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Evacuation models are running out of time

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ABSTRACT

The representation of crowd movement in existing evacuation models is typically based on data collected in the 1950s to 1980s, i.e., data that are more than 40 years old. Since the 1970s, population characteristics have changed dramatically around the world. Reports show that the percentage of elderly and obesity rates have increased significantly and this trend is predicted to continue into the future. Recent research [1–3] illustrates the magnitude by which different age cohorts of a population group can reduce the general speed and flow rates. In addition, well established studies have quantified the impact of body dimensions on speed and flow [4]. However, many existing evacuation models fail to take the changing characteristics of populations into account. This paper aims to review existing knowledge of population demographics and crowd dynamics, derive an indicative flow reduction factor for future populations, and consider the implications for computer models and building design in the future.

1. Introduction

The standard analyses of life safety in buildings and transportation systems use simple flow rates and walking speeds to calculate evacuation times. Current design guidance documents typically use a basic flow rate for a single uniform population, which has not changed since door and passageway sizes were initially regulated in the mid-20th century. The reference datasets used for current guidance documents were published more than 50 years ago [4–6] and therefore potentially pose an unquantified risk to life for groups with different mobility characteristics. In recent years, these long-established data and relationships between speed or flow and density have been questioned. Indeed, the originators of what are widely considered some of the most significant North American datasets (Fruin [6], and Pauls [7]) have stated that their datasets are no longer applicable and have asked them to be removed from future design guides [8].

The loss of confidence in the use of older 'uniform' data is due to the recognition of the ever increasing proportions of elderly, obese and mobility impaired in our society (United Nations [9,10], OECD [11]). These proportions have increased significantly since the original observations were made of the egress and circulation flows of office-workers and commuters in the 1950s–1970s. Mixed populations may have a dramatic effect on optimal crowd flow movement and ultimately safe escape. Some recent studies have reviewed flow data and formulae for people of different ages on stairs [12] and level surfaces [1–3] and the indications are that, while basic flow values for uniformly 'healthy adult' groups may not have yet changed significantly, there is a very significant drop in flow rate for primarily 'elderly' populations. A recent study by the National Institute of Standards and Technology (NIST) indicates that the mean walking speed for elderly adults in staircases was 0.28 m/s, while multiple sources [6,13,14] quote between 0.48 and 1.7 m/s for 'healthy adult' groups descending staircases. Reduced speeds and mobility will have a consequential impact on flow rate. We know that the following parameters affect individual walking speeds, but no account is taken of these factors in crowd flow analysis:

- Changes to age distribution – (United Nations [9], Ando et al. [15]).
- Population physical size: overweight and obesity rates (OECD [11]).
- Presence of disability (Boyce et al. [16]).

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Prescriptive regulations and design guides [17–23] use one uniform standard flow rate (typically 80 people/metre-width/min, sometimes more for sports stadia), and even modern computer simulation models use these unified parameters for generic populations. Homogenous approximations to populations are less valid with the increasing mixture of abilities and it is the assertion of the authors that the current modelling approaches are 'running out of time', as population demographics continue to change but the underlying mathematics do not. New approaches, matched by corresponding data are needed in order to consider the life safety implications now and in the future.

Given the changing characteristics of building users, i.e., increasing age (leading to greater incidence of disability [24], reduced walking speeds and increased use of walking aids) and higher obesity rate (reduced walking speed and less people per unit area), it is imperative to re-examine the representation of crowd movement in evacuation models. The present paper aims to take an important step in this direction by:

(1) reviewing the population demographic trends over an 80 year timeframe;
(2) reviewing the increasing sophistication of the analytical capability of evacuation models, but illustrating the simplicity of the underlying mathematics;
(3) suggesting some first mathematical accommodations for the effects of the demographic changes;
(4) discussing a possible way forward for the future study of crowd movement taking biometrics and people interaction into account.

2. Evacuation calculations: basic flow rates over 40 years

The majority of calculations for evacuation analyses are still based on simple flow rates, i.e. the rate at which a given population will 'flow' through an evacuation element (passageway, doorway or staircase), expressed in people per unit width, per unit of time. Our present understanding of pedestrian movement in populated spaces is based on relatively old data on mainly able-bodied people. The most significant datasets used in the analysis of people movement and evacuation [5,25,4,6,7,15] are derived from research conducted between the 1950s and 1980s, see Table 1. These datasets are derived from observations of the movement of able-bodied commuters (Hankin and Wright [5], Fruin [6]; Ando et al. [15]), pedestrians in normal circulation in a range of building types (Predtechenskii and Milinskii [4]) or during evacuation drills in buildings (Pauls [7]; Predtechenskii and Milinskii [4]). This early research has formed the basis of our understanding of flow phenomena and indeed formed the basis of design guidance documents worldwide, e.g., the Green Guide (Home Office [17]), SFPE Handbook of Fire Engineering (Nelson and Maclennan [18]), PD 7974-6 (BSI [19]).

Some sample flow rates from the second half of the 20th century are identified in Table 1. A commonly used value which underpins current guidance documents in the UK (Approved Document B [21]), US (NFPA 101: Life Safety Code [22]) and those of the International Maritime Organisation (IMO [23]) is 80 people/m/min, also expressed as 1.33 people/m/s. The simple flow rate approach and figure has changed little since the 1970s. For example, several earlier versions of the US and UK standards from the 1970s used the unit-width calculation of 40 people/21 in./min, which equates to 74.99 people/m/min. In fact, the standardised flow rates for this basic calculation approach have increased slightly in later documents, but for no apparent scientific reason other than the expediency of unified numbers.

The doubts cast upon some of the original data [27,6] has led on to more recent data gathering and reviews. For example, the NIST study [12] combined the collection of new staircase movement data for elderly and mixed-ability occupants, and office populations, with a review of egress movement on staircases It highlights significant differences in walking speeds for elderly populations. However, there are currently no plans to reassess or change the 'standard' flow rates adopted in current guidance, while population demographics continue to change. Terms such as 'obesity epidemic' and 'ageing society' are increasingly common. We know that factors such as age and physical attributes (e.g. body size etc) affect individual walking speed but because there are no dedicated scientific analyses of such effects on a group basis (i.e. for 'crowds'), there is currently no anticipated change in the majority of computer 'flow' models that inform evacuation standards, now or for the next 40 years.

3. The fundamental physics of 'flow'

The basic equation of crowd 'flow' is expressed in Eq. (1) below:

$$q = v \times d \tag{1}$$

where q=flow per unit width (p/m/s), v=velocity (m/s), d=density (p/m^2).

We should not forget that, like any physical model, crowd 'flow' is an expression of the rate at which quantities (of people) pass through a spatial unit (in the evacuation system) per unit of time. If parameters change which affect the crowd velocity (walking speeds) or density (concentration and size), then there is an inevitable physical implication for the flow. It is important to consider basic physics as we consider the implications of complex demographic changes and physical interactions.

Table 1
Summary of historic crowd flow rates.

Year	Source	Max. design flow (p/m/sec)	Ultimate flow (p/m/sec)	Scope of data/analysis
1958	Hankin and Wright [5]	1.48	1.92	Commuters under normal conditions
1969	Predtechenskii and Milinskii [4]	1.70	2.06	Peak flows at high density for adults in summer dress.
1972	SCICON report [20]	1.37		Data from football crowds
1973	Guide to Safety at Sports Grounds [17]	1.82(unit exit width method)		Based on Japanese data and derived from 1.0 pers/0.55 m/s unit exit width calculation
1971	Fruin [6]	1.37	4.37	Max. flow is ultimate regimented, 'funnelled' soldiers flow under pressure
1983	Polus et al. [26]	1.25–1.58	1.56	Data collected in Israel, sidewalks
1988	Ando et al. [15]		1.7–1.8	Commuters under normal conditions