Pedestrian Flow and Level of Service

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Abstract: This study analyzed properties and characteristics of pedestrian flow on sidewalks. Data were collected in the central business district of Haifa, Israel, with the aid of a videotape recorder and a digital clock. Walking speeds for men were found to be significantly greater than speeds for women; all speeds were found to be inversely related to densities. One- and three-regime linear speed-density regression models were calibrated and evaluated, and reasoning is given to support the adoption of the three regime model for speed predictions. Level of service definitions are proposed based on these analyses, and suggestions for their use in planning and design of pedestrian walkways are made.

Introduction

The movement of pedestrians in the urban environment is vital for sustaining the social and economic relationships essential to city life. Walking enables individuals to have direct contact with the environment and other people, enables the passage of people from place to place, and makes possible the access of pedestrians to areas where vehicular movement is not possible or is not desirable for safety or ecological reasons.

To enable and encourage walking for different purposes, the physical facilities must be available to support the physiological, psychological, and social needs of pedestrians and ensure them against overexertion, interference by other pedestrians, and accidents. Planning and implementing such facilities requires an understanding of the characteristics of pedestrian traffic.

On the basis of published reports, literature, and our own field studies, this work suggests definitions for service levels appropriate for the planning of pedestrian pathways under selected conditions. Some characteristics of pedestrian flows are also investigated and defined quantitatively, using the sidewalks of several commercial streets in Haifa, Israel, and models are proposed for describing the relationship among

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certain characteristics. Corroboration, both in logic and in the literature, is presented for the models developed.

Background Studies

Speed-Density Relationships.—In recent years, several studies have been conducted on the subject of pedestrian flows, some of which will be described later. Foot traffic has been found to be influenced by psychological, physiological, social, and environmental factors. The most significant factors shown in these studies for defining the characteristics of pedestrian flow are age, gender, physical fitness, the social tie to pedestrians very close by, the purpose of the walk, and topography.

It is generally useful to examine speed/volume/density relationships to develop an understanding of any traffic flow phenomena because: (1) These parameters are meaningful descriptions of flow characteristics; (2) they are conceptually easy to measure and understand; and (3) past studies of vehicle flows have identified important requirements in the relationships between these parameters that are useful in understanding flow mechanisms, service attributes, and design principles. Several studies that dealt with vehicular flow (8,6,2) described the classic linear relationship between speed and density, which was chosen as a starting point for an analysis of the characteristics of pedestrian traffic flow (9).

Older (8) investigated the relationship between the speed of pedestrians and flow density on Oxford Street in London. He found a decreasing linear relationship between the speed and density of pedestrians on pathways. The highest speeds for the lowest densities (free flow conditions) were 1.4 m/s; high density, which Older defined as four pedestrians/square meter, yielded speeds of 0.3 m/s or less. Navin and Wheeler (6) found a decrease in flow rate (volume) and speed of pedestrian traffic with the rise in density and an increase in pedestrian traffic from the opposite direction.

Hankin and Wright (4), who investigated the flow of passengers in subways, appear to be the first to have presented a nonlinear graph to express the relationship between speed and density, which was composed of several subsections, each nearly linear in itself. Fruin (2) explored extensions of basic vehicle flow relationships to pedestrian volumes, average speed, and density. However, he used the reciprocal of density and defined it in area modules of square feet per pedestrian. He found that pedestrian speeds tend to have less variability as increased crowd density restricts the ability to bypass slower moving pedestrians and to select a desired walking speed. He used a general semiparabolic curve to describe the increase in speed with increase in module size (decrease in density); the rate of increase gradually decreased as the area per pedestrian (module) increased.

Level of Service.—A number of studies have defined service levels for pedestrians based on the ranges of average area occupancy (the area of free expanse available) for a single pedestrian. Fruin (2) defined six levels of service, in a somewhat similar manner to vehicular levels of service. Fruin, as well as Oeding (7), described the factors that influence the quality and ease of pedestrian traffic flow at the different levels of service: the possibility of progressing at a desired normal walking speed,

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the reasonable chance of conflicts between pedestrians in the main traffic flow and those in crossing directions, the chance of passing a slow pedestrian, and the existence or nonexistence of two-directional traffic. In connection with this last factor, Fruin found, for instance, that a significant difference exists in the behavior of pedestrians between one-directional and two-directional traffic, when the main flow of the latter is much bigger than that of the secondary flow. In this situation, pedestrians in the main traffic flow occupy the entire walking path space and leave the free clearance space between them to the pedestrians in the secondary traffic flow. Further, Fruin found that the previously mentioned four factors are influenced by the size of the average area available to each single pedestrian in traffic flow and that they differ according to environmental attributes and characteristics of physical facilities.

Oeding's definition for level of service for walking is essentially similar to that of Fruin's. Oeding refers to five main levels of service, the boundaries of which are characterized by occupancy areas of between 3.3 m^2 per pedestrian for a high level of service and 0.7 m^2 per pedestrian for a low level of service.

Pushkarev and Zupan (10) offer a similar level of service definitions, including low densities—large occupancy spaces (above 5 m^2 per pedestrian)—which are beyond the range investigated by Oeding and Fruin. The former study is based mainly on previous findings by Michael and Hirsch (from an unpublished report) and also on qualitative observations. Pushkarev and Zupan defined a number of levels of service for walking, beginning with open flow and unimpeded flow, to dense flow and jammed flow, in which progress is nil.

Empirical Study

Data Collection Procedure.—The data for this study were collected by recording pedestrian traffic on sidewalks by means of a video-tape camera fitted with a zoom lens and a video-tape recorder. The system used consisted of portable units that could be powered by household current (220 v) or a 12-v battery. Fitted into the photographic system was a highly accurate (up to 1/100 of a second) digital clock. Two pedestrian-flow areas were marked off on the sidewalks: one, a square measuring 2×2 m; the second, an attached rectangle, measuring 3×2 m. Pedestrian speed was obtained by recording the times when crossing the boundaries of the marked-off square, and the density was obtained by counting the number of pedestrians within the boundaries of the square at the time the subject pedestrian was approximately in the middle. The attached rectangle served as a control: The speed for each pedestrian was calculated a second time on the basis of the crossing times of the boundaries of the rectangle in order to ascertain that no significant fluctuations existed in the speed of the subject pedestrian. Isolated cases in which a change in speed was noticeable or the pedestrian stopped for any reason were withdrawn from the data set.

The distance between tape-markings in the walking direction was selected judgmentally considering the facts that increasing the length of the walking area increases the degree of expected changes in the walking speed in the measurement section; reducing the length of the walk-

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ing area increases the possible relative error in determining walking speed, and makes density measures less meaningful.

The six sites for which data were collected were located in downtown Haifa (population: 410,000) and termed the Solel Boneh, Nevyim, Hechalutz, Herzel 1, Herzel 2, and Herzel 3 sites after the streets on which the studies were made. At each site, pedestrian flow was photographed for about 90 min, with several hundred pedestrians being photographed each time. A summary of the data, including number of pedestrians studied, average speeds, average densities, and some additional statistical measures, is presented in Table 1.

General Flow Characteristics.—Before interpreting the data, the movements of individual pedestrians were examined at the three initial sites for the purpose of identifying variables that seemed to have an effect on pedestrian traffic. After this investigation, it was decided to analyze the flow characteristics of pedestrians on the basis of the variables, gender, and direction, while recording the actual density for each calculated speed. Based on comparison of the results from three sites, several conclusions were drawn and are summarized in Table 2.

First, the walking speed of females was slightly but generally significantly lower than that of males. This difference was conspicuous and greater under conditions of larger speeds, as was manifested at the Solel Boneh and Nevyim sites. This finding may be explained by the greater physical size and, thus, larger strides of males. An alternative, though unsupported, hypothesis is that a larger share of the males were walking to or from work and, thus, faced arguably more severe time pressures. Second, it is possible to distinguish a similarity among the walking speeds measured at the Solel Boneh and Nevyim sites for both men (1.28 m/s) and women (1.14 m/s). The difference between these speeds and the average speeds at the Hechalutz site (1.10 m/s for men and 1.03 for females) is noticeable. This can be attributed to an increase in density

TABLE 1.—The Data Set Including Average Speeds and Density, by Direction, at the Six Different Sites

Observation number (1)	Direction (2)	Site (3)	Number of pedestrians observed (4)	Average speed, in meters per second (5)	Standard deviation of speeds, in meters per second (6)	Coefficient of variation (7)	Average density, in pedestrians per square meter (8)
1	1	Solel Beneh	165	1.223	0.315	0.258	0.281
2	2		180	1.257	0.304	0.242	0.170
3	1	Nevyim	272	1.210	0.243	0.201	0.616
4	2		483	1.234	0.319	0.259	0.422
5	1	Hechalutz	301	1.032	0.228	0.221	1.177
6	2		218	1.043	0.227	0.218	0.737
7	1	Herzel 1	287	1.170	0.280	0.239	0.589
8	2		270	1.215	0.308	0.253	0.566
9	1	Herzel 2	370	1.132	0.399	0.352	0.748
10	2		340	1.087	0.362	0.333	0.715
11	1	Herzel 3	384	1.088	0.360	0.330	0.713
12	2		353	1.100	0.355	0.323	0.678

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TABLE 2.—Comparison of Average Walking Speeds for Males and Females at Three Sites

(1)	Solél Boneh Site Male (2)	Solél Boneh Site Female (2)	Nevyim Site Male (3)	Nevyim Site Female (3)	Hechalutz Site Male (4)	Hechalutz Site Female (4)
Sample size	249	96	454	201	355	164
Mean speed, in meters per second	1.280	1.139	1.276	1.136	1.098	1.032
Standard deviation of speeds, in meters per second	0.306	0.296	0.292	0.282	0.285	0.626
Male-to-female speed ratio	1.124		1.123		1.065	
Significance of difference between mean speeds (at 5% significance level)	significant		significant		not significant	

on Hechalutz Street, which lowered average walking speeds. This led to further speed-density analyses utilizing data from all six sites, as explained in the following section.

Speed-Density Relationships.—Three alternative approaches were considered for analyzing the relationship between walking speed and density: either to analyze the data separately for each site, to pool all the individual data points for all sites, and to try to build a unified model or to aggregate the data for all sites by averaging the results for the individual sites. The first possible approach was not pursued because of the concentration of densities within relatively small ranges at each individual sites which did not permit the construction of a comprehensive model for a wide range of densities. The second approach was tried since it was felt that pooling the data is sensible, but the resulting model showed poor statistical significance. This is believed to be due to the great variability between flow characteristics of individual pedestrians. Therefore, the third approach was adopted for the purpose of this study.

For the preliminary analysis, a scattergram plot was made of the speed and density data at each site. From these graphs, it was possible to discern a general trend toward a reduction in walking speed with the rise in pedestrian density at the site, but it still was not possible to calibrate a model at this stage.

Thus, it was decided to proceed to an aggregate analysis, and the average of speeds and densities were summarized for each of the six sites separately, separating the two walking directions, as presented in Table 1.

A major concern in this effort was to develop a speed-density model for a wide range of densities. Because few observations were available at higher densities, use of the site-averaged data points would have resulted in a model more heavily weighted to lower and middle-density observations. Therefore, a series of uniform width density ranges were defined, and all data points within these ranges were averaged again. This made it possible to calibrate a regression model, the form of which would be equally influenced by observations in all density ranges. The midpoints of the six density ranges were 1.00, 1.25, 1.50, 1.75, 2.00, and 2.25 pedestrians per square meter. The resulting aggregate points are described in Table 3.

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TABLE 3.—Observed Pedestrian Speeds as Related to Constant Densities at all Six Sites

Observation number[a] (1)	Number of pedestrians (2)	Density, in pedestrians per square meter (3)	Average speed, in meters per second (4)	Standard deviation of speeds, in meters per second (5)	Coefficient of variation (6)
13	275	1.00	1.011	0.288	0.285
14	127	1.25	1.000	0.264	0.264
15	39	1.50	0.949	0.203	0.214
16	25	1.75	0.802	0.230	0.287
17	10	2.00	0.824	0.119	0.144
18	7	2.25	0.687	0.312	0.454

[a]These numbers denote points from Figs. 1 and 2.

The aggregate points representing average speeds and densities are plotted in Figs. 1 and 2. Note that the speed-density relationship appears to behave somewhat differently in the low density range (less than 0.6 pedestrians/m^2) than in the moderate density range (0.6 pedestrians/m^2–0.75 pedestrians/m^2). At low densities, speed is only slightly affected by an increase in density. At moderate densities, an increase in density results in a more significant reduction in speed. This may be explained by the hypothesis that, in this middle density range, interference between pedestrians begins to have an important effect on speed of flow. This medium density range (0.6–0.75 pedestrians/m^2) seems to be a transitional region, in which the speed/density relation is changing from the low density to the high density pattern. The higher density conditions observed in this study (0.75–2.0 pedestrians/m^2) demonstrates a steady decline in speed as a function of density. Therefore, based on tests of several alternative functional forms, it was decided that a three-regime, linear model might best represent the relationship between pedestrian density and speed.

The three regime model is demonstrated in Fig. 1 together with the data points as they appear in Tables 2 and 3. The structural form of the model is presented as

$$S = a - b \cdot D; \quad \alpha < D < \beta \qquad (1)$$

in which S = average walking speed, in meters per second; D = average density, in pedestrians per square meter; a, b = estimated intercept and slope parameter, respectively; and α, β = density limits for a given region, in pedestrians per square meter.

The density limits for the three regimes are determined by utilizing a visual and statistical approach where various limits are tested, and those selected (0.6 pedestrians per square meter and 0.75 pedestrians per square meter), represent (1) the visually most reasonable limits to differentiate between the various groups of data; and (2) the calibration of best possible models in terms of correlation coefficient and other statistical parameters.

The regime limits, estimated parameters, and the summary statistics (1) are shown in Table 4.

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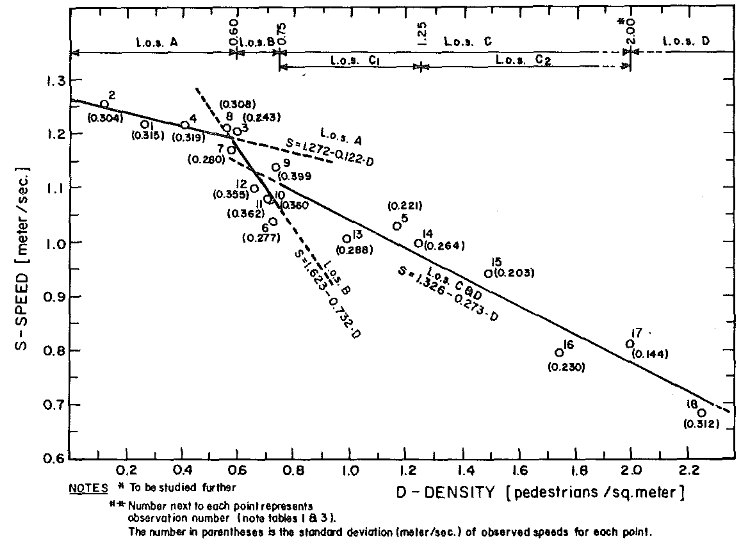

FIG. 1.—Average Walking Speed, Average Density and Levels of Service—Three Regime Model

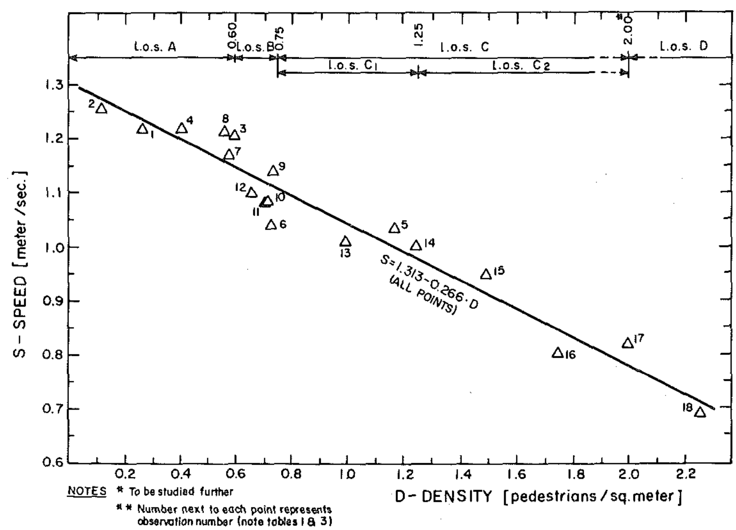

FIG. 2.—Average Walking Speed, Average Density and Levels of Service—One Regime Model

A one-regime linear model was also calibrated to check the hypothesis that a single, straight line may also represent the pedestrian speed/density relationship, in a similar manner to vehicle traffic flow models (3). The structural model is presented by Eq. 1 with only a single range for

TABLE 4.—Density Limits, Estimated Parameters, and Statistical Values for Regression Models

Regime and density limits, in pedestrians per square meter (1)	Number of aggregated data points (2)	Parameter (3)	Estimate (4)	t value (5)	F value (6)	R-square (7)
I: 0–0.60	6	a	1.272	54.31	6.05	0.602
		b	−0.122	−2.46		
II: 0.61–0.75	7	a	1.623	11.27	11.52	0.697
		b	−0.732	3.39		
III: >0.75	7	a	1.326	22.42	55.70	0.918
		b	−0.273	7.46		
One regime: 0–2.30	18	a	1.313	70.99	256.46	0.941
		b	−0.266	16.01		

Note: Equation form: Speed = $a - b \cdot$ Density.

all densities; the calibration parameters and statistics are summarized in Table 4. Fig. 2 shows this model.

The one-regime model effectively fits the aggregate data used in the calibration, and its statistical measures are qualitatively better than those of the three-linear regime model. The parameters of the third (high-density) portion of the three-regime model are virtually identical to those of the one-regime model. The low and middle density regime models are more different than the one-regime model, though only the middle density model appears to be substantially different. Thus, while the visual appearance of the data confirm the idea that the three-regime model follows the data better, for practical applications where the model itself is to be used, the one-regime model is likely to be sufficiently precise, and will certainly be easier to use.

We suggest, however, that, for understanding pedestrian flow and defining level of service, the three-regime model is more realistic. At low density sites, each pedestrian can choose his own desired speed, and the effect of density is not great. Tables 2 and 3, and Fig. 1, show that at low density sites, the standard deviation of speeds was usually larger (above 0.3 m/s) than the standard deviation of speeds for high density sites, suggesting a real difference in behavior patterns. Reasonably, the second regime, in which a relatively rapid deterioration of speed occurs, may be considered as a transition region, where the interaction effects of higher density pedestrian movement begin to develop rapidly. This transition appears to be complete once density increases beyond 0.75 pedestrians/m^2, after which speed decreases as a smooth, linear function of increasing density. Goodness of fit measures for each of the three regime component models appear sufficiently strong to underscore the validity of this formulation as a basis for developing an improved understanding of behavior.

Suggested Level of Concept for Pedestrian Flows

Based on the speed/density analysis described in previous paragraphs, as well as on some other qualitative observations of pedestrian flow performed in this study, a qualitative and quantitative definition of four suggested levels of service for pedestrians was established and is presented in Table 5 and denoted in Figs. 1 and 2. It should be noted that the density boundaries between levels A, B, and C correspond to match the density limits of the regression models for the three regimes described previously. Ranges of flow volumes for each level of service were calculated based on the Greenshield's model of traffic flow (3):

$$V = S \cdot D \cdot 60 \qquad (2)$$

in which V = average volume, in pedestrians per meter width of walkway per minute; S = average speed, in meters per second; and D = average density, in pedestrians per square meter. The volume boundaries for each level of service, calculated by Eq. 2, are presented in Table 5.

The level of service A, with densities of less than 0.6 pedestrians/m^2 seems to be suitable for a design aiming at a free flow of pedestrians (e.g., on walkways in residential area or public parks). During the research, it was observed that up to densities of about 0.6 pedestrians/m^2 no significant deterioration of speed (to be interpreted as freedom to maneuver) occurs. Further refinement of this free flow range, as suggested by others (2,7,10), does not seem justified for pedestrian flows due to the observed insensitivity of the flow measures (volume and speed) to variations in density in this range. Under these conditions,

TABLE 5.—Proposed Values for Parameters Defining Four Suggested Levels of Service for Pedestrian Flow

Description of flow (1)	Level of service (2)	Pedestrian density, in pedestrians per square meter (3)	Pedestrian area occupancy, in square meters per pedestrian (4)	Estimated flow volumes, in pedestrians per meter per minute (5)	Recommended uses when planning walk paths (6)
Free flow	A	≤0.60	≥1.67	0–40	residential areas, public parks
Restricted, impeded, unstable flow	B	0.61–0.75	1.66–1.33	40–50	public buildings, commercial areas shopping centers
Dense flow	C C_1	0.75–1.25	1.33–0.80	50–75	high rise office buildings
	C C_2	1.26–2.00	0.80–0.50	75–95	sport centers, central transit stations
Jammed flow	D	to be studied further[a]			not recommended

[a]The density, area occupancy and volume boundaries between dense and jammed flow are to be further studied. Possible boundary, to be investigated, is density of 2.0 pedestrians per square meter which yields a maximum volume for level C of about 95 pedestrians per meter width per minute.

pedestrian flow measures are likely to be more sensitive to esthetic and physical parameters, such as visual attractions, slope, or surface smoothness.

The increasingly restricted flow represented by level of service B may be suitable for designing shopping areas and public buildings where the monetary and land use constraints call for some compromises in design criteria, where pedestrians are likely to have lower needs and expectations regarding flow speeds, and where merchants and owners clearly benefit from both increased density and reduced speeds.

The lower end of level C, denoted as level C_1 at densities of 0.75 pedestrians/m^2–1.25 pedestrians/m^2, is appropriately used for design of space between high rise office buildings or campus facilities where peak flows occur routinely and over a relatively short period of time. The higher end, denoted as C_2, where the expected densities are in excess of about 1.25 pedestrians/m^2 but less than 2.0 pedestrians/m^2 and the corresponding predicted volume exceeds 75 pedestrians/m width/min, should probably be restricted to places where people's expectations of free flow are low due to extremely high volumes and densities, e.g., at or near sport centers, central transit stations, or similar facilities. In such high volume cases, the costs of moving to level of service B are likely to be high and difficult to justify. The density limit between dense (level of service C) and jammed flow cannot be established precisely here because of insufficient data. It is felt that density of 2.0 pedestrians/m^2 might be the upper limit for level of service C. However, a fourth level of service, D, characterized by jammed flow, is certainly observed under such conditions as gathering of large crowds in front of a narrow gate. Fruin (2) suggests the criterion of 2.15 pedestrians/m^2 as a limit above which the flow is jammed. Pushkarev and Zupan (10) propose a range for the jammed level of 1 pedestrians/m^2–5 pedestrians/m^2. This study suggests the value of 2.0 pedestrians/m^2 and above (corresponding to volumes of 95 or more pedestrians/m width/min) as the lower range limit for level of service D. This probably should be avoided as a design value, although peak loads on some facilities may be in this range.

Summary and Conclusions

This study dealt with an analysis of the characteristics of street pedestrian flow on sidewalks in the center of the city of Haifa. Data were collected with a videotape recorder. Based on the quantitative analysis, both one- and three-regime linear models were defined and tested. It was found that with the increase in pedestrian density, there was a significant decrease in walking speed. It was further found that male pedestrian speeds were significantly greater than that of females. In the course of the study, proposed service level ranges were defined for pedestrian traffic. These could be useful as criteria in planning pedestrian walkways, as suggested in Table 5.

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Appendix II.—Notation

The following symbols are used in this paper:

a = estimated intercept;
b = estimated parameter;
D = average density, in pedestrians per square meter;
LOS = level of service;
S = average walking speed, in meters per second;
V = average volume, in pedestrians per meter width of walkway per minute;
α = lower density limit for a given region; and
β = upper density limit for a given region.

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