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DOI

[10.1016/j.trpro.2015.07.003](https://doi.org/10.1016/j.trpro.2015.07.003)

Publication date

2015

Document Version

Final published version

Published in

Transportation Research Procedia

Citation (APA)

Duives, D. C., Daamen, W., & Hoogendoorn, S. P. (2015). Proposition and testing of a conceptual model describing the movement of individual pedestrians within a crowd. In *Transportation Research Procedia* (Vol. 9, pp. 36-55). Elsevier. <https://doi.org/10.1016/j.trpro.2015.07.003>

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21st International Symposium on Transportation and Traffic Theory

Proposition and testing of a conceptual model describing the movement of individual pedestrians within a crowd

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Abstract

Our understanding of crowd movements has rapidly improved over the course of the last decades. This study shows that the empirical research has not kept up with the pace of the simulation studies. Based on an extensive literature review, this study proposes a conceptual model describing the movements of individuals within a crowd. The model features the relationships between the macroscopic flow variables and characteristics of the pedestrians, their physiologic environment and the surrounding infrastructure in which they reside. Using trajectory data sets gathered during large-scale pedestrian events in the Netherlands, the conceptual model has been statistically tested. The results show that the proposed framework is capable of explaining trends featured by the macroscopic flow variables based on the before mentioned characteristics.

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Peer-review under responsibility of the Scientific Committee of ISTTT21

Keywords: framework; operational pedestrian movement dynamics; large scale events; empirical research;

1. Introduction

Large-scale events take place frequently. During many of these events, the safety of pedestrians poses no problems. Nevertheless, every year several events turn into a disaster. The stampedes and crowd crushes that occur during such a calamity leave many (fatally) wounded individuals behind. Although catastrophic crowd events are rare, temporary overcrowding occurs much more frequently during large-scale events. Consequently, during most events there is a

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considerable probability that highly dangerous situations arise. In order to predict and prevent these potentially dangerous situations a good understanding of how pedestrians move during large-scale events is necessary. A correct assessment of current crowd movements and prediction of future crowd movements at large-scale pedestrian events is an essential first step in the prevention of precarious situations.

Our understanding of crowd movements has rapidly improved over the course of the last decades. The work of among others Henderson (1971), Fruin (1971) and Predtechenskii et al. (1978) provided methods to quantify the dynamics of pedestrian movements. In recent years, among others Seyfried et al. (2005), Daamen et al. (2003b) and Moussaïd et al. (2009), has improved our understanding of the exact relations between the pedestrian movement dynamics and the macroscopic and microscopic flow characteristics proposed by these earlier research attempts.

An extensive review of the research literature shows that even though numerous studies have been performed, the research has been disjointed. As a consequence, our understanding of the interrelations between the flow variables and other characteristics concerning the pedestrian, the crowd and the infrastructure is still limited. Besides that, the research has been focused on very specific relations between one of the macroscopic variables (generally walking velocity) and one of demographic, environmental and infrastructure characteristics.

As a result, the interplay and correlations between these characteristics under study has been left underexposed. For example, even if the influence culture on the walking velocity is understood, it is unclear how a third factor (e.g. an intersecting flow system) presents itself within the same flow system, due to the interplay between all three characteristics of the situation.

The objective of this study is to determine a conceptual model of constituent behavioral hypotheses that connects the relationships mentioned in literature. For the first time, this paper puts forward a comprehensive theory and conceptual model of related behavioral hypotheses which explains how the characteristics of the pedestrians, the physiological environment and the infrastructure influence the resulting operational movement dynamics of the crowd. The behavioral hypotheses incorporated within the conceptual model generate insights into the interrelations between velocity, density, flow, distance headway, the angle of interaction, the variability of interactions, age, temperature and the number of pedestrians within the infrastructure.

The paper describes the development and the subsequent statistical testing of the proposed conceptual model. Since only part of the behavioral hypothesis in the conceptual model could be derived directly from previous empirical research, preliminary tests have been performed to establish the validity and sign of the behavioral hypothesis that are part of the conceptual model using data sets featuring the movement of pedestrian crowds at various large-scale pedestrian events in the Netherlands.

This study shows that it is possible to predict general trends in the movement dynamics of crowd using the proposed conceptual model. The finalized conceptual model also shows that a complex interplay between the incorporated factors exist, which is more than just the simple addition of factors.

The remainder of this paper elaborates on the development and testing of the conceptual model. Section 2 details the results of a comprehensive literature review. In the review the factors which influence pedestrian movement dynamics, according to the contemporary research literature, are determined. Subsequently, a conceptual model is proposed in section 3. In section 4 the data gathering methodology, the general characteristics of the data and a mathematical definition of the variables used in the conceptual framework process are mentioned. The conceptual model is put to the test in section 5. Preliminary statistical tests are performed on behavioral hypothesis mentioned in the conceptual model. Subsequently, a final version of the conceptual model is presented. Section 6 concludes this paper with some conclusions and a discussion of the possibilities for future research.

2. Review of literature featuring empirical research into crowd dynamics

Many research papers indicate factors which influence the actual physical movement dynamics of pedestrians during large-scale events. Some of the descriptive factors mentioned in the research literature relate to the demographic characteristics of the pedestrians, such as the age, gender and cultural background. Other factors relate to the characteristics of physiological environment in which pedestrians reside, such as precipitation, sunshine, temperature and wind. The research literature often also makes mention of factors related to the characteristics of the flow situation.

The focus of this study is on crowd movement dynamics during large-scale outdoor events. Therefore, especially studies considering the factors that are influence the operational movement behavior at these events are reviewed. Due to the space restriction the following section will only mention the findings that mention and/or underpin behavioral hypotheses which directly relate to the movement dynamics of crowds

In this paper the current body of knowledge is reviewed with respect to the insights which quantify how pedestrians' movements are influenced by the characteristics of the individual (section 2.1), their environment (section 2.2) their one-

to-one interactions with other pedestrians (section 2.3), and the overall behavior of a crowd of pedestrians during a certain flow situation (section 2.4).

2.1. Personal characteristics

Several studies within and outside the field of traffic engineering focused on the relation between age of a pedestrian and the walking velocity adopted by the pedestrian (Navin et al. (1969), Boles (1981), Henderson (1971), Crosbie et al. (1997), Knoblauch et al. (1996), Bohannon (1997), Dunbar et al. (2004)). Since the quantitative relationships those studies depend severely on the employed age-groups, the results vary between studies. Yet, all studies agree that the average walking velocity of pedestrians grow older, for pedestrians over 18 years old.

Besides age, also the influence of gender on the movement dynamics of the pedestrian has been. Several European studies in the 80ies and 90ies mention, as a byproduct of their study, that there is a significant difference between the walking velocity of men and females (Knoblauch et al. (1996), Boles (1981), Tanariboon et al. (1986), Crosbie et al. (1997), Bohannon (1997)).

A correlation between walking velocity and the culture of the pedestrians has also been described in the research literature by among others Tanariboon et al. (1986), Tanariboon et al. (1991), Koushki (1988), and Tian et al. (2011). Pedestrians were found to move slower on average in Africa and Asia than in most Western countries. The results of Tian et al. (2011) do furthermore suggest that cultural differences have a more widespread effect on pedestrian movement behavior than only the influence on the average walking velocity. However, the influence of these effects has not been quantified in this study.

2.2. Physiological environment

During large-scale pedestrian events the movement behavior of pedestrians is not only governed by the characteristics of the pedestrian. Most large-scale events take place outdoors. In such situation the physiological environment of the pedestrians, consisting of the weather conditions and the stability of the underground, has also been found to influence their behavior. The influence of the stability of the underground is underexposed in the research literature, hence this section only considers the effects of the most predominant weather phenomena on operational movement behavior.

Precipitation and sun shine are known to influence the decision to walk (Aultman-Hall et al. (2009)). Besides studies which examine the decision to walk or not, studies which investigate the effect of precipitation and/or sunshine on the movement dynamics of pedestrians are rare. Knoblauch et al. (1996) shows that the average walking velocity increases slightly for respectively drizzle, rain and snow.

Several other studies elaborate on the relation between temperature and pedestrian movement behavior (Hoel (1968) as mentioned in Walmsley et al. (1989), Rotton et al. (1990)). The findings of these studies disagree with each other. Yet, based on the differences in the results it might be concluded that pedestrians react different depending on the duration of the period a pedestrian experiences a certain temperature.

Also wind is mentioned as a factor of influence by some studies. Hunt et al. (1976) summarized previous findings with respect to the response of individuals to wind. This study concludes that in steady uniform wind conditions pedestrians had limited difficulties walking at wind speeds below 13 m/s. The study also shows that in non-uniform and gusty winds, average winds speeds higher than 9 m/s will affect the walking performance. Jordan et al. (2008) furthermore concludes that the orientation with respect to the wind direction and the body weight of a person severely affected the stability of pedestrian movements.

2.3. One-to-one interaction

Pedestrians do, however, not always move in unoccupied space. Interactions with other stationary obstacles, and stationary and/or moving pedestrians also occur. Since this study is focused on the crowd dynamics, the focus of this literature review is on the interaction between pedestrians. These interactions between individuals can take place via spoken signals, body-to-body interaction or the interpretation of physical signals on a distance. In this review only the empirical research with respect to this last category is discussed.

Several researchers studied the microscopic interaction behavior of pedestrians (among others Goffman (1971), Wolf (1973), Hill (1982), Versluis (2010) and Moussaïd et al. (2009)). Most of these studies only mention the qualitative influence of the characteristics of the interaction on the movement dynamics of pedestrians. To the authors knowledge only the studies of Versluis (2010) and Moussaïd et al. (2009) mention quantitative results with respect to the macroscopic flow variables. Moussaïd et al. (2009) ascertains that in head-on encounters, a binary decision takes place,

during which pedestrians have a bias to one side. Versluis (2010) furthermore shows that the side on which pedestrians pass each other is dependent on the direction of the approach. The more bidirectional the interaction between the two pedestrians becomes, the more pedestrians prefer passing each other on the culturally biased side. Versluis also concludes that an increase in goal-orientation and group size independently increases the probability of passing downstream of another pedestrian in crossing situations.

2.4. Influence of flow situation on movement of the individual

Crowd movements arise from the aggregate motion of lots of interacting pedestrians. All of which take their own decisions, have their own goal and create their own trajectory. The following section reviews the research literature that details the influence of the characteristics of the flow situation within an infrastructure on the crowds' movement dynamics. Sifting through the research literature, it was found that the studies can roughly be divided into five categories, being: uni-directional movement, uni-directional movement while rounding a corner, uni-directional movement through a bottleneck, bi-directional movement, and intersecting flows. Since the research literature exhibits similarities within a category, and many differences between categories, underneath the research literature detailing the influence of these five flow situations is discussed in separate paragraphs.

2.4.1. Uni-directional – Straight

Most studies featuring uni-directional straight flow situations, pedestrians walk in the same direction through a straight corridor, mention quantitative results concerning the macroscopic flow variables (among others Lam et al. (1995), Milinskii (1951), O'Flaherty et al. (1972), Tanariboon et al. (1986), Tanariboon et al. (1991), Mori et al. (1987), Koushki (1988), Sarkar et al. (1997), Daamen et al. (2003a), Seyfried et al. (2005), Kholoshevnikov et al. (2008), Helbing et al. (2007), Zhang et al. (2010), Rahman et al. (2012), Zhang et al. (2013)). These empirical studies all agree that the velocity of a pedestrian is negatively correlated with the density experienced by a pedestrian.

Some of these studies have tried to unify their results by means of a 'Fundamental diagram' which relates velocity, density and flow rate (O'Flaherty et al. (1972), Tanariboon et al. (1986), Tanariboon et al. (1991), Mori et al. (1987), Koushki (1988), Sarkar et al. (1997), Daamen et al. (2003a), Seyfried et al. (2005), Kholoshevnikov et al. (2008), Helbing et al. (2007), Zhang et al. (2010), Rahman et al. (2012), Zhang et al. (2013)). But currently these attempts have not yet resulted in a uniform diagram. The shape of the curve, the capacity, the free-flow velocity and the jam-density are still not entirely agreed upon.

2.4.2. Uni-directional - Exiting and entering

All studies which feature the movement of pedestrians through a bottleneck, (Yanagisawa et al. (2009), Cepolina et al. (2005), Kretz et al. (2006b), Zhang et al. (2008), Daamen et al. (2010) and Wei (2011)), found a decline of the flow rate (P/m/s) with a decreasing bottleneck width. Some mention a step-wise decline (Hoogendoorn (2004)), other studies mention a linear decline (Kretz et al. (2006b), Seyfried et al. (2009), Liddle et al. (2009), Song et al. (2011)).

Liddle et al. (2009) also shows that the bottleneck length has no influence on the flow rate. Only really short bottlenecks perform differently, since the pedestrian will turn their body for the short moment they are at the bottleneck. Due to these body turning movements around the corners of the bottleneck, more pedestrians can enter and exit the bottleneck at the same time. This movement has only been registered for experiments with very short bottlenecks, such as for instance door openings.

To the authors' knowledge no studies directly relate the walking velocity to the geometry of the bottleneck. Berg (2009) did, however, show that the walking velocity increases after the moment of passing the bottleneck.

Few studies mention the results with respect to the influence of the bottleneck geometry on the density. Seyfried et al. (2009) found that the initial density upstream of the bottleneck has a major impact on the functioning of a bottleneck. Liddle et al. (2009) shows that the density is highest upstream of smaller bottlenecks.

Besides research studies that investigate the characteristics of the bottleneck to one of the macroscopic flow variables, only four studies relate these variables by means of a fundamental diagram (Daamen et al. (2003b), Seyfried et al. (2009), Song et al. (2011)). These results are far apart from each other in shape, free flow velocity and jam density. As such, it is difficult to draw conclusions based on these results. Besides the differences between the fundamental diagram at one location, Daamen et al. (2003b) also shows that depending on the measurement location, the fundamental diagram changes shape. This finding does suggest that there are differences in pedestrian movement behavior before, during and after passing a bottleneck. Duives et al. (2015) further substantiates this anticipation effect.

2.4.3. Uni-directional - Rounding a corner

Four studies consider the movement of pedestrians through a corridor which is bend along an angle (Zhang et al. (2012a), Steffen et al. (2009), Dias et al. (2012), Gorrini et al. (2012)). The first only show the trajectories of this specific movement (Steffen et al. (2009)). Zhang et al. (2012a) describes the quantitative differences in movement dynamics upstream and downstream of the corner by means of a 'Fundamental diagram'. Two of the four studies mention the negative influence of the turning angle of the corridor on the average specific flow rate. Dias et al. (2012) finds a statistical difference of 21% in flow rate between a straight and 90° angle corner in controlled experiments using ants as test subjects. This study also shows that in the case of a straight corridor, more short headways and less long headways were found, compared with the angled path case. Gorrini et al. (2012) mentions a similar decrease of the flow rate in a controlled experiment with students. A significant decline of both walking velocity and flow rate were found between paths with 45-60, 0-60, 0-90 and 45-90 degree angles.

2.4.4. Bi-directional

Most of the research into bi-directional flow situations, movement of two groups of pedestrians through a straight corridor in opposite directions, does not agree the influence of bi-directional flow situations on the reduction of the flow rate (Navin et al. (1969) according to Zhang et al. (2012b), Fruin (1971), Lam et al. (2002), Kretz et al. (2006a), Helbing et al. (2005), Zhang et al. (2012b)). Navin et al. (1969) have been one of the first to mention the slight reduction of flow dependent on directional imbalances. Lam et al. (2002) mentions that when the flow ratios are equal, the effect of a bi-directional pedestrian flow is not substantially different from that of a uni-directional pedestrian stream. Helbing et al. (2005) even mentions that counter flows are significantly more efficient than unidirectional flows. Yet, Kretz et al. (2006a) shows a decrease of the flow rate with respect to uni-directional flows, however not to the extent one would expect. This study also shows that pedestrians react to the existence of a bi-directional flow by accepting higher densities and using the available space more efficiently, which explains the diminishing decline of the flow rate.

Besides the overall quantitative differences with respect to the flow rate, several studies also researched the interaction between the flow situation and the two other macroscopic flow variables. Alghadi et al. (2002) mentions that the velocity of directional groups is dependent on the concentration levels of each of the opposing pedestrian streams present. Daamen et al. (2007) discovers a reduction of the free speed due to the interaction with other flows. A recent study by Guo et al. (2012) also indicates that the walking velocity is negatively correlated, not only with the densities of the opposite-direction and the pedestrians moving in a similar direction in their immediate surroundings, but also with the densities of the pedestrians moving along in the same direction ahead of them in their stream.

2.4.5. Intersecting movements

The last strand of empirical research into flow situations relates to intersecting flows. In this study pedestrians are assumed to be intersecting when their average velocity vectors are under an angle between 10 and 170 degrees and the movement of at least one of the pedestrians is influenced by the presence of the other. Of the five attempts to study intersecting movements only three mention quantitative results. Both Wong et al. (2010) and Plaue et al. (2011) present a fundamental diagram. However, except for the negative relation between walking velocity and density, not a lot of similarities exist between the two graphs. Free flow velocity, jam density and the shape of the curve differ. This might be due to the cultural difference between the two studies (Western Europe vs. Asia).

(Asano et al. (2007) according to Asano et al. (2010)) furthermore concludes that the crossing angle of the two flows negatively influences the walking velocity of pedestrians. An intersection with a 90-degree crossing angle, pedestrians tend to avoid collision by waiting (temporal avoidance) rather than changing direction sideways (spatial avoidance). A more elaborate study by Wong et al. (2010) also deduces a negative relation between the intersection angles ranging from 45° to 180° and the walking velocity of pedestrians. The latter also mentions that the walking velocity is asymmetrically affected in case of an unequal flow distribution.

3. Conceptual behavioral model derivation

In the previous section several results concerning the relation between the flow variables and the characteristics of the person, physiologic environment, the interaction and the flow situation were found. Even though the research has been fairly specific and unsystematic, one can combine all the currently known relations into a conceptual model of behavioral hypothesis. Using only the relations found in the literature review, the conceptual model shown in figure 1 can be established.

From this conceptual model it can be derived that empirical research, performed during the last decades, has been focused especially at directly relating characteristics of the pedestrian, the environment, the infrastructure and the flow

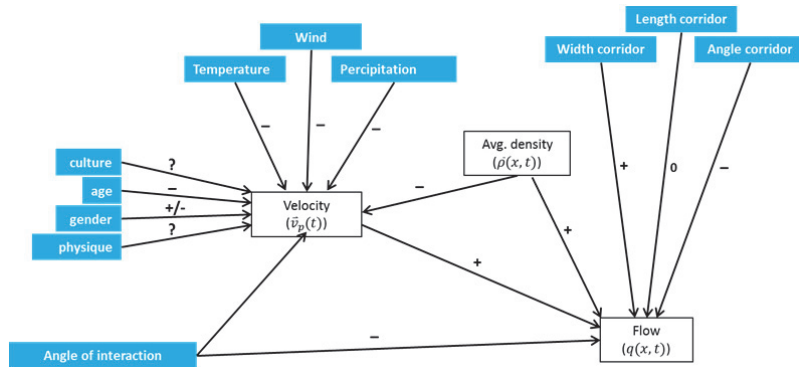


Figure 1: Initial empirical conceptual model of related behavioral hypothesis deduced from the research literature featuring the results from empirical studies into crowd movement dynamics. (+) positive relation, (-) negative relation, (?) undetermined

situation to the macroscopic flow variables walking velocity and flow rate. Velocity is in the initial model interpreted as a microscopic variable while flow rate is interpreted as a macroscopic variable. The direct connection of both microscopic and macroscopic variables within the initial model without an understandable transformation boundary makes it difficult to determine whether (and how) these explained findings are interrelated or whether these findings can also be described by underlying microscopic behavior of the pedestrians that make up the crowd.

The modeling work by among others Helbing et al. (1995), Campanella (2009), Paris (2007) and Moussaid et al. (2011) does suggest that microscopic factors such as distance headway, visibility and several behavioral thresholds also severely influence the movement dynamics of crowd. To the authors knowledge, no empirical proof has yet been produced which details the influence of these factors on the crowds' movement dynamics. Yet, since most well-known pedestrian simulation models employ these factors to specify the microscopic walking behavior of their agents, it is safe to assume that the most influential of these factors might need to be included in the conceptual model in order to allow for the correct prediction of crowd movements.

Due to the discrepancies between the initial empirical conceptual model and the theoretic findings deduced from pedestrian modeling research, the authors have decided to redevelop the initial conceptual framework. Throughout this attempt the fundamental flow variables are used as a first steppingstone. Blocks of interrelated behavioral hypothesis are accordingly added to this steppingstone in such a manner that the behavioral hypotheses found in the research literature are still adhered to. Findings from pedestrian modeling community and some logical reasoning are used to determine the configuration of the new conceptual model.

There has been chosen to specifically include four additional blocks, because the empirical or theoretical research literature contains hints that factors, related to these four blocks, influence the movement dynamics of crowds. Two of the building blocks added to the conceptual model are related to upper and lower bounds on the walking velocity and distance headway. The third block is related to the impact of infrastructure. The last block is related to the impact of interactions between pedestrians.

A more in-depth explanation of the choices for these building blocks and their configuration can be found in the following section. Accordingly the total framework is represented in section 3.6. For mathematical definition of the factors mentioned in the following section, one is referred to section 4.3.

3.1. The first stepping stone of fundamental relations in pedestrian transport

A theoretical framework is used as a first stepping stone in the process of rebuilding the conceptual model of related behavioral hypotheses since it provides a solid foundation for further development the conceptual model. A theoretical framework that is often used in both pedestrian and vehicular traffic is the relation between velocity $\bar{v}(x, t)$, density $\bar{\rho}(x, t)$ and flow $q(x, t)$ at an aggregated level (space mean averages). By means of this framework, two of the three macroscopic flow variables can be related to the two microscopic flow variables velocity and distance headway. As a consequence, the framework allows for a clear cut transition boundary between the macroscopic and microscopic variables. The stepping stone of the new conceptual model can be summarized as follows from figure 2.

As one can see, the authors assume that instead of a direct relation between the velocity of an individual pedestrian and space mean density, this relation is found in the empirical research literature as a result of the combination of two underlying relations between respectively, the individual velocity and the distance headway, and the distance headway

and the space mean density. Several researchers have, shown that pedestrians adapt their individual walking velocity $\vec{v}_p(t)$ based on the minimum time/distance headway $h_{p,q}(t)$ (Johansson (2009), Paris (2007)).

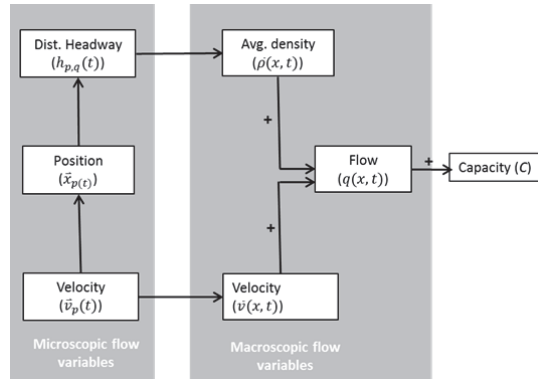


Figure 2. Relations between microscopic and macroscopic flow variables that provide the stepping stone for the new conceptual model of related behavioral hypothesis.

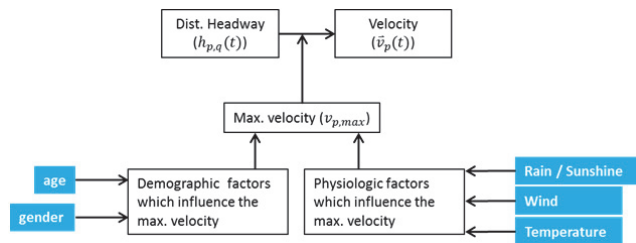


Figure 3. The block of interrelated behavioral hypothesis that provide a boundary on the walking velocity.

3.2. An upper limit on the velocity of pedestrians

In most microscopic pedestrian simulation models the movability of the population within the models is partly managed by means of a velocity threshold, which is often named the free flow velocity. The models incorporate an upper limit on the velocity to prevent agents from adopting physically impossible speeds. Unlike, for instance, the density, the walking velocity of a pedestrian is not regulated naturally. Therefore, an upper limit on the velocity needs to be included in the conceptual model. In the review of empirical studies, it was found that several demographic and physiologic factors influence the walking velocity of pedestrians.

It can be logically assumed that many of these factors (e.g. age, gender, temperature) limit the physical capabilities of pedestrians. This lets the authors to assume that several demographic and physiological factors do not directly influence the adopted velocity, but do instead influence the free flow walking velocity of a pedestrian. Figure 3 presents a visualization of the proposed adaptation of the configuration of the related behavioral hypotheses mentioned in this paragraph.

3.3. Intervening factors in headway-velocity relation

Besides a threshold on the maximum adopted velocity, the authors assume that there are also factors which serve as a similar threshold on the distance headway. The lower limit on the distance headway is naturally determined the minimum distance between centers of individuals when they are in physical contact with each other, and as such the body circumference (physique) of the pedestrians. Besides a lower limit induced by physical properties, many microscopic simulation models also employ a threshold which governs the strength of the influence of the interactions on the current velocity depending on the current distance headway with respect to surrounding obstacles and other pedestrians. This social lower bound is often named “minimum preferred distance headway”.

Empirical evidence has shown that the culture of an individual influences the free flow walking velocity of an individual. The authors hypothesize that culture does, however, not influence the walking velocity directly. Instead, the culture of an individual influences the distance headway that individual minimally prefers. Even though no research is

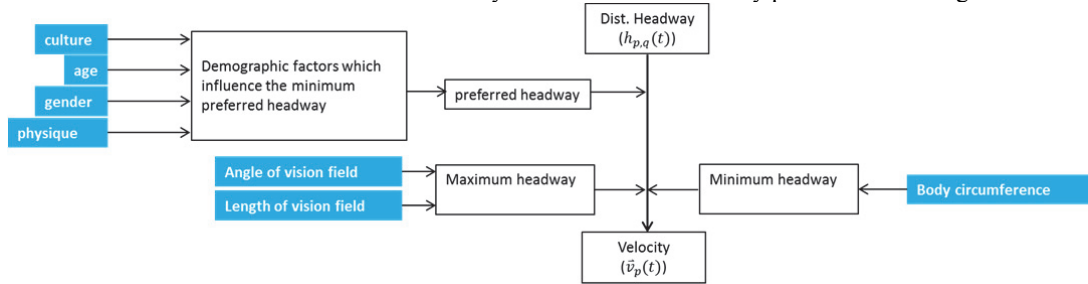


Figure 4. The block of interrelated behavioral hypothesis which provide a boundary on the minimum distance headway

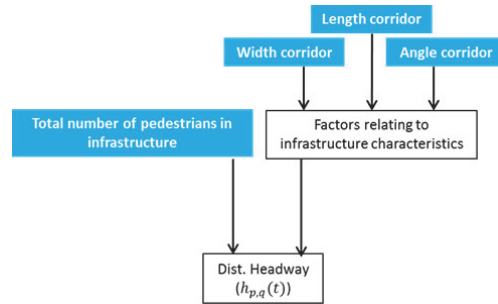


Figure 5. The block of interrelated behavioral hypothesis describing the influence of the infrastructure.

available with respect to other demographic factors of individuals on the flow variables, it is expected that several demographic factors also influence the walking velocity through the minimum preferred distance headway.

Additionally, logically speaking besides a preferred minimum headway, there must also be a maximum distance headway at which pedestrians are not influenced by other pedestrians anymore. A distance headway at which there is no interaction between pedestrians anymore. In most simulation models this threshold is often enforced through the region of influence or radius of the vision field. The maximum length and angle with respect to the current movement direction of a pedestrian’s vision field can be mentioned as possible explanatory factors behind the possible existence of a maximum headway. The block of interrelated behavioral hypotheses which are mentioned in the preceding paragraphs are presented in figure 4.

3.4. Influence of infrastructure characteristics on headway

The literature mentions relations between the length, width and angle of the corridor, and the flow rate within the corridor. These findings lead the authors to assume that the movements of individuals are partly governed by the geometry of the infrastructure in which they reside. In order to assure that all behavioral hypotheses are included in the conceptual model, the influence of the characteristics of the infrastructure is one of the blocks added. In the research literature the properties of the infrastructure were directly related to the flow rate within the infrastructure.

The authors do, however, suggest, that microscopic interactions between individual cause this causal relation between the characteristics of the infrastructure and the macroscopic flow variable. For instance, if the width or length of the infrastructure changes, also the space available for a pedestrian’s movements changes. As a consequence, also the average space available for the movements of a pedestrian changes, and therefore the distance headway between pedestrians. Bends in corridors are also known to decrease the overall space available space for pedestrian movement due to risk avoidance (Dias et al. (2012), Steffen et al. (2009)). As such, it can be extrapolated that adaptations of the characteristics of the infrastructure lead to an adaptation of the distance headways retained between individuals. The configuration of this block of related behavioral hypotheses is visualized in figure 5.

As one can see, only a few characteristics of the infrastructure are mentioned. It is assumed that other characteristics, such as level differences or variability of the substratum, will also need to be added to the conceptual framework.

However, since no papers were found in the research literature which detail their influence, for now they have been left out.

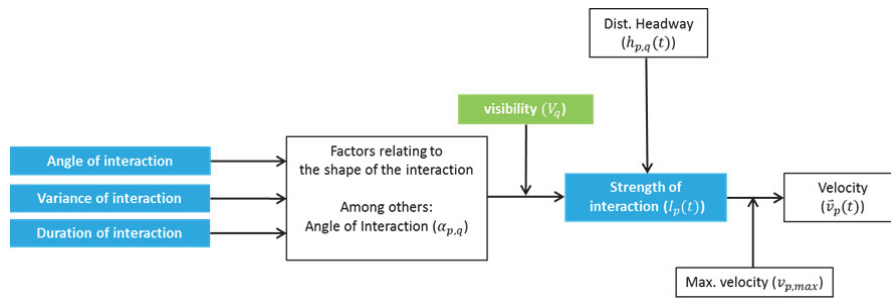


Figure 6. Relation between characteristics of a flow element and the walking velocity of an individual.

3.5. Influence of interaction on walking velocity of individual

The literature review mentions that the angle at which flows intersect is negatively correlated with flow rate within the infrastructure. In order to assure that all of the found behavioral hypotheses are included in the conceptual model, also the influence of the interaction between individuals is one of the blocks added to the first stepping stone of the conceptual framework. Also in the first configuration of the conceptual model, the angle of interaction is directly related to a macroscopic flow variable.

The authors do, however, assume that at a microscopic level a similar relation exists between the shape of the interaction between pedestrians and the walking velocity. The work by Paris (2007) and Moussaid et al. (2011) indicates that taking the interactions between the individuals within the vision field into account is imperative to realistically model the movement dynamics. Therefore, also the characteristics which detail the interaction between pedestrians are added to the conceptual model.

If one assumes that a pedestrian adopts a walking velocity based on the shape and intensity of the surrounding interactions, the interaction variables are logically placed in between the distance headway (input of the decision process) and the velocity (output). Several properties of an interaction can be logically derived, being the distance between two individuals (distance headway), the angle under which pedestrians perceive each other, the angle under which they approach each other and the duration of an interaction.

Combining the relations found in the research literature with the logically deduced factors, the configuration depicted in figure 6 arises. As one can see the variable “Strength of interaction” is added to the model. In this variable all properties of the interaction are summed and weighted. The authors assume that the interactions between pedestrians are to some extent additive, but that the extent to which interactions are accounted for in one’s choice behavior depends on the centrality of the interaction with respect to the current movements of the individual. This is in line with the contemporary Social Force (Helbing et al. (1995)) and Vision-based (Paris (2007), Moussaid et al. (2011)) modeling approaches. In section 4.3.7 the strength of interaction will be detailed.

3.6. Conceptual model

When one combines the theoretical framework presented in section 3.1 with the initial conceptual model and the four building blocks of interrelated hypotheses, a more comprehensive conceptual model of related behavioral hypotheses takes shape. This conceptual model is presented in figure 7. In the visualization of the conceptual model the signs of all relations, which were depicted in figure 9, have been omitted, because the complex interplay of the behavioral hypotheses in the new conceptual model does not allow for a correct representation of these findings. These earlier findings have, however, been used to determine the logic behind the conceptual model.

Each of the variables in the new configuration of the conceptual model is either related to a cause (i.e. the demographic, physiologic, and infrastructure characteristics) or an effect (i.e. the microscopic and macroscopic flow variables). When taking the new additions into account, at the heart of the conceptual model a cyclic relation arises between the microscopic walking velocity, the distance headway and the strength of the interaction.

Based on the research literature, the direction of this cyclic relation cannot be determined. However, based on the logical inference that pedestrians have the opportunity to improve their current position through an adaptation their velocity, but have no opportunity to single-handedly alter neither their distance headway nor their interactions with other

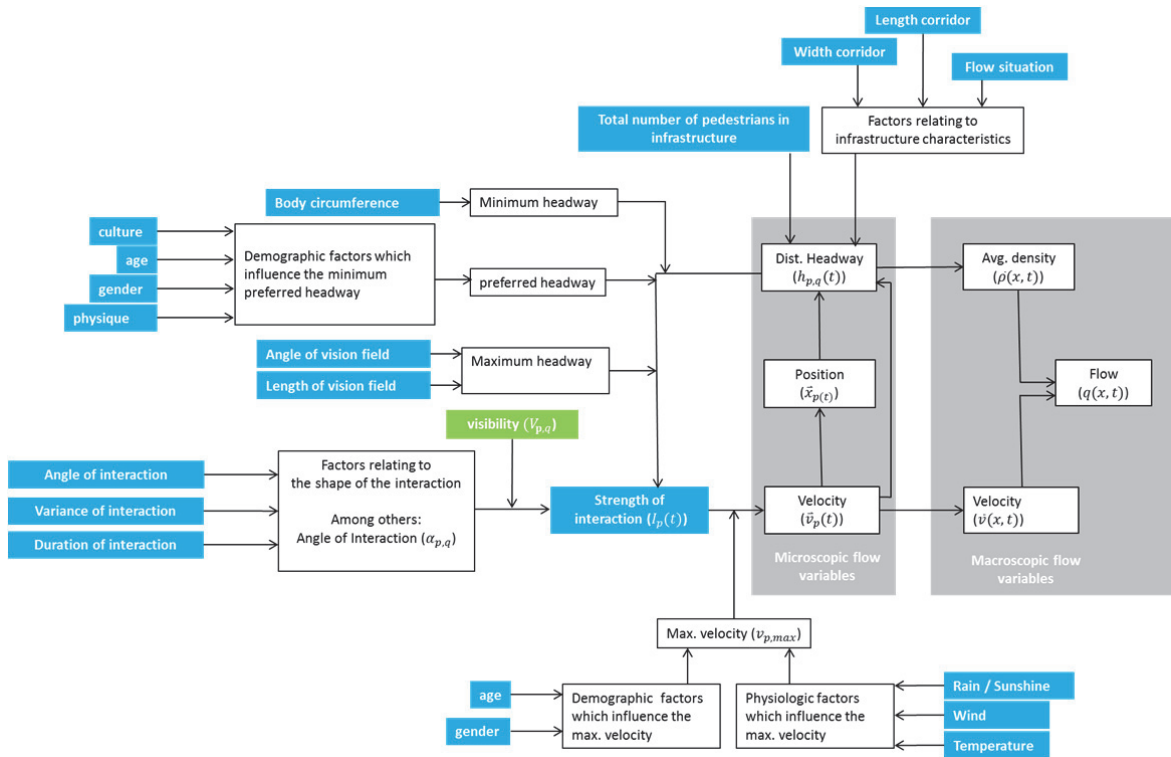


Figure 7: Full conceptual model of related behavioral hypothesis developed using the findings from the literature review, the pedestrian modeling community and logical reasoning.

pedestrians, it is hypothesized that the distance headway (and the interaction) are the cause and the velocity adaptation the effect. As such, the current direction of the depicted cyclic relation is assumed to be counter clockwise.

Due to the assumed direction of the cyclic relation of velocity, headway and interaction, many variables are impacting the walking velocity. Even though the existing literature mainly focused on explaining the adopted walking velocity of pedestrians, the current configuration of the conceptual model is solely produced through the logical linking of causes and effects. That is to say, many factors are hypothesized to influence the physical abilities of pedestrians, hence many factors are assumed to influence the maximum velocity which pedestrians can adopt.

The new conceptual model is made up out of a multitude of variables. Many of which have never been put into context before. In its new configuration, the model's structure allows for the clear separation between variables used to describe the aggregate motion of the crowd (macroscopic flow variables), the variables used to compute the actual movement of pedestrians (i.e. microscopic flow variables), and the variables used to describe the situation in which pedestrians move (i.e. demographic, physiologic, and infrastructure characteristics). As a result, this conceptual model allows for the structured testing of hypothesis related to the motion of pedestrians.

4. Data sets acquisition methodology and definition of quantitative properties

In the previous section a conceptual model of related behavioral hypothesis is proposed based on findings from the empirical research into crowd movement dynamics, insights from the field of pedestrian modeling and assumptions based on logical reasoning. In order to test whether the proposed conceptual model is valid, the configuration of the model is tested using empirical datasets. A short description of all data sets used in this study is provided in section 4.1. The acquisition of videos featuring operational crowd movements and the deduction trajectories from these video sequences is briefly mentioned in section 4.2. Last of all, the mathematical definition of all measures mentioned in the conceptual model is presented in section 4.3. For a description of the hypotheses tested in this study, the methodology of testing and the testing results one is referred to section 4.3.7.

Table 1: Case studies used in this study

Case study	Environment	Location	Date	Time
Marathon Amsterdam	Sports event – walking not the main objective	Museumbrug – Amsterdam	20-10-2013	11:00-17:00
4Daagse	Sports event – walking main objective	Markt – Wijchen	17-07-2013	10:00-14:00
4Daagse	Sports event – walking main objective	Oude groenelaan – Lent	16-07-2013	11:00-16:30
Koningsdag Amsterdam	Music event	Museumbrug – Amsterdam	30-04-2013	10:00-17:00

4.1. Case studies

To study the differences in the operational movement dynamics of pedestrians in distinct settings several case studies are used. The data sets are expected to be generic enough. That is to say, it is assumed that a mixture of all data sets can be used to test the conceptual model. In table 1 the large-scale events and their main characteristics are mentioned. A more detailed description of the situations is provided in the remainder of this section.

4.1.1. Marathon Amsterdam

The TSC Amsterdam Marathon was held in the city of Amsterdam on Sunday October 20th 2013. During the course of one day, 42,600 runners completed a run of 10km, half marathon or a marathon. During this case study, the movements of the visitors on the terrain are studied. In total 214 trajectories, consisting of 13663 data points have been used in this study.

4.1.2. 4Daagse – Wijchen en Hatert

The International Four Days Marches are held in Nijmegen, The Netherlands, every year. During the 97th version of the Marches 42.493 pedestrians started on Tuesday July 16th. All participants walked a march of 30km (youth, elderly, impaired), 40km(adults) or 50km(mainly military and security personnel) every day for four days. Most participants appeared to move unhampered. During the four days Delft University of Technology has recorded the uni-directional movement behavior of the participants at several places along the routes. In this study two sequences are used, being the uni-directional movements of pedestrians along a straight corridor (Wijchen – 312 trajectories, 217777 data points), and their uni-directional movements while moving around a corner (Hatert – 255 trajectories, 20993 data points).

4.1.3. Koningsdag – Amsterdam

On the 27th of April 2013 during Coronation Day, 700,000 visitors assembled in the city center of Amsterdam to take part in the festivities. During the entire day, the pedestrian movements were studied at the Museumbrug. On the bridge a bi-directional flow of pedestrian arose from and to the Museumplein (232 trajectories – 10581 data points). At the intersection behind the bridge crossing movements were seen (214 trajectories – 13663 data points). Many pedestrians walked around in small groups.

4.2. Video recording

The movements of the pedestrians have been monitored using a Multi-camera Stand Alone Video Installation (McSAVI). These installations are designed to record videos during large-scale pedestrian events within or near moving crowds. Due to its limited size, a McSAVI does not provide any hindrance to the movement of pedestrians, nor does it influence flow dynamics. The distraction due to the presence of the installations is limited, since most pedestrian appear to be completely unaware of being studied. The video installation recorded from a height of 8-10 m with a birds-eye view with a recording speed of 8-10 frames per second.

By means of the software MODT-2 the trajectories have been recovered from the video sequence semi-automatically using a combination of manual detection and automated tracking (see Duives et al. (2012) for more details). The tracking is done by means of a simple velocity predictive Kalman filter and histogram-based object tracking. Detection rates up to 100% can be reached with MODT through the combination of manual detection and automated tracking procedures. The parameters and algorithm of the software program ImageTracker (Knoppers et al. (2012)) are used orthorectify the trajectories. The software corrects for lens distortion, searches for the transformations necessary to match sequential images.

The world trajectories can potentially still be unstable (i.e. the trajectory can still float slightly within one person). Swaying of stationary pedestrians adds to this instability. Therefore, a filter has been applied in order to slightly smooth the trajectories. A locally weighted linear regression method is used to smooth the trajectory data. The regression weight is quadratic polynomial and chosen in a way that the algorithm is resistant to sudden outliers. The smoothing procedure is potentially capable of also removing the naturally present randomness of human movement within the trajectories (both swaying and sudden increases/decreases in velocity). However, since the span of the algorithm is small (max. 10% of the data of a single trajectory), only the large outliers are smoothed.

4.3. Definition of quantitative variables within conceptual model

The conceptual model mentions several variables for which no or only a vague definition has been established in the field of pedestrian modeling. In the following paragraphs for these variables a mathematical description is given. First, a mathematical definition for the flow variables velocity, density and distance headway is provided. Accordingly new definitions are provided for the angle of interaction, duration of interaction, and strength of interaction.

4.3.1. Microscopic velocity

During this study the microscopic walking velocity is computed as follows:

$$v_p(t) = \frac{x_p(t_2) - x_p(t_1)}{t_2 - t_1} \quad (1)$$

where $x_p(t_1)$ is the location of pedestrian p at time t_1 . Due to the tracking procedure (tracking heads) and the used definition of walking velocity, the movements of the upper body are taken into account in the velocity computation.

4.3.2. Local density

In this study the authors want to account for the local variability within the flow situation in the density. Therefore, there has been chosen to compute the density by means of an adapted version of the ‘X-T method’ as defined by Edie (1963):

$$x_p(t) \in X_c \Rightarrow k(x_p, t) = k(c, t) \quad (2)$$

$$k(c, t) = \frac{\sum q(t_{q,end} - t_{q,begin})}{A_c * T} \quad (3)$$

Where:

$$t_{q,end} = \min(t + 1/2 t_{limit}, t_{q,leaving cell}) \quad (4)$$

$$t_{q,begin} = \max(t - 1/2 t_{limit}, t_{q,entering cell}) \quad (5)$$

$$t - 1/2 t_{limit} < t_{q,entering cell} < t_{q,leaving cell} < t + 1/2 t_{limit} \quad (6)$$

Where $t_{q,begin}$ is the moment that pedestrian q enters the time-space box c , $t_{q,end}$ the moment that pedestrian q exits time-space box c . For any pedestrian p the local density is determined for the time-space box where the pedestrian forms the middle point.

4.3.3. Distance headway

In this study anisotropic behavior of pedestrians is assumed, therefore a vision field is included in the computation of the distance headway. The minimum distance headway belonging to pedestrian p with respect to all other pedestrians q is

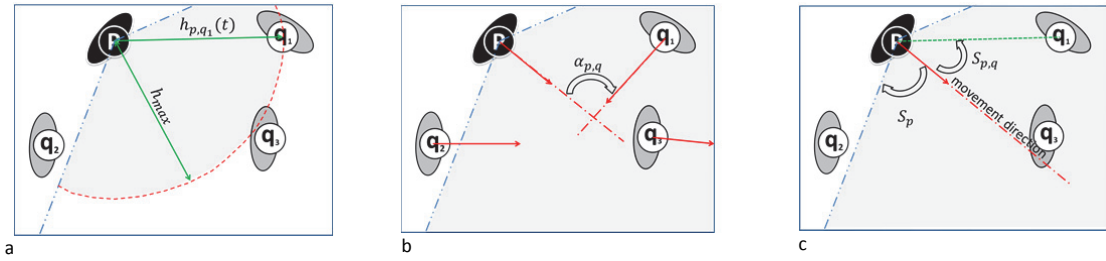


Figure 8: Visual representation of variables quantifying the interaction between pedestrians

defined as follows in this paper:

$$h_{p,q}(t) = \min |x_q(t) - x_p(t)| \quad \forall x_q(t) \in S_p(t) \tag{7}$$

where

$$S_p(t) = \left\{ x \in X: \widehat{v}_p \cdot \left((x) - x_p(t) \right) \geq 0.5 \cap (x) - x_p(t) \leq h_{max} \right\} \tag{8}$$

where \widehat{v}_p is the normalized vector of the walking velocity, $x_q(t)$ the location of pedestrian q , $x_p(t)$ the location of pedestrian p , h_{max} is the maximum interaction distance (see figure 8a), and $S_p(t)$ the vision field of 120° of pedestrian p at time t . In this interpretation, only pedestrians in front of the pedestrian of focus within 60° of the current angle of movement are taken into account in the computation of the minimum headway. The maximum distance headway is set to be $3m$.

4.3.4. Angle of interaction

The interaction between two pedestrians has been defined as the dot-product of the normalized velocity vectors of the two individuals. See eq. 9 and figure 8b for a visual representation of the angle of interaction. The angle of interaction can be interpreted as the angle between the current movement directions of pedestrians p and q .

$$\alpha_{p,q} = \widehat{v}_p \cdot \widehat{v}_q \quad \forall x_q(t) \in S_p \tag{9}$$

4.3.5. Duration of interaction

Besides the angle of interaction, also the duration of the interaction can be quantified. This time aspect of the interaction has been quantified as the total time that a pedestrian q has been residing within the vision field of pedestrian p until the current moment in time. As a result, the history of the interaction between individuals is taken into account.

$$T_{p,q}(t) = \sum_{i=2}^{i_{current}} C_i * (t_i - t_{i-1}) \quad \text{where } C_i = \begin{cases} 1, & x_q(t) \in S_p \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

here i represents the frame number for which the computation is being performed and C_i a binary constant.

4.3.6. Angle of sight

In order to establish whether the angle between the current location of pedestrian q and the current movement direction of pedestrian p are of influence on the walking velocity of pedestrian p , also the angle of sight has been quantified. Figure 8c provides a visualization of the angle under consideration and eq. 11 provides the mathematical description.

$$s_{p,q}(t) = \widehat{v}_p \cdot \left(x_q(t) - x_p(t) \right) \tag{11}$$

Table 2. Hypothesis derived from the framework tested using the data sets mentioned in the methodology by means of linear regression analysis, where ** is significant at the 95% level. Number of data points considered in the regression depends on level of aggregation (Individual - n = 90912, Trajectory – n=1188).

Variable 1	Variable 2	Aggregation	α	Std(α)	β	Std(β)	Sign	t-stat	Sign.
Velocity	Density	Individual	-0.154	0.002	1.349	0.004	-	-75.71	**
Velocity	Distance Headway	Individual	0.338	0.004	0.644	0.006	+	85.10	**
Velocity	Flow	Individual	-0.154	0.002	1.349	0.004	-	-75.70	**
Density	Flow	Individual	0.948	0.01	0.588	0.012	+	94.83	**
Distance headway	Density	Individual	-0.21	0.002	1.690	0.005	-	-86.06	**
Distance Headway	Number of people in infrastructure	Time step	-0.002	0.0005	1.36	0.017	-	-2.97	**
Max. Velocity	Temperature	Sequence	0.048	0.021	0.420	0.45	+	2.20	**
Max. Velocity	Velocity	Trajectory	1.06	0.020	0.267	0.020	+	52.4	**
Velocity	Angle of interaction	Individual	-0.277	0.003	0.712	0.005	+	92.25	**
Velocity	Angle of Sight	Individual	0.293	0.004	0.804	0.005	+	62.89	**
Velocity	Cumulative duration of interaction	Individual	0.112	0.017	0.914	0.031	+	6.296	**
Velocity	Variance of Interaction duration	Trajectory	0.537	0.085	1.136	0.102	+	6.30	**
Velocity	Variance of Interaction angle	Trajectory	-0.454	0.046	1.230	0.023	-	-9.89	**
Velocity	Total interaction	Individual	-0.012	0.000	1.14	0.003	-	-25.66	**

4.3.7. Strength of interaction

In the proposed model all variables relating to the kind of interaction between pedestrians p and q come together in the model in a variable named the ‘Strength of Interaction’. In the remainder of this paper this variable is computed as followed:

$$I_p = \sum_q \left[\frac{1}{h_{p,q}} * (\alpha_{p,q} + 1) * \frac{S_{p,q}(t)}{S_p} * T_{p,q}(t) \right] \quad (12)$$

5. Hypotheses tests

In this paper the testing of the conceptual model is performed based on trajectory data gathered at large-scale events. To the authors’ knowledge, the first time that empirical trajectory data is used to test a conceptual model of related behavioral hypothesis which describes the movement dynamics of pedestrians in a crowd. Comprehensively testing the entire conceptual model is a daunting task that is considered a milestone too far to be considered in this paper. Even though testing by means of multi variate models or factor analysis, while considering the influence of several variables at once, would be preferential, this study starts out by testing the basic configuration of the model by means a straightforward regression analysis of individual pairs of variables.

5.1. Testing the conceptual model

This study starts out by testing the basic configuration of the model by means of a straightforward regression analysis of individual pairs of variables. The authors assume that if all relations between the variables are tested and found to be significant, the proposed configuration of the conceptual model carries some weight. This does, however, not guarantee that the entire conceptual model is correct. Given the fact that no conceptual model was presented before, this study creates a valuable stepping stone for further discussion and research. Within the proposed conceptual model of related behavioral hypothesis several conditional relations are present (among others the headway-interaction relation), which cannot be tested using regression analysis. Therefore, testing the configuration of the conceptual model by means of multi variate models or factor analysis, while considering the influence of several variables at once, would be preferential.

Yet, comprehensively testing the entire conceptual model is a daunting task that is considered a milestone too far to be considered in this paper.

From the final conceptual model of related behavioral hypothesis, presented in operational movement decisions, several behavioral hypotheses can be deduced. The behavioral hypotheses that are tested in this study are mentioned in table 2 and table 3. Every row represents one behavioral hypothesis consisting of the relation between variable 1 and variable 2. As one can see, several of the relations, which are tested in this study, have also been derived in previous studies. The authors have chosen to repeat these hypothesis tests in order to establish the validity of empirical data sets used in this study. Since the results of these specific hypothesis tests are similar, it is assumed that the current data sets are sufficient to test the configuration of the conceptual model.

The unique empirical data sets described in section 4.1 have been used to test all hypotheses. After filtering, 1188 trajectories consisting of over 90 thousand data points (approximately 8-10 fps) have been considered in this study, featuring several distinct flow situations. The data can be provided upon request. In this preliminary study the time correlation of the data points has not been considered.

Linear regression has been used to test the gradient of the estimated relations. The authors do, however, not suggest that all these relations are indeed of a linear nature. Linear regression has only been used to determine the presence and sign of the relation between the variables. A more thorough investigation, considering more different data sets, will be necessary to determine the exact shape of the relationships between the factors mentioned in the conceptual model. In all cases, the relation detailed by eq. 13 is estimated for all hypotheses. Accordingly the hypotheses test detailed in eq. 14 is used to test the significance of the gradient.

$$Y_i = \alpha + \beta x_i \quad (13)$$

$$H_0: \beta = 0, H_1: \beta \neq 0 \quad (14)$$

In table 5 the column “Aggregation” mentions the aggregation level at which the data sets are compared. The comparison can be based on individual data points per time step (Individual), data points per pedestrian averaged per trajectory (Trajectory), data points per time step averaged for the population (Time step), or data points averaged over both time and population per sequence (Sequence). The following columns represent the variables of the regression analysis. The last three columns represent the sign of the found relation, the t-statistic of the hypothesis test of the gradient and the significance level of the test.

The results show that all tested hypotheses are indeed significant. The sign of the tested hypothesis are as expected. When comparing the signs of the tested behavioral hypotheses with relations depicted in the initial conceptual model, the signs of the tested hypotheses agree with the findings in the empirical literature. Furthermore, also the signs of interlinked hypotheses agree. For instance, while the minimum distance headway and the walking velocity are positively correlated, the relations hypothesized to be in-between in the conceptual model (i.e. the minimum distance headway and total interaction, and the total interaction and walking velocity) are both negatively correlated.

There are, however, among the findings two remarkable results. First of which is the fact that all behavioral hypothesis relating to the quantification of the interaction between individual pairs of pedestrians are significant. This provides preliminary proof that the Vision-Based models indeed provide a good description of crowd movement dynamics. A second remarkable finding is that the average walking velocity was found to be positively correlated with the temperature of the environment. It is expected that this anomaly in the results might be due to other correlated factors within the same data sets such as for instance the flow situation or event characteristics.

For all relations expressed in table 3, the sample means have been compared in order to determine whether the samples indeed belong to distinct subpopulations. The following hypothesis test is used to test all behavioral hypothesis mentioned in table 3.

$$H_0: \mu_{pop1} = \mu_{pop2}, H_1: \mu_{pop1} \neq \mu_{pop2} \quad (15)$$

In table 3, every row represents one behavioral hypothesis. The following two columns express the respective means of the subpopulations which are compared. The mean value, the standard deviation and the number of data points belonging to the respective subpopulations are subsequently mentioned. The last two columns express the t-statistic of the hypothesis test and the corresponding significance level.

The table shows that gender is indeed of influence on the movement of pedestrians. The results moreover show that also the flow situation within the infrastructure significantly affects the distance headway adopted by pedestrians. However, also in this case correlations with other factors are expected, such as for instance the goal-orientation and the

Table 3. Hypothesis derived from the framework tested using the data sets mentioned in the methodology a comparison of the mean of the subpopulations. The mentioned abbreviations represent uni-directional straight movements (U-str), uni-directional movements around a corner (U-round), bi-directional movements under a 180 angle (B-str) and randomly intersecting movements (X).

Relation	Pop 1	Pop 2	μ_{pop1}	σ_{pop1}	N_{pop1}	μ_{pop2}	σ_{pop2}	N_{pop2}	t-stat	
Gender – min. distance headway	Female	Male	1.05	0.46	2307	1.39	0.62	8256	-24.39	**
Gender – max. velocity	Female	Male	1.45	0.51	50	1.84	0.56	163	-4.33	**
Gender - velocity	Female	Male	1.23	0.40	2492	1.51	0.39	9006	-31.17	**
Infrastructure – min. distance headway	U-str	U-round	0.92	0.17	4440	1.56	0.37	16769	-112.2	**
Infrastructure – min. distance headway	U-str	B-str	0.92	0.17	4440	0.76	0.3	6265	32.19	**
Infrastructure – min. distance headway	U-str	X	0.92	0.17	4440	0.88	0.6	24030	4.76	**
Infrastructure – min. distance headway	U-round	B-straight	1.56	0.37	16769	0.76	0.3	6265	153.23	**
Infrastructure – min. distance headway	U-round	X	1.56	0.37	16769	0.88	0.6	24030	131.25	**
Infrastructure – min. distance headway	B-str	X	0.76	0.3	6265	0.88	0.6	24030	-14.91	**

distance headway distribution.

5.2. Discussion of the testing results

Based on the hypotheses tests some of the behavioral hypotheses can be confirmed (visualized in operational movement decisions with bold lines). Others could not be tested using the current data sets (relations drawn with slim lines). The figure shows that the basic structure of the conceptual model of related behavioral hypotheses is confirmed by the hypotheses tests.

The microscopic variables distance headway and walking velocity now form the core of the conceptual model. Both variables are influenced by a number of factors which relate to the characteristics of the pedestrian, its physiological environment, the interaction between individual pedestrians and the overall flow situation. The location of the microscopic variables at the heart of the framework shows that the movement decisions of an individual are not necessarily based on only the aggregate features of the crowd movement, but might instead be influenced by the local interactions between individuals

In the deduced conceptual model most of the explanatory factors do not directly relate to the macroscopic flow variables. Instead, most characteristics are known (or hypothesized) to influence intermediate parameters, that in turn are used by pedestrians in their operational movement decision-making process. Due to the indirect effects of the explanatory factors on the relation between distance headway and walking velocity, the proposed model does explain why it is difficult to determine one relation, which is applicable under all circumstances, between the macroscopic flow variables (often related in the fundamental diagram).

Furthermore, the framework shows that, while studying one relation between 2 variables, one will need to account for the some of the other characteristics as well. For instance, one cannot study relations between flow and infrastructure without accounting for several other factors such as for instance the flow situation and the demographic composition of the crowd.

5.3. Validity of the conceptual model

The behavioral hypotheses found in the research literature sometimes leave a lot of room for interpretation. The authors' acknowledge that the proposed model is only one way of interpreting and connecting the found relationships. The configuration of the conceptual model has been developed in a manner that allows all the trends, which were discovered by previous studies, remain valid. As such, a shift in the indicated relations is possible, but is considered not likely. Similarly, the majority of the relations depicted in the current configuration are not expected to change direction, since causes and effects are easily distinguishable. Yet, as already stated, the direction of the relation cycle velocity-headway-interactions is more difficult to determine.

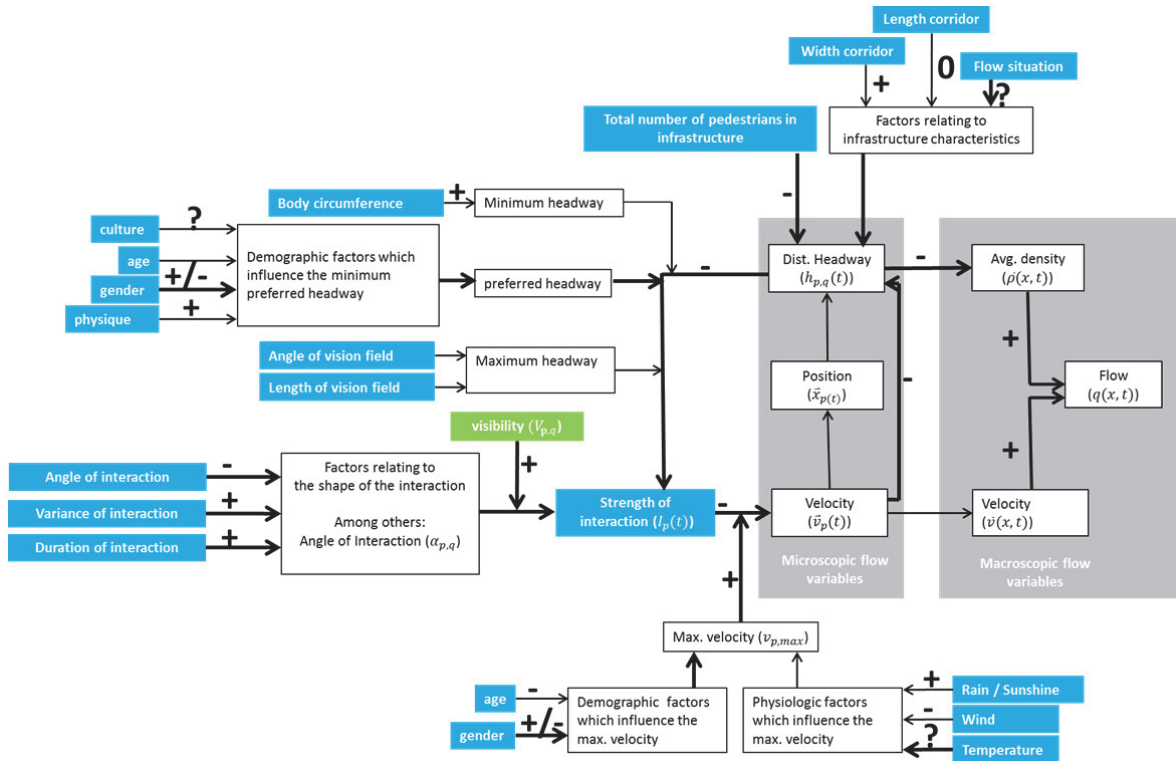


Figure 9: Conceptual behavioral model after hypothesis testing. The bold relations have been tested in this study; the light arrows represent the behavioral hypothesis for which empirical proof was provided in previous studies. The sign represents whether a relation was found to be significantly positive (+), negative (-) or depending on the characteristic (+/-) or undetermined due to either expected correlations or low significance of the results (?).

Within this study the trends in the empirical research literature, which relate several factor within the pedestrian’s environment to the flow variables, have been combined into a conceptual model. The authors do, however, not suggest that the conceptual model is entirely comprehensive. Since the research literature, detailing empirical research into crowd dynamics, has been used as a basis for the conceptual model, the authors might have missed some influential factors that have not yet been mentioned in the research literature. Especially the introduction of new variables might have a far-reaching effect on the predicted crowd movement dynamics described by the proposed conceptual model, since these new variables might introduce new correlations between existing branches of the conceptual model. Self-organization is one of the concepts which might, in the future, link several branches of the proposed framework. Nevertheless, it is expected that by developing the model this way, the most important sources of influence on the movement dynamics of pedestrian crowds have been covered.

Future research will quantitatively prove whether the proposed model is complete and whether the currently untested parts of the structure of the conceptual model are also valid.

6. Conclusion

In this study a conceptual model of related behavioral hypotheses describing the movements of individual pedestrians within a crowd has been developed based on an extensive review of empirical research literature and insights from the pedestrian modeling community. In this model the characteristics of the individual pedestrian, the pedestrian’s physiological environment and the flow situation have been related to the macroscopic flow variables velocity, density and flow. Using pedestrian trajectory data sets gathered during several large-scale events in the Netherlands, the hypotheses underlying the conceptual model have been tested. Several new variables have been introduced which quantify the interactions between individuals within a crowd. The basic structure of the proposed conceptual behavioral model, presented in operational movement decisions, is confirmed by the performed tests.

The current definition of the variables related to this interaction includes the influence of the angle of sight and influence of the angle of interaction. The findings imply that the way in which pedestrians determine the importance of interactions based on the presence and movement direction of others within their vision field plays an important role in the operational movement decisions of pedestrians within a crowd. This has also been suggested by the work of Paris (2007) and Moussaïd et al. (2011) in simulation studies.

All tested behavioral hypotheses were found to be significant. As such, the testing results corroborate the proposed configuration of the conceptual model. Besides the implied decision behavior of individual, the testing results also show that this conceptual behavioral model can be used to link characteristics of the crowd, the environment and the infrastructure to the macroscopic flow variables describing pedestrian movements. When all intermittent relations are understood completely, a pedestrian infrastructure can be assessed based on only these high-level properties substantiated by the insights when to use and when not to use such aggregated rules of thumb.

This study has only tested a part of the behavioral hypothesis in the proposed conceptual model due to limitations in the testing procedure and available data sets. In the future, also the remaining behavioral hypotheses in the conceptual model need to be tested in order to improve the explanatory power of the proposed model. Especially, the relations in the heart of the framework can currently not be established.

In order to create a solid basis for future research and the further development of the conceptual model, an inside-out testing strategy is required. A first step could be to establish the direction of the cyclic relation velocity-headway-interaction. Further testing of the relations at the heart of the conceptual model is an intricate job, which calls for more in-depth specialized studies into specific relations within the conceptual model. That is to say, new specialized data sets will need to be acquired to test the relation between several variables. Also more intricate testing strategies are required to take into account the interdependence between more than two variables. Besides the testing of specific relations within the conceptual model, also the configuration of the entire model should be tested by means of these more sophisticated testing strategies.

Additionally, the authors determined the configuration of the conceptual model based on the findings from contemporary empirical research and added some features based on the results of studies from the pedestrian modeling community. As a result, only characteristics that were already under consideration within the research community have been added. The influence of many other characteristics of pedestrian movement dynamics has been hinted at, but never quantitatively proven. Examples of these characteristics are among others: self-organization, goal-orientation, distraction, tactical choices, stress, and intoxication. Another direction for future research is the addition of additional variables to the model to improve its applicability to all forms of pedestrian crowd movements.

Acknowledgements

The research presented in this paper has been sponsored by the Dutch Foundation of Scientific Research MaGW-NWO. The authors thank the municipality of Amsterdam, the organizing board of the 4Daagse, the organization of the Bevrijdingsfestival Wageningen, and the organization TSC Amsterdam Marathon for their support of this research in word and deed. The authors finally acknowledge E. Scharp, ing. B. Bierenbroodspot, ir. W. Krouwel and ir. N. van Gelder for their assistance in the empirical research.

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