalks	Shopping streets	Bus terminal	Intermodal transfer terminal
Maximum flow rate (ped/m/sec)	1.23	1.30	1.35	1.53
Density at maximum flow rate (ped/m^2)	1.85	1.95	2.00	2.10
Speed at maximum flow rate (m/sec)	0.66	0.65	0.68	0.74
Author of the study	Current study	(Older, 1968)	(Fruin, 1970)	(Sarkar & Janardhan, 2001)

To compare the reliability and the predictive power of the flow-density relationship derived using the weighted regression method with those of the flow-density relationship derived using the OLS method, one should evaluate the ability of the corresponding estimated Equations (5) and (6) to produce flow rates close to reality. Using the same equations, the flow rates based on the observed densities can be calculated and these can be compared with real observed flow rates. As such, for the same observed density, two calculated flows are available: one by Equation (5) and another by Equation (6). The difference between the flow rates obtained from the relationship of Equation (5) or Equation (6) and those that are empirically observed is then evaluated using the value of root mean square error (RMSE). Here, the values of RMSE for Equation (5) and Equation (6) are 0.098 and 0.081, respectively. This suggests that, considering the effect of speed on the flow-density relationship, the weighted regression method rather than the OLS method could estimate flow rates more precisely. In addition, it is visualized from Figure 3 that the weighted regression method can produce a parabolic flow curve that is more fitted to the observed flow rates.

The parabolic flow curve of Equation (6) and the speed line of Equation (4) derived from the weighted regression method shows that the maximum flow of 1.13 ped/m/sec occurs at density 1.66 ped/m^2 with speed 0.68 m/sec. Thus, the maximum flow is overestimated by the OLS method, and this maximum occurs at a speed that is higher than the OLS-estimated speed. In addition, since the weighted regression method produces low values of jam density and maximum flow, it further supports that the variation in flow rates follows the trend of variation in densities, as found at Commissioner's Market Sidewalk in subsection, Sample Characteristics, of 4th section.

5.3 Speed-Flow Relationship

The relationships of speed and flow as derived using the OLS and the weighted regression methods are calculated based on Equations (1), (3), and (4), and these are depicted in the scatter diagram of Figure 4. The equations for speed-flow curves are as follows:

$$\hat{q} = \frac{v}{0.36}(1.33 - v) \qquad \text{(by OLS method)} \qquad (7)$$

$$\hat{q} = \frac{v}{0.41}(1.36 - v) \qquad \text{(by weighted regression method)} \qquad (8)$$

Although each flow has two corresponding speeds, one for the upper stage and another for the lower stage; each speed, however, does not have two corresponding flows. That is, there is only one unique pedestrian flow *q* for each speed *v*. At the upper-stage level, speed and flow have a negative relationship. At this stage, there would be no downstream bottleneck that affects the forward movements. Nevertheless, the decrement of speed is caused by the increment of physical interactions among the pedestrians. After the maximum flow, speed and flow have a positive relationship. At this stage, as the maximum flow is forwarded, there will be a downstream bottleneck, and thus flow rate decreases thereafter. In such a situation, the more increment of physical interactions among the pedestrians reduces speed as well.

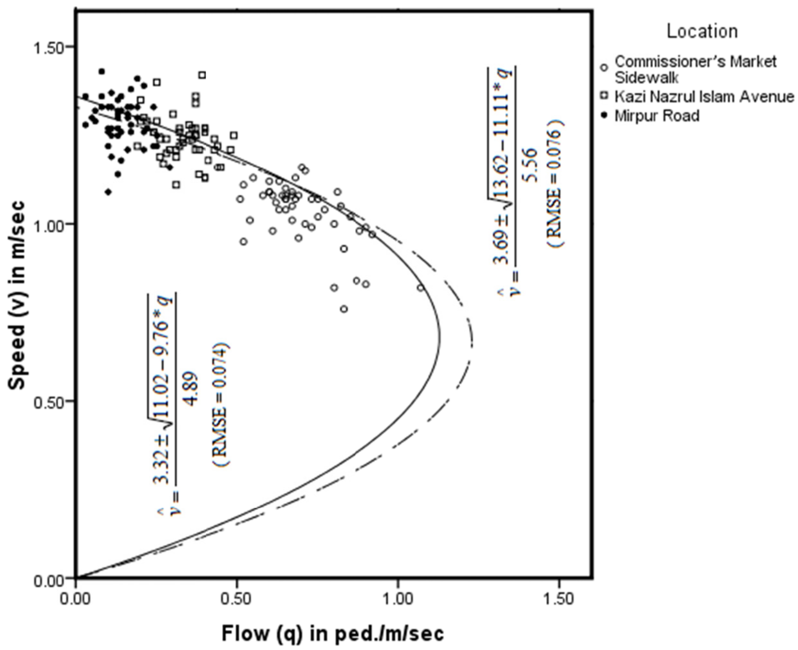

Figure 4. Speed-flow relationship for sidewalks in Dhaka

Although it was done in some previous studies, it seems unusual to use the pedestrian speed to estimate the flow rate instead of using the flow rate to estimate the corresponding speed. Hence, in this study we have revised the above Equations (7) and (8) as follows:

$$\hat{v} = \frac{3.69 \pm \sqrt{13.62 - 11.11 * q}}{5.56} \qquad \text{(by OLS method)} \qquad (9)$$

$$\hat{v} = \frac{3.32 \pm \sqrt{11.02 - 9.76 * q}}{4.89} \qquad \text{(by weighted regression method)} \qquad (10)$$

It can be proved that both roots of Equation (9) or Equation (10) must be positive, if $q \le q_{max}$.

From Table 2, we find that the minimum speed for the observed data set is 0.76 m/sec, which is higher than the speed corresponding to the maximum flow produced by the OLS method (0.66 m/sec) and the weighted regression method (0.68 m/sec). It is assumed, therefore, that for the collected data only upper-stage speeds need to be approximated by Equations (9) and (10). Such assumption is also supported by Seneviratne and Morrall (1985). They mentioned that the conditions relating to the backward bending portion of the conventional speed-flow curve are rarely observed on sidewalk sections. As a consequence, the sign before the square root in Equations (9) and (10) should only be positive. The difference between the speeds obtained from relationship of Equation (9) or Equation (10) and the ones empirically observed is evaluated using the RMSE value. The RMSE values for Equation (9) and Equation (10) are found to be 0.076 and 0.074, respectively. Thus, considering the effect of density on the speed-flow relationship, the weighted regression method provides a more accurate estimation of speeds. In addition, using Equations (7) and (8), the OLS method is found to provide a 10% invalid flow rate estimation, i.e., a negative value of flow rate in terms of corresponding speed. For the weighted regression method, the invalid estimation is reduced to 5.33%.

5.4 Pedestrian Module

With the increment in density, the required area for a pedestrian to keep a certain distance from surrounding pedestrians decreases, and pedestrians feel uncomfortable. Thus, Fuin (1970) suggests using the reciprocal of the density, called the pedestrian module, to visualize the relative comfort experienced by a pedestrian. The pedestrian module measures the available surface area for a pedestrian, denoted by *M,* and expressed as m^2/ped. Figure 5 shows how the surface area for a pedestrian (relative comfort) decreases with the increment in density on the sidewalks in Dhaka.

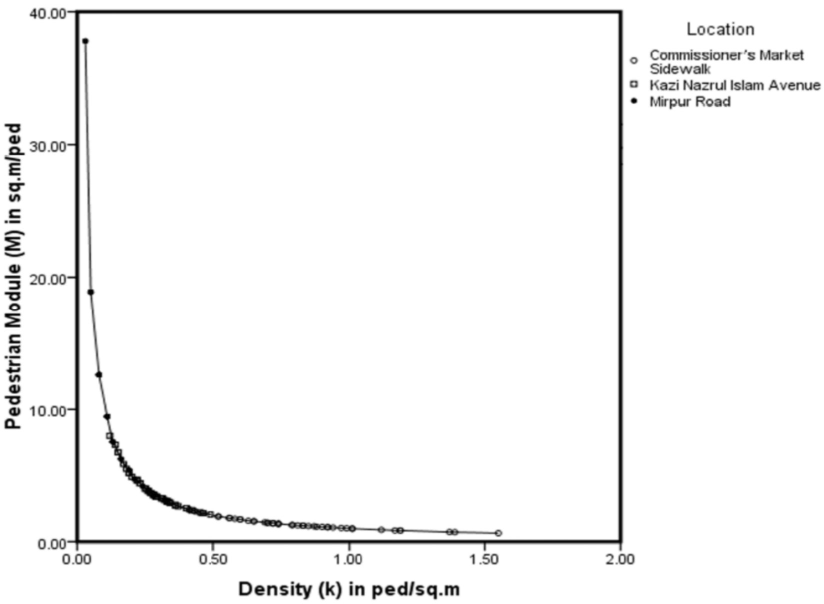

Figure 5. Pedestrian module - density relationship for sidewalks in Dhaka

Since the weighted regression method has been found to be more promising for the study of pedestrian characteristics, the speed-pedestrian module and the flow-pedestrian module should be examined based on the relationships estimated and derived by the weighted regression method. The speed-pedestrian module and the flow-pedestrian module relationships are based on the following equations and are graphically shown in Figures 6 and Figure 7, respestively.

$$\hat{v} = 1.36 - \frac{0.41}{M} \quad \text{(speed-pedestrian module)} \quad (11)$$

$$\hat{q} = \frac{1.36}{M} - \frac{0.41}{M^2} \quad \text{(flow-pedestrian module)} \quad (12)$$

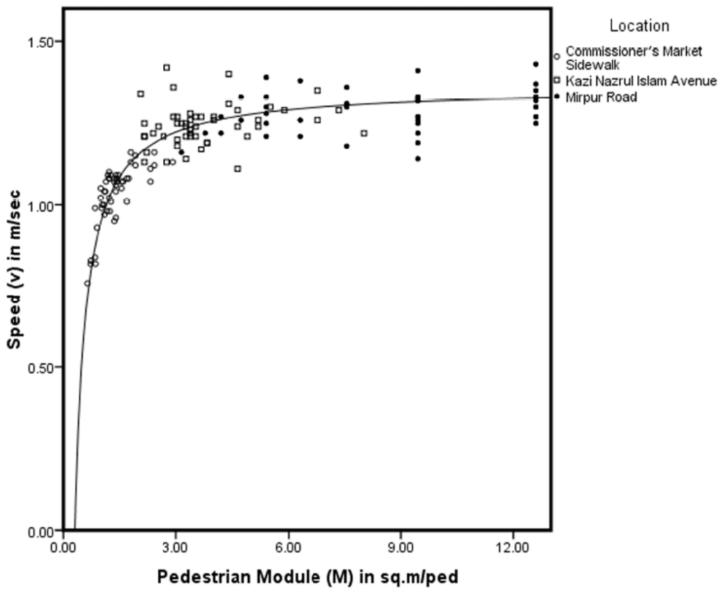

Figure 6. Speed-pedestrian module relationship for sidewalks in Dhaka

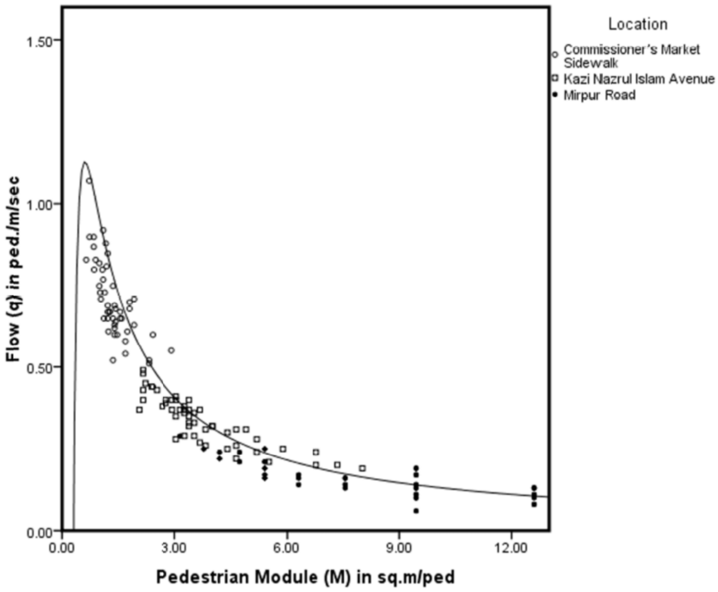

Figure 7. Flow-pedestrian module relationship for sidewalks in Dhaka

It is found from Figures 6 and 7 that, considering all the factors (sex, age, etc.) that affect the movement and flow of pedestrians, an average minimum area of 0.30 m^2 is needed for a pedestrian to commence movement, and thus flow would not be stopped on the sidewalks in Dhaka. From Rahman et al. (2012) we have the pedestrian free flow speed at 1.2 m/sec. Thus, it can also be concluded from Figure 6 that, to facilitate free flow speed on the sidewalks in Dhaka, a minimum area of 2.5 m^2 must be ensured for each pedestrian. However, Figure 7 illustrates that, for maximum flow, an occupancy area of 0.61 m^2 is needed for a pedestrian.

6. Summary and Conclusion

In this study a comprehensive analysis of the characteristics of pedestrian flow on the sidewalks in Dhaka was carried out based on the traditional OLS method and the weighted regression method. The weighted regression method, although a generalization of the OLS method, was shown to be a logically better technique to model pedestrian flow characteristics more adequately. In addition, the study tried to understand the different relationships among the flow characteristics of pedestrians on the sidewalks in Dhaka, which in turn would help the concerned policymakers design and make appropriate improvements of the sidewalks to ensure safe, smooth, and comfortable movement for pedestrians. From the comparison of pedestrian characteristics of Dhaka with those of other studies on uninterrupted pedestrian characteristics, the study also recommends refraining from the direct adoption of foreign design and parameters and to instead use local design and parameters for pedestrian facilities on sidewalks in Dhaka, Bangladesh.

One of the limitations of the current study is that the free flow speed has not been included in the basic relationship of speed-density. Hence an appropriate modification in the speed-density relationship is necessary to explicitly incorporate free flow speed, which is influenced by a number of physiological, psychological, and environmental factors. In addition to free flow speed, other relevant determinants and functional factors should also be incorporated. Finally, the method adopted in this paper for the study of pedestrian flow characteristics on the sidewalks can be used to study those of characteristics on other facilities e.g. stairways, signalized crossings of a city.

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