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Modelling of Pedestrian Speed-Density and Volume-Density Relationships in Outdoor Walkways

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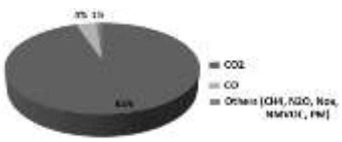

Abstract

The aim of this study was to model pedestrian flow parameters needed in the design of pedestrian facilities. The study also characterized the flow with a view to understanding pedestrian interaction problems especially with regards to their congestion. Twenty-five locations across Kano metropolis were selected for study, thirteen locations from the city district while twelve sites were chosen from the Waje district. All the sites were high flow pedestrian locations that met the study objectives. The data was categorized into four; young male, adult male, young female and adult female. The results indicated that adult women walked faster than their male counterparts in the City district while young males were faster than the female. The adult female recorded an average speed of 73.90 m/min against the speed of 71.30 m/min for the adult male. The average characteristics of the pedestrian in the city district are speed 67.30 m/min; density 11.23 Ped/m^2 and volume 33.60 Ped/m/min. In the Waje district, however, the male pedestrian whether adult or young walked faster than their corresponding female counterparts with speed of 71.45 m/min for the adult male and 59.90 m/min for the adult female. The young male was faster than the young female by 17.9%. The average pedestrian flow parameters for the Waje district indicated a combine speed of 60.21 m/min; density of 8.72 Ped/m^2 and volume of 30.92 Ped/m/min. The pedestrians in the city district had a higher flow rate, higher density and higher speed than those of the Waje district. This means the city district is a little more concentrated than the Waje district in terms of pedestrian flow. The aggregate average flow parameters of pedestrians in the metropolitan area gave the following parameters: speed 68.92 m/min; density 10.03 Ped/m^2 and volume 32.33 Ped/m/min. The predictive models for Kano showed a free flow speed of 59.55 m/min and a maximum flow rate of 73.0 Ped/m/min. Comparing the Kano pedestrian model with other countries it was found that the Kano pedestrian walked slower than pedestrians from Singapore and the United States.

Keywords: Pedestrian characteristics; flow; density; walking speed; young male; adult male; adult female

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1.0 INTRODUCTION

Modelling approaches to pedestrians' flows follow similar patterns with vehicular flows. Macroscopic models such as the Greenshields [1], Greenberg [2], Underwood [3], Eddie [4], Koshi *et al.* [5] and Hall *et al.* [6] that relate volume and density and speed and density have failed to produce information on the critical density as well as information on the state of the traffic for vehicles and pedestrians as well. Recently, the fundamental diagram approach employing a quadratic function between volume and density has been used with success to predict the state of traffic for vehicular flows. In this paper, it is argued that models of vehicular flow employing the quadratic function approach could equally be applied to pedestrian flows. What is required of both pedestrian and vehicular flow analysis is the ability to determine the state of flow under varying dense flow conditions.

While it is agreed that pedestrian movement is quite unlike vehicular movement because of the many self organised features of pedestrians, the observed behaviour of pedestrians in walkways indicate that pedestrians herd from one point and aim to reach a destination at another point. In this paper, the aim is to model pedestrian movement behaviour in outdoor walkways and to see if macroscopic properties could be derived in a similar manner to vehicular traffic using the quadratic function between flow and density.

The rest of the paper is organised as follows; section 1 introduces the subject of the paper while section 2 presents a review of the literature on the subject. Section 3 details the data collection procedure adopted for the study and in section 4 the results are presented. The discussion and conclusions follow in section 5.

2.0 LITERATURE REVIEW

Efforts in pedestrian modeling in the literature have mainly been in understanding their microscopic and macroscopic conduct in different scenarios. Microscopic models are used when individual pedestrian conduct is of interest in the study. Microscopic models that have been applied to mimic pedestrian behavior have also been applied to individual vehicles in spite of the differences in behavior between a pedestrian and a vehicle. In addition to car–following models, cellular automata models such as the Two Process Model

[7], Lattice Gas Model [8], Floors Model [9], Pre-fixed Probabilities Model [10], Dynamic Parameters Model [11], Real-coded CA Model [12] and Multi-grid Model [13] have been widely used for microscopic modelling.

Macroscopic models are used in dense pedestrian flow conditions. Since pedestrians are not completely channelized in their movement, they therefore exhibit features that are different from vehicles. Dense pedestrians flow conditions need to be analysed similar to vehicular flows because the overall flow pattern is akin to vehicular macroscopic behavior. Macroscopic pedestrian modelling efforts are rich in the literature and a summary is provided by Chandra and Bharti [14] as shown in Table 1.

Table 1 Pedestrian characteristics studies for different countries [14]

Source	Country	Pedestrian flow type	Facility	Speed-Density Relationship
Older [15]	Britain	Shoppers	Walkway (Indoor)	v= 1.31-0.34k
Navin and Wheeler [16]	USA	Students	Walkway(Outdoor)	v=2.13-0.79k
Fruin [17]	USA	Commuters	Walkway(Outdoor)	v =1.43-0.35k
Lam *et al*. [18]	China	Mixed	Walkway (indoor)	v=1.29-0.36k
			Walkway (outdoor)	$v=e^{0.38-0.57k}$
			crosswalk	$v=1.47e^{-0.347k2}$
Virkler and Elayadath [19]	USA	Mixed	Walkways (indoors)	$v=1.01e^{-0.247k}$ k <1.07
				v=0.61ln(0.432/k) k >1.07
Teknomo [20]	Japan	Mixed	Crosswalks (Simulation)	v=1.02-0.36k (One way)
				v=1.2-0.217ln(100k) (Two way)
Sarkar and Janardhan [21]	India	Mixed	Walkways (Indoor)	v = 1.46 -0.35k
Tanaboriboon and Guyano [22]	Thailand	Mixed	Walkways (Indoors)	v = 1.2 -0.22k
Tanaboriboon *et al*. [23]	Singapore	Mixed	Walkways (Indoors)	v = 1.23-0.26k

Pedestrian characteristic study trends shown in Table 1 highlights the research in the area. Earlier works by Older [15], Navin and Wheeler [16] and by Fruin [17] set the pace for pedestrian studies. Later, Wilson and Grayson [24] did a study on the relationship between pedestrian speed, age and gender and they noted that the males walk faster than the females by 3.78% with the walking speed reducing with rising age. Polus *et al.* [25] did a similar work and found that walking speeds of men were significantly greater than those of women. Crosswalk studies of pedestrians was done by Griffiths *et al.* [26] which revealed that the crossing speed at un-signalized crossing produced a mean walking speed of 1.72 m/s for the young, 1.47 m/s for the middle-aged, and 1.16 m/s for the elderly. Tanaboriboon *et al.* [23] working in Singapore investigated school age children in crosswalks and found their crossing speeds to be similar to the elderly pedestrians at 0.9 m/s. In a Bangkok study, Tanaboriboon and Guyano [22] observed walking speeds on a signalized intersection and found crossing speeds of male pedestrians to be 1.31 m/s and those of female pedestrians to be 1.23 m/s. Bowman and Vecellio [27] opined that 15% of the older pedestrians crossed at speeds below 0.7 m/s in Sweden while Coffin and Morrall [28] recommended a design speed of 1.0 m/s to be used at mid-block crossings with a large proportion of older pedestrians in a study in Canada.

Further studies by Knoblauch *et al.* [29], Tarawneh [30], and Carey [31] all found higher crossing speeds by younger pedestrians than the older age groups with consistent higher speeds for males than females. The Manual of Traffic Studies [32] recommends a pedestrian crossing speed of 1.1 m/s to 1.2 m/s while the US Institute of Transportation Engineers (ITE) suggests speed of 0.75 m/s at a location with higher proportion of older pedestrians. This value is expected to accommodate 87% of pedestrian population. The crosswalk speeds given in the Highway Capacity manual [33] are based on the proportion of older (above 65 years) in the total pedestrian stream. For less than 20% elders, it suggests a speed of 1.2 m/s and above that it is taken as 1.0 m/s. The Manual on Uniform Traffic Control Devices [34] suggests a standard value of 1.21 m/s to allow users to walk from the curb to the far side of the travelled way.

Aside the characteristics of pedestrians, one dimensional and two dimensional models have also been applied to pedestrian studies as in the case of vehicles. The Greenshields model [1] with its characteristic speed-density relationship has been used for pedestrian flows and is given as:

$$v(\rho) = v_f \left(1 - \frac{\rho}{\rho_m}\right) \quad (1)$$

Where v_f is the free flow speed and ρ_m is the maximum density. In the Greenberg model [2], the speed – density function is given as:

$$V(\rho) = v_f \ln\left(\frac{\rho_m}{\rho}\right) \quad (2)$$

Underwood [3] modeled the speed–density function as

$$V(\rho) = v_f \exp\left(\frac{-\rho}{\rho_m}\right) \quad (3)$$

Eddie [4] provided two disjointed functions, one for the free flow region and the other for the congestion region that is a combination of Greenshields and Greenberg's models. Other models such as the Northwestern University model, Drew model, Pipes-Munjal model and the multi-regime model give similar expressions for the speed-density relationships. All of these models are incapable of giving traffic state information at critical density.

3.0 DATA COLLECTION

This study involves a comprehensive data collection for twenty-five pedestrianized locations within Kano Metropolis in North-West Nigeria. Thirteen locations were identified in the city district while twelve locations were outside the city district called the Waje District. The pedestrians were observed for speed and volume as well as their walking behaviour. All the observation points were outdoor walkways along road corridors characterized by dense pedestrian flows. In order to reflect dense flow conditions, the data was re-organised to remove singularities in the movement. Pedestrian behaviour were segregated into male, female, adult and the young. To determine the speed of a pedestrian, a measured course was predetermined and a randomly picked pedestrian in a typical dense flow situation was timed over this measured course of 30 m. The 30 m measured course was used because pedestrians consistently covered this distance without changing their behaviour. The flow rate was abstracted form video recordings every 30 minutes during the observation period which lasted from 8.00am to 6.00pm daily for seven days during the month of July 2013.The speed measurements were manually captured while video technology was used for observing the flow rate and pedestrian behaviour. In all cases, the observation period was during daylight, weekdays and weekends and during normal weather conditions. The sample size for the city district was 15,106 while that of the Waje district was 9,093.

4.0 RESULTS

4.1 Temporal Profiles

The results of the volume study for both districts are shown in Figures 1 and 2. In Figure 1, the variation of volume by time of day for all the sites are shown. All the sites except site WD12 exhibit similar trends. At the start of the day, pedestrian volumes are low and they rise steadily during the day to a maximum during the evening rush period. Site WD12 is a university campus and it shows a dissimilar trend. Maximum volumes are observed during the early hours corresponding to rush hour lecture periods and decline steadily during the day as other activities such laboratories, take prominence and off campus students depart the university campus. WD06 site gave the maximum flow rates across the day, doubling the observed values for any site at a particular point in time. Site WD05 follows with high flow rates. It is a high density residential area. If the study was extended to night periods, site WD05 will still see high pedestrian flows because activities in the area extend well into the night.

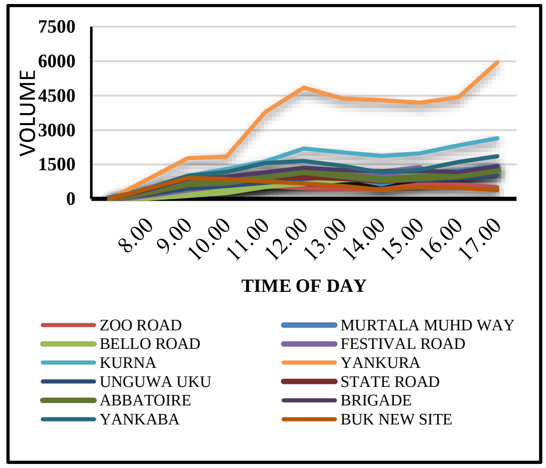

Figure 1 Pedestrian volume trends for waje district

Figure 2 shows the pedestrian flow trends for the city district of Kano. Site CD12 is the famous Kurmi market which recorded the highest flow rates for the city district. Like site WD06 in the Waje district, site CD12 is the single most important attraction point in the city, with large surges of pedestrian flows within and outside the market. The market is located in the popular high density residential neighbourhood in Kano city. All the other locations in the city exhibit similar trends in the pedestrian movement.

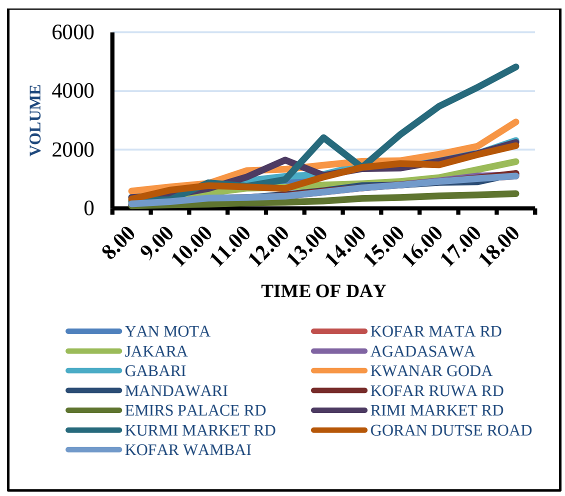

Figure 2 Pedestrian volume trends for city district

4.2 Pedestrian Characteristics.

The detailed features obtained for the twenty-five sites are summarized in Tables 2 and 3 respectively for both Waje and City Districts. From Table 2, three corridors stand out for their high pedestrian volumes and densities. These are WD01, WD06 and WD05 sites. These corridors exhibited much lower walking speeds than was observed for other corridors for all categories of pedestrians. This could be attributed to conflicts resulting from cross flows, the presence of mini-markets, narrow downtown road encroached by hawkers and the prevalence of high low income groups. The walking speeds, however, were above the mean walking speed observed for the Waje area. Corridors with characteristically high walking speeds include site WD12, i.e. Bayero University, New Campus. Site WD09 is close to an abattoir, site WD10 is a high density residential area and site WD02, is a corridor at the heart of the central business area. It is much straight forward to attribute reasons for these observations. In site WD12-the university campus, majority of the population are young and of middle age.

Table 2 Pedestrian characteristics for waje districts

SITE No	LOCATION	VOLUME	AVERAGE DENSITY	Mean Walking Speed (m/min)				
	WAJE DISTRICT	Ped/m/min	Ped/m^2	MALE		FEMALE		COMBINE
				YOUNG	ADULT	YOUNG	ADULT	MEN AND WOMEN
WD01	ZOO ROAD	90	1.48	66	77	67	67	61
WD02	MURTALA MUHD WAY	20	0.32	84	82	83	71	63
WD03	BELLO ROAD	15	0.39	47	52	39	46	38
WD04	FESTIVAL ROAD	20	0.33	70	75	57	59	60
WD05	KURNA	65	1.12	56	71	55	60	58
WD06	YANKURA	81	1.47	76	65	72	54	55
WD07	UNGUWA UKU	16	0.26	79	69	58	63	62
WD08	FIRE SERVICE	17	0.27	72	80	65	66	62
WD09	ABBATOIRE	18	0.25	83	72	76	70	73
WD10	BRIGADE	22	0.28	86	73	52	42	78
WD11	YANKABA	27	0.63	53	80	43	51	43
WD12	BUK NEW SITE	10	0.15	66	82	65	73	67

Table 3 Pedestrian characteristics for city district

SITE No	LOCATION	VOLUME	AVERAGE DENSITY	Mean Walking Speed (m/min)				
	CITY DISTRICT	Ped/m/min	Ped/m^2	MALE		FEMALE		COMBINE
				YOUNG	ADULT	YOUNG	ADULT	MEN AND WOMEN
CD01	YAN MOTA	38	0.59	82	70	55	54	64
CD02	KOFAR WAMBAI	18	0.30	78	71	62	61	61
CD03	JAKARA	27	0.43	71	69	62	61	63
CD04	AGADASAWA	19	0.30	76	73	69	67	64
CD05	GABARI	39	0.57	76	75	63	62	69
CD06	KWANAR GODA	49	0.74	84	74	85	72	66
CD07	MANDAWARI	20	0.32	68	68	65	64	63
CD08	KOFAR RUWA RD	20	0.25	83	76	67	66	81
CD09	EMIR'S PALACE RD	8	0.13	73	71	64	61	62
CD10	KOFAR MATA RD	46	0.60	102	101	84	84	77
CD11	RIMI MARKET	37	0.54	78	74	74	68	69
CD12	KURMI MARKET	80	1.23	71	68	68	62	65
CD13	GORAN DUTSE RD	36	0.53	73	72	72	69	68

Elderly persons are few. Furthermore, most persons are time conscious and are moving towards a target. Site WD09 is essentially a meat market, no special reasons were found for the particularly high walking speeds but generally pedestrians walked purposely both towards and away from it. Site WD08 is along a fire service station. The fire service area is a sensitive area. On call, the fire brigade uses the access area to reach call areas. In addition, there is a train crossing barrier adjacent to the fire service for in-coming trains. Pedestrians' conscious of this walk briskly along the corridor to avoid being hurried over by security personnel. At site WD10 men were particularly noted to walk much faster than their female counterparts. However, the area recorded the highest combine walking speed for all categories of pedestrians with a speed of 78 m/min. In most cases, pedestrians were observed to want to catch a minibus or in hurry to go to work. In the evening the contrary occurred where pedestrians walked faster to reach home after work. Female pedestrians at site WD10 recorded a low walking speed of 42 m/min.

Table 3 shows the results for the City District of Kano. Here only CD12 Kurmi market has results that are comparable to WD01 Zoo road corridor in Waje District. The pedestrian flow and density clearly demonstrates its importance as an attraction point. The flow and concentration in the whole area averages 33.60 Ped/m/min and 11.23 Ped/m/min respectively and compares with 32.33 Ped/m/min and 10.03 Ped/m^2 for Kano Metropolis. Generally pedestrians in the City walked faster than their counterparts in the Waje area. The summary of the results for both Waje and City districts are presented in Tables 4 and 5 respectively.

In the City district, male pedestrians generally walk faster than their female counterparts. However, adult females walked fastest, surpassing their male counterparts by 3%. The highest walk rate in the City district was by adult female at 82.60 m/min while at the same time young female recorded the slowest walk rate at 57.40 m/min. The average density and volume observed for the district are 11.23 Ped/m^2 and 33.60 Ped/m/min respectively. Female pedestrians recorded the highest walk rate for the City district with a speed of 82.60 m/min. As would be expected they also recorded the lowest speed of 57.40 m/min.

In the Waje district, male pedestrians walked faster than their corresponding female counterparts walking a speed of 71.45 m/min for adult male and adult female of 59.90 m/min. Again the highest walk rate was recorded by male pedestrians with 79.33 m/min while the female pedestrians walk slowest with 46.17 m/min. The average density of pedestrians in the Waje district was 8.72 Ped/m^2

lagging the city District by 22%. Also the average volume for the Waje district was 30.92 Ped/m/min again lagging the city district by 4.2%.

Table 6 shows the results for the whole of Kano Metropolis which reveals that male pedestrians walked faster than their female counterparts with 74.18 m/min for male and 66.24 m/min for female giving a combined walking speed of 63.86 m/min. The average density for the metropolis is 10.03 Ped/m^2 while the average volume for the metropolis is 33.32 Ped/min.

Table 4 Pedestrian flow parameters for city district

Location	Characteristics		Mean Walking Speed (m/min)				
			MALE		FEMALE		COMBINE
			YOUNG	ADULT	YOUNG	ADULT	BOTH
CITY DISTRICT	Mean Walking Speed		71.70	63.90	54.30	73.90	67.30
	Standard Deviation		6.30	5.90	7.10	8.20	6.80
	Range	High	81.30	72.10	66.50	82.60	69.20
		Low	69.8	62.10	57.40	70.20	52.90
	Density		11.23 Ped/m^2				
	Volume		33.60 Ped/m/min				
	Sample Size		15,106				

Table 5 Pedestrian flow parameters for waje district

Location	Characteristics		Mean Walking Speed (m/min)				
			MALE		FEMALE		COMBINE
			YOUNG	ADULT	YOUNG	ADULT	BOTH
WAJE DISTRICT	Mean Walking Speed		69.90	71.45	57.40	59.90	60.21
	Standard Deviation		5.31	4.15	3.16	4.49	3.43
	Range	High	79.33	77.72	66.13	68.38	79.88
		Low	65.47	63.29	46.17	43.91	47.52
	Density		8.72Ped/m^2				
	Volume		30.92Ped/m/min				
	Sample Size		9,093				

Table 6 Pedestrian characteristics for kano metropolis

Location	Characteristics		Mean Walking Speed (m/min)				
			MALE		FEMALE		COMBINE
			YOUNG	ADULT	YOUNG	ADULT	BOTH
Kano Metropolis	Mean Walking Speed		74.18	72.74	66.24	62.50	68.92
	Standard Deviation		5.63	3.78	3.61	4.74	4.82
	Range	High	83.70	77.30	73.80	81.90	72.40
		Low	70.20	64.10	53.80	69.30	67.60
	Density		10.03Ped/m^2				
	Volume		32.33Ped/m/min				
	Sample Size		24,198				

4.3 Modelling of Speed-Density and Volume–Density Relationships.

As noted in the literature review, models of macroscopic pedestrian behavior fail to give the complete traffic state at any point as well as at the critical density for assessment of flow constraints. A method most suited for this is the quadratic function relationships between volume and density. This method also assumes a linear relationship between speed and density. In order to see the relationships between the pedestrian flow parameters, dispersion plots were used for the bivariate flow-density and speed-density. Functions for these plots were derived as in Alhassan and Edigbe [35] and Alhassan [36]. The aggregated data for the two districts were used to demonstrate the plots and the corresponding functions obtained are shown in Figures 3 and 4, respectively. In Figure 3, the model equation is stated as in equation 4 below:

$$q = -1.2135k^2 + 59.757k - 5.8482 \quad (4)$$

The volume-density function (eq. 4) is first differentiated with respect to the density k and results in

$$\frac{dq}{dk} = -2.2427k + 59.757 \quad (5)$$

This gives k = 24.621.

The evaluation of the volume for this density gives a value of 73.0 Ped/min. This would represent the maximum volume and the critical density would be approximately 25 Ped/m/min. Thus the pedestrian traffic state would be volume; 73.0 Ped/min, density; 25 ped/m/min.

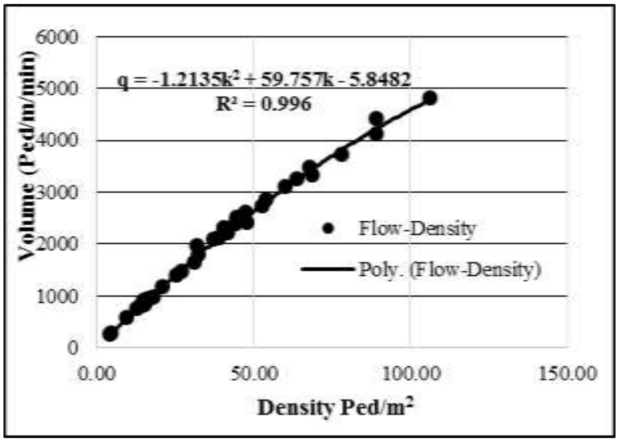

Figure 3 Pedestrian volume-density model

The flow-density plot is very useful in understanding congested flow situations in pedestrian evacuations as well as everyday congested situations. This could reveal system constraints and hence development of counter measures for amelioration schemes. For the volume–density plot shown in Figure 3, there is a clear increase of volume with increase in density. This rises to the maximum value called critical density above which congested conditions could manifest. This plot could therefore be used to indicate congested situations on pedestrian facilities. The model equation for the volume-density is $q = -1.2135k^2+59.757k-5.8482$.

The speed-density plot is shown in Figure 4 and it is used to understand the maximum speeds that could be sustained without congested conditions forming. The relationship between the speed and density is linear with speed decreasing with increased density. The speed-density model for the whole of Kano Metropolis is $u= -0.1373k+59.547$.

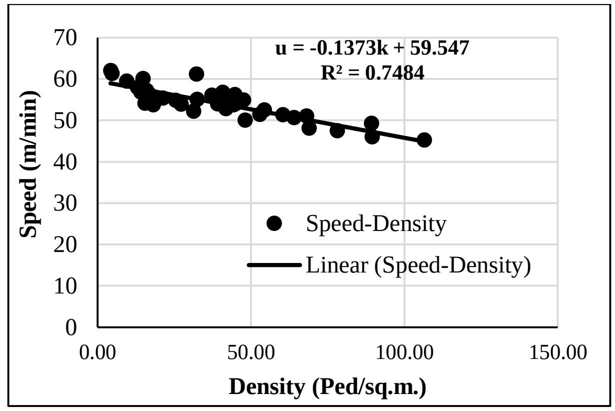

Figure 4 Pedestrian speed-density model

The model equation for the speed-density predicts a free walking speed of 59.547 m/min and a critical density of 24.621 Ped/m^2 from the volume-density relationship. Current levels of flow indicate that Kano has a density of 10.03 Ped/m^2, volume of 32.33 Ped/m/min and average aggregated speed of 68.92 m/min. The pedestrian flow problem is still sparsely populated in spite of localised clusters of heavy flow. The city is gradually assuming a cosmopolitan outlook with pedestrians coming from diverse social leanings. In order to see how Kano compares with other countries around the world, Table 7 summarises the results from other countries and compares the functions and pedestrian features from these countries with Kano. The parameters for the Kano pedestrian differs markedly from pedestrians of other countries. The pedestrian walks slowest among his peers in the Singapore and the United States. This may be due to distractive mode of walking, whereby pedestrians would exchange pleasantries with people that come along their path.

Table 7 Comparison of pedestrian models between Kano and other countries

COUNTRIES	Kano-Nigeria	Singapore	U.S.A.
Speed-Density Equation u=f(k)	u=59.547-0.137k	u =73.9-15.3k	u=81.4-20.4k
Flow-Density Equation q=f(k)	$q=59.757k-1.2135k^2-5.85$	$q=73.9k-15.3k^2$	$q=81.4k-20.4k^2$
Speed-Flow Equation q=f(u)	-	q=u(73.9-u)/15.3	q=u(81.4-u)/20.4
Free-Flow Speed u_f	59.86m/min	73.9m/min	81.4m/min
Maximum Flow Rate q	72.4ped/m/min	89ped/m/min	81ped/m/min
Average Walking Speed	68.92m/min	74.0m/min	82.5m/min

■5.0 CONCLUSIONS

From the twenty-five different locations used in this study, it may be concluded that:

- The high density pedestrian concentrations in the Waje district include sites WD06, WD01 and WD05. In the city district high pedestrian concentration areas are at sites CD12, CD06 and CD10.
- Adult women walked faster than their male counterparts in the city district while young males were faster than the female. The adult female recorded a speed of 73.90 m/min against the speed of 71.30 m/min for the adult male. The characteristics of the pedestrian in the city district are speed 67.30 m/min; density 11.23 Ped/m^2 and volume 33.60 Ped/m/min.
- In the Waje district, male whether adult or young walked faster than their corresponding female counterparts with speed of 71.45 m/min for the adult male and 59.90 m/min

for the adult female. The young male was faster than the young female by 17.9%. The pedestrian characteristics for the Waje District indicated a combine speed of 60.21 m/min; density of 8.72 Ped/m^2 and volume of 30.92 Ped/m/min.

- The pedestrians in the city district had a higher flow rate, higher density and higher speed than those of the Waje district. This means the city district is a little more concentrated than the Waje district.
- The aggregate characteristics of pedestrians in the metropolitan area gave the following parameters: Speed 68.92 m/min; density 10.03 Ped/m^2 and volume 32.33 Ped/min. The predictive models for Kano showed a free flow speed of 59.86 m/min and a maximum flow rate of 72.40 Ped/m/min.
- Compared to other countries the Kano pedestrian walked slower than pedestrians from Singapore and the United States.

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