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# Recent developments in pedestrian flow theory and research in Russia

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## Abstract

Predtechenskii and Milinskii's seminal work [Predtechenskii VM, Milinskii AI. Planning for foot traffic flow in buildings. Revised and updated edition. Moscow: Stoiizdat; 1969] in relation to pedestrian flows is well known. However, analysis of the experimental results and observations obtained from this series of experimental studies revealed the inherent statistical non-homogeneity of pedestrian flow speeds [Kholshevnikov VV. The study of human flows and methodology of evacuation standardisation. Moscow: MIFS; 1999]. As such, the results of these individual experiments cannot be integrated to produce a valid general expression $V=f(D)$ for each type of pedestrian flow path, where $V$ is the flow velocity and $D$ is the flow density. This paper presents further pedestrian flow research conducted in Russia post 1969.

In this paper pedestrian flow is treated as a stochastic process, i.e., that which might be observed in a series of experiments as a manifestation of the random function $V = f(D)$. A fundamentally new random methodology to mathematically describe this function is presented. Corresponding computer simulation models "Analysis of Foot Traffic Flow Probability" (known by the Russian acronym ADLPV) [Kholshevnikov VV. Human flows in buildings, structures and on their adjoining territories. Doctor of science thesis. Moscow: MISI; 1983; Kholshevnikov VV, Nikonov SA, Levin YP. Human flows modelling and computations. In: The study of architecture design issues. Tomsk: TGU; 1983; Kholschevnikov VV, Nikonov SA, Shamgunov RN. Modelling and analysis of motion of foot traffic flows in buildings of different usage. Moscow Civil Engineering Institute; 1986; Kholshevnikov VV, Nikonov SA, Shamgunov RN. Modelling and analysis of pedestrian of pedestrian flow movement in various facilities. CIB W14/87/41987; Bradley D, Drysdale D, Molkov V, editors. Retrospective review of research on pedestrian flows modelling in Russia and perspectives for its development. In: Proceedings of the fourth international seminar "fire and explosion hazards", Londonderry, UK, 8–12 September 2003. p. 907–16; Nikonov SA. A development of an arrangements concerning fire evacuation in public buildings on the basic of foot traffic flow modelling. PhD thesis, (Supervisor V.V. Kholshevnikov). Moscow: HFSETS; 1985; Isaevich II. A development of multi-variative analysis of design solution for subway stations and transfer knots based on foot traffic flow modelling. PhD thesis, (Supervisor V.V. Kholshevnikov). Moscow: MISI; 1990] and "Free Foot Traffic Flow" (known by the Russian acronym SDLP) [Kholshevnikov VV. Human flows in buildings, structures and on their adjoining territories. Doctor of science thesis. Moscow: MISI; 1983; Aibuev ZS-A. The formation of foot traffic flows on large industrial territories. PhD thesis, Moscow: Moscow Civil Engineering Institute; 1989; Nikonov SA. A development of an arrangements concerning fire evacuation in public buildings on the basic of foot traffic flow modelling. PhD thesis, (Supervisor V.V. Kholshevnikov). Moscow: HFSETS; 1985; Kholshevnikov VV, Shields TJ, Samoshyn DA. Foot traffic flows: background for modelling. Proceedings of the second international conference on pedestrian and evacuation dynamics, University of Greenwich, 2003, p. 420] are described. The high degree of correspondence between observed pedestrian flows and the output from these models has been sufficient for the models to be accepted by statutory authorities and used in building design and regulation in Russia [Building regulations. Fire safety of buildings and structures. SNiP II-2-80. Moscow: Stroizdat; 1981.[12]; State Standard 12.1.0004—91 (GOST). Fire Safety.

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General requirements. Moscow, 1992; Building Regulations. Building accessibility for disabled people. SNiP 35-01-2000. Moscow: Stroizdat; 2000] for many years.
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## 1. Introduction

As far back as 1938, Russian scientists, based on experiments conducted from 1933 to 1935, concluded that: "safe building evacuation is time dependent" [15]. At present many building codes in use around the world are fundamentally similar in that they refer to the numbers of exits, travel distances, etc., which are essential components for prescriptive provision of means of escape from fire. Their use in prescriptive codes is based on know how, rather than underpinning, fundamental principles which can be expressed in terms of time and associated human behaviour [16]. However, in the past two decades, the emphasis has significantly shifted from prescriptive rule-based fire safety regulation towards engineering fire safety in building design, supported by performance-based fire safety regulation and codes. As such, understanding of the principles of people movement and behaviour in fire has become much more important. Much work has been undertaken in Russia in the past seven decades in an attempt to determine these principles and associated human behaviour.

In 1951 Milinskii established a statistical data base of human flow parameters, comprising field observations of some 3585 counts of travel speed against density of flow, together with 2303 counts of door traffic capacity for doors which ranged from 0.5 to 2.4 m wide at densities of 1–9 persons/m$^2$ [17]. The visual method of observations which was used required the participation of 160 observers. One hundred and forty-eight counts of body dimensions were also recorded and presented as *f, the horizontal projected area, m*$^2$, in order to express density of flow ($D$) in m$^2$/m$^2$ as:

$$D = \frac{Nf}{lb},$$

where $N$ is the number of people, $l$ the length of the pathway (m), $b$ the width of pathway (m).

For the first time, fundamental laws of pedestrian flow relating to:

- changes of flow characteristics at the interface of route sectors with different widths or route types ($j$);
- merging and branching of flows;
- dynamics of crowding and bottlenecking at the interface of a sector with insufficient traffic capacity, and
- convergence and divergence of a flow

were determined.

The results of this work have been presented in [1,18–21], and the most important outcomes of this work are briefly summarised below.

## 2. Fundamental laws of pedestrian flow

Changes in flow characteristics ($V$ and $D$) at the interface of a sector of width $b_i$ to a sector with width $b_{i+1}$ are determined by changes of intensity of flow from $q_i$ to $q_{i+1}$:

$$q_{i+1,j} = \frac{q_{i,j} b_i}{b_{i+1}}. \quad (1)$$

The intensity of flow $q = VD$ person/(m/min) or m$^2$/(m/min) is the product of flow velocity and density of flow.

In the case of the merging of several flows, the intensity of flow can be described as

$$q_{i+1,j} = \frac{\sum q_{i,j} b_i}{b_{i+1}}. \quad (2)$$

Delay of a flow at the interface of the next sector occurs because of its inherent traffic capacity, i.e. if the sector cannot accommodate all the people approaching it. Denoting the number of people coming from the previous sector as $P_{i,j} = q_{i,j} b_i$, and the traffic capacity of the adjacent sector as $Q_{i+1,j} = q_{\max,j} b_{i+1}$ then, if $Q_{i+1,j} \geqslant \sum P_{i,j}$ the flow is unimpeded. Alternatively, if $Q_{i+1,j} < \sum P_{i,j}$ at the interface with the adjacent sector $i+1$, movement delay develops with duration $\Delta t = \sum N_i \left( (1/Q_{i+1,j}) - (1/\sum P_{i,j}) \right)$. The condition $q_{i+1,j} > q_{\max,j}$ used in the calculations is indicative of imminent movement delay.

The speed ($V_1$) of movement at the interface between two parts of a flow of different densities, so called reforming, is given by:

$$V_1 = \frac{q_1 - q_2}{D_1 - D_2}, \quad (3)$$

where

- $D_1$ and $q_1$ are the density of the first part of the flow and intensity of its movement, and
- $D_2$ and $q_2$ are the density of the second part of the flow and intensity of its movement.

The graphical method used in the analysis, which clearly illustrates flow movement, was developed in the fifties based on the above expressions and the linear relation $l = Vt$ [1,21]. Given the lack of available computing power at the time, this was the method of calculation developed to

**Nomenclature**

| | |
|---|---|
| $D$ | density of flow ($m^2/m^2$) |
| $D_{o,j}$ | is a threshold value of flow density on the pathway $j$ ($m^2/m^2$), i.e. as soon as the threshold density is exceeded it influences flow speed |
| $N$ | number of people |
| $l$ | length of the pathway (m) |
| $b$ | width of pathway (m) |
| $q$ | intensity of flow (person/m/min) |
| $P_{i,j}$ | number of people coming from previous sector $i$ |
| $Q_{i+1,j}$ | traffic capacity of adjacent sector |
| $\Delta t$ | duration of movement delay (s) |
| $V$ | speed of movement (m/s) |
| $e$ | psychological stimulus/emotional state |
| $V^e_{o,j}$ | the average free travel speed of people at a density of flow in the range of density where density does not impact travel speed ($D = 0$–$0.5$ person/$m^2$) for route type $j$ (m/s) |
| $V^e_{D,j}$ | is the average travel speed of people at the middle of each flow density interval for route type $j$ (m/s) |
| $P(V_n)$ | of pedestrian free travel speed |

describe human flow movement along egress routes, and flow formations towards building exits.

It is clear that, for such calculations, a mathematical relationship between $V$ and $D$ was required [22]. The results of 69 experiments and observations, conducted in Russia, which generated 24,000 values of travel speed with associated densities are presented in Figs. 1–4. However, examination of the data sets from which Figs. 1–4 are derived indicated their non-homogeneity [3]. This can also be said for the datasets describing horizontal pedestrian flows [1]. Whilst a relationship between pedestrian flow, speed and density existed, the fundamentals underpinning this relationship $V = f(D)$ had not yet been addressed.

The widespread use and acceptance of empiricism and mechanistic approximations re travel speed and flow density continues. However, the fundamental theory is lacking. Building design decisions, whether forced by compliance with prescriptive codes or as a part of performance-based design, should be based on fundamentals, not mechanistic approximations derived from one off, seldom if ever to be repeated, experiments. This paper focuses on the research conducted in Russia to develop and validate fundamental theories in this respect. In the following paragraphs the potential impact of emotional state on travel speed is introduced and a theory of pedestrian movement which relates speed of movement to flow density, nature of pathway traversed and emotional state is developed.

## 3. Potential emotional impact on travel speed

Pedestrian flow represented in terms of elementary flow models, i.e. people moving in an orderly fashion in the same direction, although still embedded in some national building codes, is long out of date. In fact, the location of people within pedestrian flows can be quite random/stochastic, the spacing between people is variable, and local congestion occurs and dissipates within different parts of the flow. This is precisely why the density of pedestrian flow is a conditional statement as is speed of flow.

In early experiments in Russia the conditional statement—speed of flow—was derived from visual observations of some given part of the flow [17]. However, with the development of improved research techniques [34] and visual aids [35], travel speed was redefined in terms of an average from data obtained from several sectors in a pedestrian flow when extended over many tens of metres. Travel speed in any

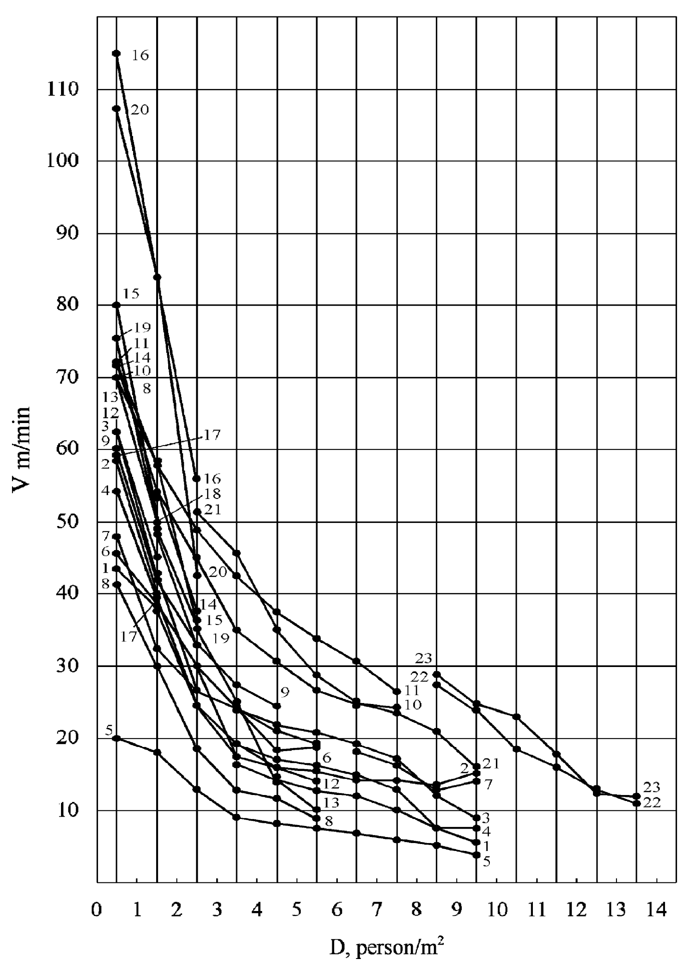


Fig. 1. Empirical relations between travel speed and density of pedestrian flow (horizontal). *Buildings*: theatres, cinemas 1—[17], 5—[23]; universities 2—[17]; industrial 3—[17]; transport structures 4—[17], 13, 14—[24]; sports 6—[25]; other 7—[17]; trade 8—[26]; schools: senior group 9—[27], middle 10—[27], young 11—[27]; *Streets*: shopping centre 12—[26]; transport junction 15—[24], 16—[28], 18—[29], *Industrial unit*: 19—[29]; *Underground stations*: 20—[30], 21—[31]; *Experiment*: 22, 23—[32].

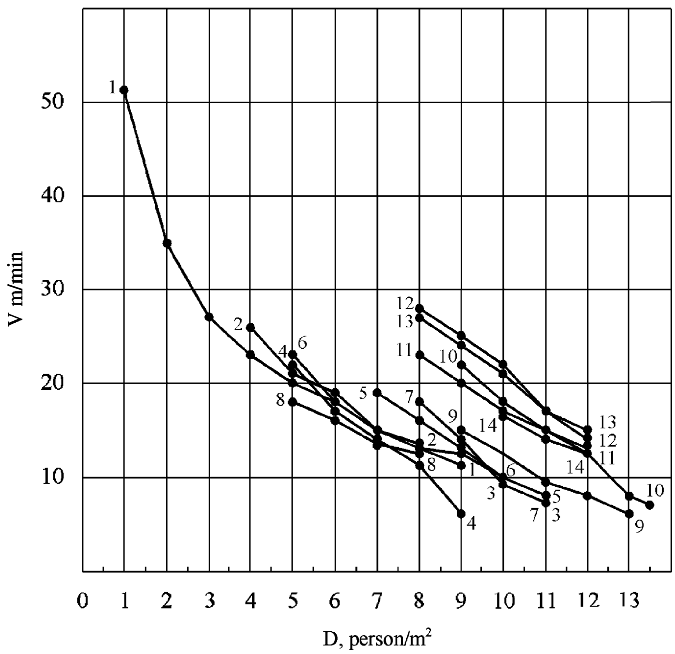

Fig. 2. Empirical relations between travel speed and density of pedestrian flow (door opening). *Buildings*: different: 1—[17]; retail buildings 2,3,4—[32]; *Sport structure*: 5—[32]; *Underground station*: 6,7,8—[32], 9—[31]; *Experiment*: 10,11,12,13,14—[32].

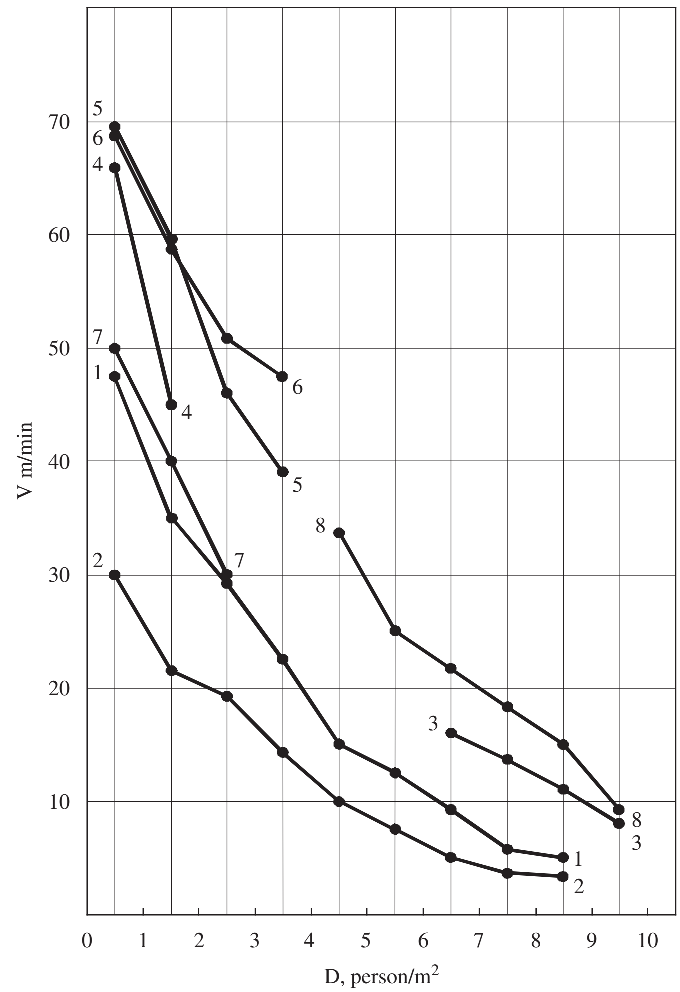

Fig. 3. Empirical relations between travel speed and density of pedestrian flow (stairs descent). *Buildings*: multi purpose 1—[17]; sports building 2—[25], 3—[31]; university: 4—[33]; schools: middle group 5—[27], young group 6—[27]; *Street*: transport junction: 7—[24]; *Experiment*: 8—[32].

interval of time, characterised by a particular, random density value depends on a number of factors. In this case randomness is a characteristic of a real process and hence, in terms of a mathematical description, the relation between travel speed and density is a random function.

Speed of travel as a behavioural response may be related for example to lateness for work or running to catch a bus, i.e., the end goal can influence the travel speed of an individual. Consequently, the motion activity of an individual is governed by processes which depend upon the psychological drivers experienced by that individual in temporal and spatial terms. This complex interaction between psychological and physiological systems has been termed psychophysiology, which has been defined as the scientific area of psychology and physiology, which studies physiological mechanisms, which realise psychological phenomena [36–40].

Each system has its own function. Psychological input to a process can be produced at some cost and used or consumed to produce some required output. The higher the level of use of say psychological input into some process, e.g. motion, the higher the corresponding level of satisfaction. Thus, the level of satisfaction is also a function of product volume $f(x)$. Travel speed is a consequence of some psychological input into the functional systems of individuals and is linked to motion and excitation [36,37]. Unfortunately, psychophysiological theory of functional systems does not yield a usable mathematical model of system interaction. Consequently, it is not possible to immediately determine the type of function which could properly describe the processes under discussion. In [3] it was proposed that the principle of coordinated optimum theory of non-antagonistic games [38] might be a vehicle for developing the kind of interactive model alluded to previously. In non-antagonistic games, participants seek to improve their respective positions without harm to themselves or other participants. Thus the state of coordinated optimum is the best solution, i.e. optimal with the achievement of such a state, and the concerted actions of so-called conflicting individuals [39]. Using the concept of coordinated optimisation anyone producing an output of volume ($x$), with associated costs effects $g(x)$, characterised by a satisfaction of $f(x)$ to maximise the goal function ($V$) can be represented thus:

$$V = f(x) - g(x). \quad (4)$$

The maximum of this function:

$$\mathrm{d}V/\mathrm{d}x = 0, \quad (5)$$

with

$$f'(x) = g'(x) > 0 \quad (6)$$

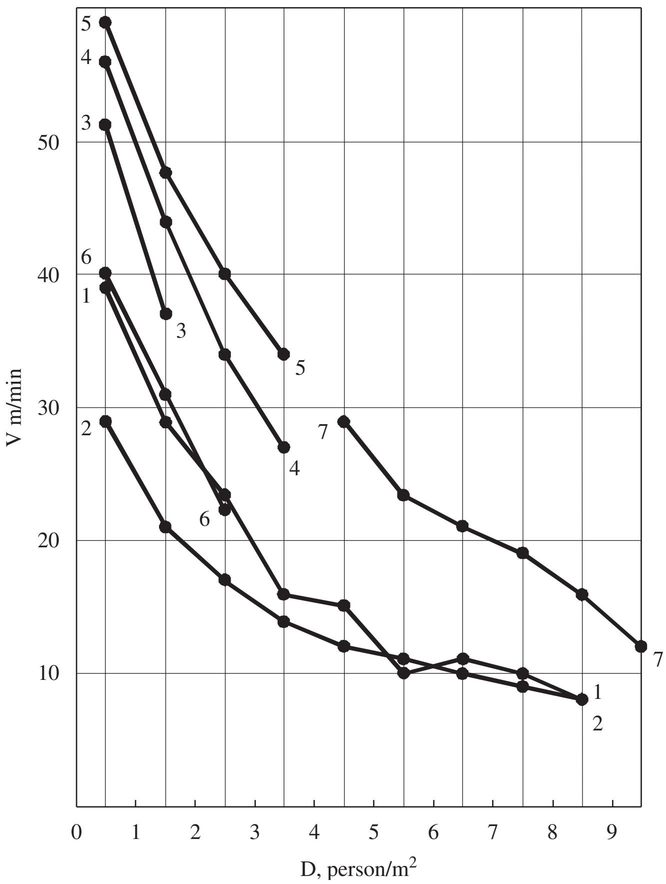


Fig. 4. Empirical relations between travel speed and density of pedestrian flow (stairs ascent). *Buildings*: different 1—[17]; sports buildings 2—[25], 3—[32]; university 3—[33]; schools: middle group 4—[27], young group 5—[27]; *Street*: transport junction: 6—[24]; *Experiment*: 7—[32].

describes the optimal conditions, i.e. that for a given value of $x$, the satisfaction reward obtained is at least equal to the costs involved. It follows that if $f''(x)<0$, and $g''(x)>0$, then:

$$d^2V/dx^2<0. \tag{7}$$

The shape of this cost function is typical beyond economies of scale i.e. costs increase per unit of production. For example, for living organisms, the more tired one becomes, the more effort is expended to execute a task previously executed with less effort. The shape of the satisfaction reward function has similar real life analogies. Needs, so to speak, are not boundless and can increase at a pace greater than output can satisfy. So, as with things in a material system, there is a balance state which means that, for a greater volume of $x$ production, there is balance between satisfaction and the associated costs/efforts, which is the solution of Eq. (6). Based on the principle of coordinated optimisation it can be said that:

- as the psychological response is in direct proportion to psychological stimuli, the travel speed is related to each level of psychological stimuli;
- for certain psychological stimuli the psychological response could lead to travel speed reduction; and
- for uncontrolled needs, e.g. evacuation from a fire threatened space, travel speed has to more rapidly increase than the psychological stimuli may facilitate, i.e.

$$dV/dx = f'(x) - g'(x) > 0 \quad \text{and}$$
$$d^2V/dx^2 > 0. \tag{8}$$

It should also be noted that these conditions are bounded.

The above discussion seeks to define the common, but necessary, requirements and conditions for the type of function required to describe the relation between travel speed, density, psychological stimulus and type of route. This relationship is further developed below.

## 4. Development of relation between travel speed, density, emotional state and type of route

The observed maximum travel speed of pedestrians in a flow and of the flow by itself is dependent on at least three factors: psychological stimulus/emotional state ($e$) (discussed above), the flow density ($D$) and the nature of the pathway traversed ($j$).

Flow densities can vary greatly, with a maximum flow density of approximately 9 persons/m$^2$. Such a flow density was first obtained by Milinskii [17] mostly in public assembly type buildings, i.e. stadia, theatres and universities. Tenable limits in terms of maximum possible flow density achievable in forced egress situations were studied by Kopylov [32]. These measurements were made in an experimental transforming arena, i.e. a full-scale model of an egress route with variable corridor and door widths and in a specially constructed $1\times1$ m frame. Kopylov found that the most frequent maximum flow density during movement along the arena was 9–10 persons/m$^2$. The maximum possible density of people located within the $1\times1$ m frame under medical control, and thus the tenable limit of density, was established to be in the region of 13–14 persons/m$^2$ for healthy young males (with an average body square 0.085 m$^2$). Given these findings, Russian building codes [13] adopted the maximum value of flow density for egress route design to be 0.9 m$^2$/m$^2$.

In the following analysis, and in order to eliminate interactions, route type, density and the emotional state of the pedestrians have been treated separately.

It is well-known that low densities of flow ($D\leqslant0.5$ person/m$^2$ approximately) do not affect the travel speed of pedestrians [1] and it has been established that certain emotional levels correspond to certain travel speeds. Therefore, it is possible to determine the influence of flow density on travel speed against free travel speed thus:

$$R^T_{D,j} = (V^e_{o,j} - V^e_{D,j})/V^e_{o,j}, \tag{9}$$

where $V^e_{o,j}$ is the average free travel speed of people at a density of flow in the range of density where density does not impact travel speed ($D = 0$–$0.5$ person/m$^2$) for route type $j$. $V^e_{D,j}$ is the average travel speed of people at the middle of each flow density interval for route type $j$.

The empirical relationship for the range of densities can be described by $R^T_{D,j} = f(D_j)$ for each series of experiments presented in Figs. 1–4. However, this set of functional/empirical relationships needs a theoretical underpinning for the type of function which describes this phenomenon.

It is hypothesised that the density of pedestrian flow is a synthesised parameter which determines the psychophysiological experiences of the persons in the flow. However, the relationship between all of the factors influencing flow density is not necessarily linear, and the relation between intensity of influence and human response might best be described by a psychophysiological law. Analysis of the general psychophysiological law [40], the Weber–Fechner law [41] and Steven's law [42], together with the form of the empirical curves obtained for the studies reported in this paper, Figs. 1–4, suggest the Weber–Fechner law is most applicable in this instance. The nature of the theoretical function is therefore proposed as:

$$R^T_{D,j} = a_j \ln(D_i/D_{o,j}), \tag{10}$$

where $a_j$ is an empirical constant for each type of pathway, $D_i$ is the prevailing density of the flow, m$^2$/m$^2$, $D_{o,j}$ is a threshold value of flow density on the pathway $j$ (m$^2$/m$^2$), i.e. as soon as the threshold density is exceeded it influences flow speed.

The values of $D_{o,j}$ and $a_j$, derived from an analysis of the empirical results given in Figs. 1–4, are given in Table 1.

Fig. 5 shows the lower and upper confidence limits for the random function against a theoretical profile of $R^T_{D,j}$. Correlation coefficients of 0.984–0.996, respectively, indicate good functional relationships and confirm the validity of the underlying hypothesis.

Combining Eqs. (9) and (10), the relation for travel speed is:

$$V^e_{D,j} = V^e_{o,j}(1 - RD^T_{D,j}) = V^e_{o,j}[1 - a_j \ln(D_i/D_{o,j})]. \tag{11}$$

This function is the product of the random elementary function and the non-random value of travel speed. This treatment of travel speed and density is compatible with the observed stochastic values of the phenomenon. The relationship between travel speed and emotional state is developed below.

Table 1
Values of $a_i$ and $D_{oj}$ for each route type

| Route type | $a_j$ | $D_o$ (person/m$^2$) |
|---|---|---|
| Horizontal outdoors | 0.407 | 0.69 |
| Horizontal indoors | 0.295 | 0.51 |
| Door aperture | 0.295 | 0.65 |
| Stair downwards | 0.400 | 0.89 |
| Stair upwards | 0.305 | 0.67 |

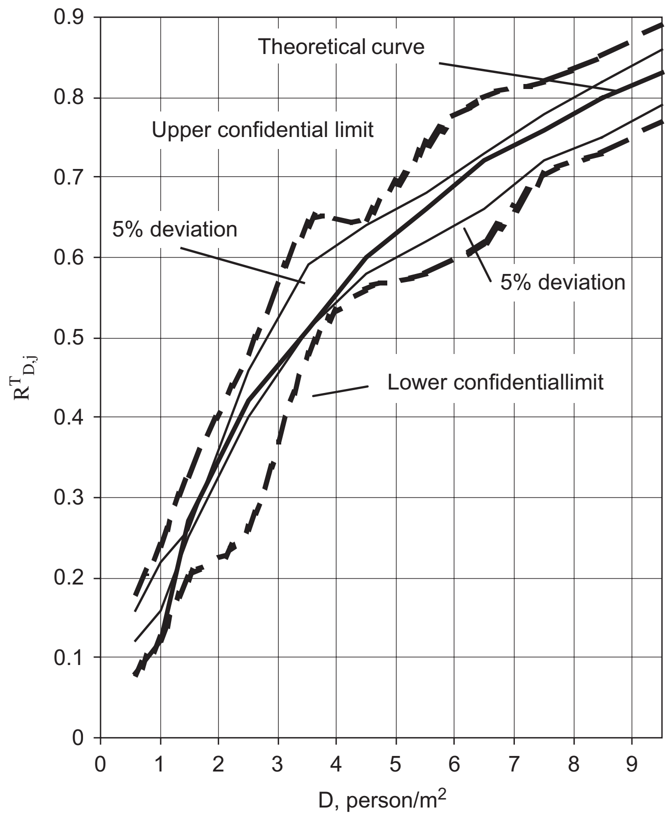


Fig. 5. An example of relation $R_T = f(D)$ approximation: horizontal path in buildings.

## 5. Psychological impact on pedestrian travel speed

Statistical analysis of the empirical relation between travel speed and density of flow has illustrated the non-homogeneity of the majority of empirical studies [3]. The exception, however, was in the first density range (0–1 person/m$^2$) where the samples were homogeneous, even for different route types. Analysis of the experimental conditions showed that the induced psychological stress levels in this series of experiments were similar. Analysis also indicated that, the higher the psychological stress level, the higher the travel speed, e.g. travel speeds in rush hour in an underground system were higher than people exiting a theatre after a performance. However, this type of analysis is limited by the scale of psychological stress levels apparent in the situations from which the empirical data has been derived, i.e. foot traffic flow for comfortable movement, normal movement, and movement under evacuation (but not real emergency) conditions.

Movement under real fire emergency conditions, however, is dependent on an individual's exposure to the fire and their perception of threat. In this situation persons can control their behaviour and an indicator of such control is travel speed. Recent Russian studies [2,3] have sought to develop an understanding of the relationship between emotional state and travel speed. These theories are developed in the following paragraphs.

Movement control requires high activity of nerve centres, finely attained psychophysiological interactions and high activity of the central nervous system. This response may be initiated by the emergence of a potential threat and produces changes in corresponding physio-biochemical reactions of the human body. Significant neuro-emotional tension can thus be generated. Negative emotional states can also develop under conditions where information is lacking.

Understanding with respect to human behaviour has attracted the attention of physiologists, psychologists and psychiatrists for a long time [43] and there have been many attempts to simulate emotional state and corresponding behaviour [44]. The results of such work indicate that changes in emotional state result in specific changes in the activity of some centres of the nervous system. If we conditionally partition negative emotional state development into three stages then for each stage there will be a particular level of activity. Hence the need for emotion scaling in evacuation simulation becomes apparent.

The conceptual relationship between motion and level of emotional state expressed in relative units [45] is illustrated in Fig. 6. The transition in emotional condition related to some threat or danger has three characteristic stages.

The first stage ($0<e<0.3$) is related to detecting weak signals of potential danger. In this stage there is an adjustment of the body's systems with respect to its preparation for some anticipated danger [45, p. 64].

The second stage ($0.3<e<0.7$) is described as a condition of increased activity that accompanies behaviour directed at elimination of the danger [45, p. 64]. Increased activity develops as the threat becomes obvious and the person begins to actively interact with the ambient environment to mitigate the threat; movement also increases in all dynamic attributes (velocity, acceleration, effort). There may also be increased efficiency in processing information and decision-making heuristics.

When the threat is very real and options to avoid it are quickly diminishing, the third stage appears ($0.7<e<1.0$). This has been described as the stage where all avoidance expectations are related to increasing feelings of powerlessness and worse case scenarios. This is characterised by a sharp decline in activity and inhibited evacuation behaviour may occur [45, p. 65]. In extreme cases, people may exercise what they perceive as their only option, however hopeless in reality that may be.

Fig. 6 clearly indicates that as the level of emotional response increases relative to the increasing life threatening danger, attention and control can rapidly decrease, as the transition to total immersion in the life threatening event approaches. As actual observations on travel speed indicate, and fire safety engineering tenability levels may dictate, the maximum values in the scale in Fig. 6 should not exceed 0.7. The general form of the plot of the emotional activity growth follows the conditions given previously in Eqs. (5) and (6). With more work in this field related to fire emergency evacuation, the scale and relationships illustrated in Fig. 6 will become more refined. For now, they suffice to illustrate, discuss and present the concept.

It is generally accepted that differences in pedestrian travel speed may be influenced by the emotional states of the individuals involved, which in turn may be related to the particular circumstances. Consequently, it may be assumed that the travel speed of pedestrians associated with higher emotional levels is at the tail of the statistical distribution of the free travel speed, i.e. extreme values [46]. Using extreme value sample theory it is possible to obtain a relationship between free travel speed and corresponding emotional state level. With reference to the foregoing, a double exponential law describes the distribution of the extreme value probability $P(V_n)$ of pedestrian free travel speed:

$$P(V_n) = \mathrm{e}^{-e^{-x}}, \quad (12)$$

where $x = \alpha(V_n - g)$ is the mean normal deviation, $\alpha > 0$ and $g$ are coefficients based on actual observation and established using standard techniques.

Using this approach, motion categories and corresponding free travel speeds for different routes were obtained from analysis of observations in Figs. 1–4. Thus, the parts of the general expression which describes the law related to travel speed changes, were established for all route types and categories of movement. The relations between stress level and free travel speed are presented graphically in Fig. 7. Mathematical analysis of these curves [2,3] revealed several representative zones which correspond to the categories of movement given in Table 2.

It is important to note for flow calculations that the intensity of movement $q = VD$ function is the mono-extreme.

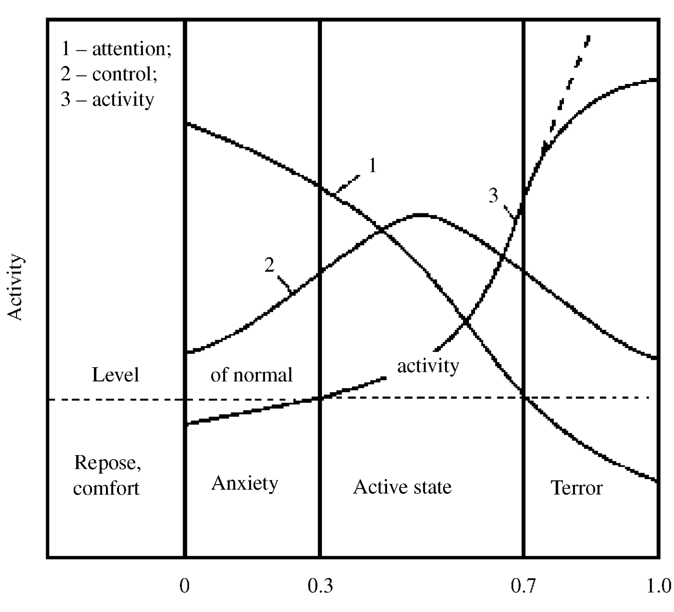


Fig. 6. Relationship between emotional state and activity from [45].

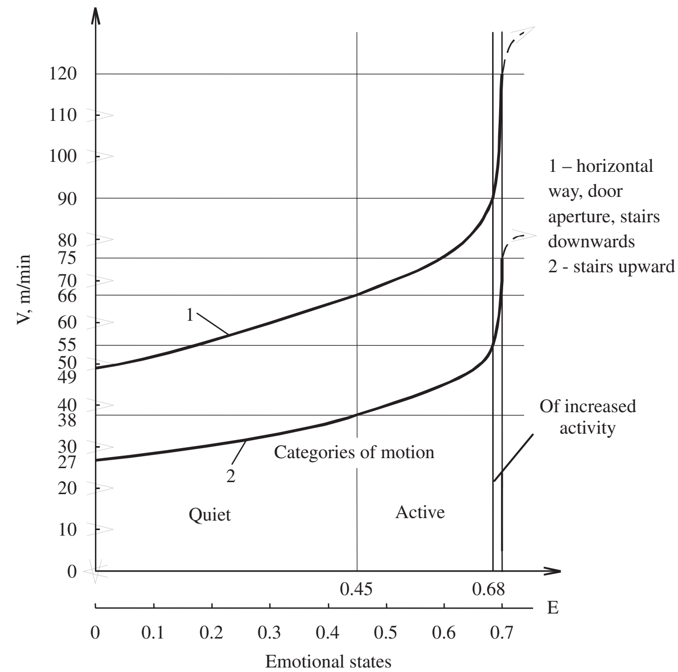


Fig. 7. Relation between unimpeded travel speed and psychological stress level [2,3].

Table 2
Categories of movement, unimpeded travel speed and emotional state level

| Categories of movement | Level of emotional state | Unimpeded travel speed $\bar{V}_o$ (m/s) | |
|---|---|---|---|
| | | Horizontal way, door aperture, stairs downward | Stairs upward |
| Comfortable | 0.00 | <0.82 | <0.45 |
| Quiet | 0.45 | 0.82–1.10 | 0.45–0.63 |
| Active | 0.68 | 1.11–1.50 | 0.64–0.92 |
| Of increased activity | 0.70 | 1.51–2.00 | 0.93–1.25 |

The maximum of this function is at the point:

$$D_{q_{\max}} = e^{(1/a_j - 1 + \ln D_{o,j})}, \tag{13}$$

where the first derivative $q_j = DV_{o,j}(1 - a_j \ln D_i/D_{o,j})$ is equal to 0.

From Eq. (13) we can see that the maximum point does not depend on free travel speed (and emotional stress level), but depends on magnitudes which describe the threshold density and route type. The correctness of the maximum point is proven by actual observations. The presence of the maximum point is also the criterion for the function $V = f(D)$. The absence of the maximum point suggests the unlimited traffic capacity ($Q = qb$) of an egress route with width b. But this suggestion is contrary to actual observations, which indicate traffic congestion in cases of limited traffic capacity.

The graphical relationships for evacuation computation in Russian Building Fire Codes [13] are based on the above and illustrated in Fig. 8. It is interesting to note that studies of disabled persons in pedestrian flow, conducted in Russia [47,48], revealed that the relationship between travel speed and flow density was also described appropriately by the established laws, with only the parameters $V_{o,j}$, $a_j$, $D_{o,j}$ varying.

## 6. Pedestrian flow modelling and validation

It is extremely difficult to establish general analytical expressions for pedestrian flow parameter computations through simple equations which describe discrete changes in flow on route sectors, randomness of travel speed of a person in the flow, flow merging, different route sizes and so on. For this reason, in pedestrian flow theory, as in many other areas, another method has been chosen to reproduce pedestrian flow.

Different modelling algorithms might be applied but useful application strongly depends on available computer capacity. At the advent of the computational age, the

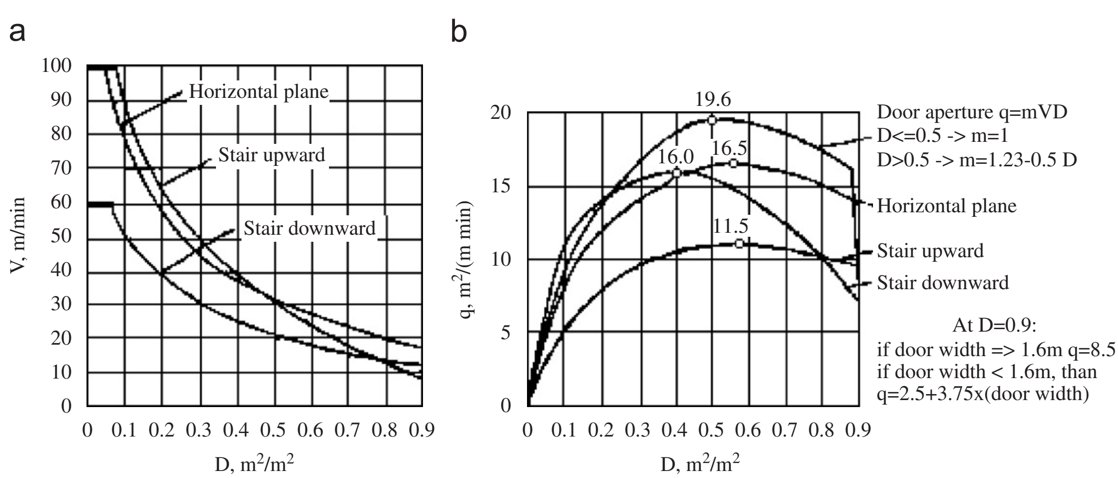


Fig. 8. The relationships between the parameters of pedestrian flow used in Russian Building Codes: (a) average travel speed (category "of increased activity"); (b) intensity of movement against density of flow.

algorithms used in Russia and elsewhere were conditioned by the limitations of available computers. Against this backdrop, the model ADLPV was developed [3–7,9,10]. In this model, an entire building is divided into elemental sectors and, based on the number of people passing through each sector to another adjacent sector in a discrete time period, the parameters of pedestrian flow are computed. This first pedestrian flow model, simulated the stochasticity of pedestrian flow, and was used in Russia for building design for several decades.

Increases in computing power and the development of new theories regarding the relationship between emotional state and travel speed, enabled the development of another model SDLP [3,8,9,11]. This model simulates the movement of large numbers of people during prolonged periods of time more precisely than ADLPV considering individual travel speeds for the case of $D_i \leqslant D_{o,j}$.

Development of computational techniques enables the representation of pedestrian flow including the modelling of the biomechanics of each person's movement in a flow. The success of pedestrian flow modelling depends, first of all, on how precisely and faithfully models can represent the psychophysiological laws of human behaviour in pedestrian flows. This is the human factor that distinguishes the mass movement of people from a mass of inanimate particles.

The laws and models used in the theory of pedestrian flows, as well as in other theories, are based on reality. The larger the volume of initial actual real data, the greater the expectation that the derived laws and distilled models replicate the general trend. However, situations which have not been covered by analysis always emerge and consequently they are always the strictest test for the validation of the developed theoretical laws which represents a variety of the real situations. Consequently, additional large-scale work was conducted to validate the developed theories and models in situations, which had not been investigated previously. These situations included:

- observations of human flows in large sport complexes designed for the Olympic Games—1980 (stadium with 45,000 spectators capacity, swimming complex on Mira Avenue, sports complex on Lavochkin Street) and in theatres in several cities [49];
- observations of pedestrian flows in the world famous museum "The Hermitage", and in Russia's largest trade complex, Children's World [9];
- unannounced evacuations in multi-story office buildings [9] and actual observations and analysis of pedestrian flows in the communications network of Moscow Underground System [10];
- observations and analysis of pedestrian flows in industrial areas of one of the largest automobile plants in Russia (VAZ in Tolliatti and ZIL in Moscow) [8].

These investigations confirmed a high degree of correlation between the observed and experimental flow movement. For example, the relationship between pedestrian's travel speed and density in the Moscow underground system (derived from some 3382 counts of travel speed against density), measured in the rush hour (high active movement) and at other times (active movement) is compared at a certain point in the underground system with the model ADLPV in Fig. 9. Fig. 9 indicates that the model results are within acceptable reliability intervals. Fig. 10 also compares the egress dynamics of people at a point in an industrial plant obtained using the model SDLP with actual observations. Fig. 10 suggests that the SDLP model is robust in terms of the general dynamics of pedestrian flow.

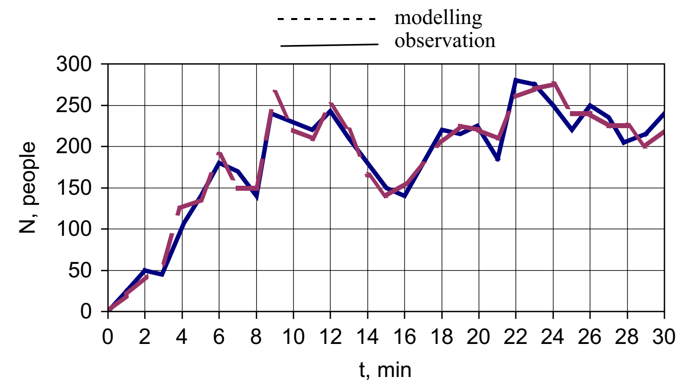


Fig. 9. Comparison of actual observations at a point in Moscow underground system's communication path and modelling by ADLPV.

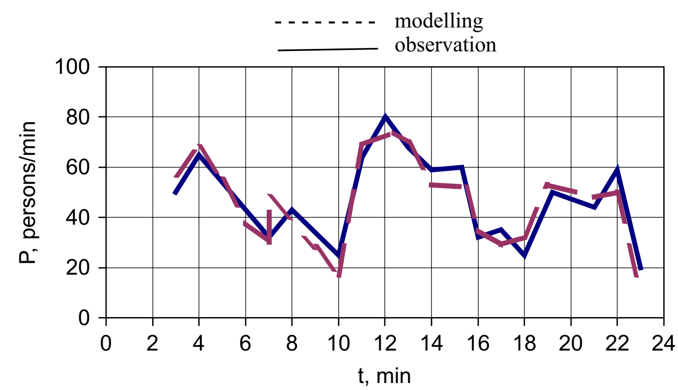


Fig. 10. Comparison of actual observations at a point in an industrial plant (250 m from the original source of pedestrian flow) and modelling by SDLP.

The relationships embedded with the models were also found to give good approximation for mobility impaired pedestrian flow when compared against actual observation data [47,48] These concepts have also been adopted in Russian building codes, viz the provision of evacuation and rescue routes for people with disabilities [14].

## 7. Conclusions

From the standpoint of general principles for modelling, human flow is a complicated system, consisting of sets of interacting elements, i.e., people. The parameter for their respective systems' functioning is travel speed $V_i$. The value of the functioning parameter for each person depends on their individual properties, (physiological and psychological characteristics of people in the flow) and it changes as an interaction between people and common factors occurs (emotional state, route type, and physiological reactions). The magnitude of people–elements interactions depends on their mutual locations, e.g., densities of flow, fluctuations as flow progresses, general intensity of flow movement and egress route sizes, etc. Manifestation of the influence of these factors on a person depends on many individual characteristics with respect to their perception and subsequently induced psychophysiological body system reaction. This is why the value of the observed human behaviour parameter, travel speed, has a fluctuation range which is described in the theory of probabilities as the probability density distribution of $V_i$. Here we have a general case for studying a phenomenon.

This paper has been prepared as part of ongoing collaborative work between the authors and their respective institutions. It has described the development of pedestrian flow theory and research in Russia over the decades since Predtechenskii and Milinskii published their seminal research [1] on foot traffic flow in buildings. The work described in this paper has demonstrated, for the first time, the application of psychophysics and psychophysiology theory of functional systems to establish rules which relate pedestrian flow density and emotional state of persons to their travel speed, as a quantifiable aspect of human behaviour in a real changing emergency situation.

The laws of pedestrian flow parameters and the simulation models presented in this paper reflect the stochastic nature of pedestrian flow. They provide a realistic picture of pedestrian flow dynamics on different egress routes and with pedestrians exhibiting different levels of emotional stress.

The validity of the theoretical findings in comparison with the results obtained from observed evacuation studies justifies their wide application in the design of buildings and use in codes.

This represents a new stage in foot traffic flow research. It is based on rich empirical data and up-to-date methodologies, derived from psychophysics and psychophysiology, mathematical game and probability theory, mathematical system modelling and programming.

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