# GROUP FORMATION AND KNOWLEDGE SHARING IN PEDESTRIAN EGRESS SIMULATION

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Abstract: Pedestrian simulation has been a topic of research for several decades, especially in regards to pedestrian egress. Only recently, though, have researchers begun to consider the effects that groups have upon pedestrian egress. Both empirical studies and simulation models predict a decrease in pedestrian speeds when pedestrians travel in groups. In this study, we show that this decrease in speed does not necessarily correspond to an increase in egress time as additional factors such as the amount of knowledge gained through the formation of groups must be considered. The sharing of route costs helps pedestrians maintain proximity to each other and under certain circumstances, pedestrian egress times are actually improved by the formation of groups. We also show that the inclusion of communication costs, sharing knowledge, and group decision-making all have a strong impact on predicted egress times.

## 1 INTRODUCTION

In recent years, accurate pedestrian simulation has become an important research topic (Santos and Aguirre, 2004; Hoogendoorn and Bovy, 2004; Pan, 2006; Helbing and Johansson, 2009). Pedestrian simulation models can be employed in the design of safe facilities, validation of fire codes, and the automatic tracking and surveillance of pedestrians in live video feeds (Antonini et al., 2006). Real-world experiments are too dangerous and too expensive to be a practical way of learning about egress efficiency. For this reason, simulation models have been developed to demonstrate crowd behavior in an emergency. Unfortunately, these systems currently fail to capture many important characteristics of pedestrian behavior such as group formation and information sharing.

In coalition formation theory, a coalition will only form if the utility achieved by the agents in the coalition is greater than the utility each agent could achieve alone (Shehory and Kraus, 1998). This assumption of individual rationality is common for multi-agent systems (Russell and Norvig, 2010). In pedestrian egress, pedestrians frequently move together in groups. From the above assumptions, the utility of pedestrians should be greater by joining a group than if they were to travel as individuals, yet most of the literature indicates that group formation has a negative effect on flow rates, average speed, and egress times (Moussaïd et al., 2010; Qiu and Hu, 2010; Yang et al., 2005; Zhao et al., 2008). From this data, two logical conclusions can be drawn, given that individuals do form coalitions. First, the utility of pedestrians during egress is affected by more factors than just egress time. Such factors may include emotions, altruism, social influences or stress. Several researchers have considered this perspective (Bosse et al., 2011; Hoogendoorn et al., 2010; Kułakowski and Gawroński, 2009; Ozel, 2001). Second, other benefits are gained so that the overall egress time is not always negatively affected. Such benefits may include information sharing or stress reduction. In this paper, we describe a new pedestrian simulation model with special consideration of group formation, group decision-making, and information sharing. We show that these factors can have a significant impact on egress times and, in certain situations, egress time can be improved through the formation of groups.

## 2 RELATED WORK

Several researchers have found negative effects on flow rates, and average speed when group movement is considered. Moussaid et al. conduct empirical studies to determine several group parameters including size, structure formation, and speed (Moussaïd et al., 2010). The average speed is found to decrease with increasing group size. Similarly, Qiu develops a framework for group modeling in (Qiu, 2010) which predicts decreased flow rates for pedestrian groups. Initially, the simulation model predicts an increase in flow rate as group size increases. As group size continues to increase, however, the flow rates decrease. Both Moussaid and Qiu use a similar idea of representing group interactions through the use of a social cohesion force which simulates group members' desire to maintain a close proximity to each other. Neither model, however, addresses the issues of route selection and information sharing in a group setting or the cost of communication.

Ji and Gao consider the effect of multiple leaders with perfect evacuation route knowledge (Qingge and Can, 2007). In their simulation model, they find that including more leaders increases the egress efficiency, in terms of total egress time, up to a certain saturation point, after which including more leaders decreases the egress efficiency (Qingge and Can, 2007). This occurs because, as the number of leaders increase, more pedestrians receive conflicting directions from multiple leaders which in turn hinders their ability to quickly egress from the building. Murakami et al. conduct a similar test using fire drills in a simulated model (Murakami et al., 2002). Leaders can instruct evacuees to either follow them or to take a certain route. In their experiments, the dedicated leaders are known beforehand and given additional information regarding which exits to take. We study the more general case where leaders are not known nor are they given special training prior to the simulation.

Yang and Zhao et al. use a simulation model to measure the effect of grouping upon egress time (Yang et al., 2005; Zhao et al., 2008). They classify grouping as either spatial or directional (Zhao et al., 2008). Spatial grouping relates to individuals' desire to be close physically. Directional grouping relates to the desire of individuals to move in the same direction as others. Their model indicates that spatial grouping is detrimental to egress efficiency. However, directional grouping is found to increase the egress efficiency. This is one of the few papers that show any benefit to grouping. We are interested in showing that even spatial grouping can lead to additional benefits.

Tsai et al. have developed a sophisticated model for simulating pedestrian egress with family groups and authority figures (Tsai et al., 2011). Their model includes pedestrians with imperfect knowledge of the layout, children and parent pedestrians, and trained authority pedestrians. They point out that most previous simulators do not accurately model pedestrian egress because the agents are omniscient and do not suffer from the effects of fear or stress. Their model shows that egress times are significantly impacted when pedestrians have imperfect knowledge, seek to maintain a group formation, and experience the effect of stress or fear. Their model is still unrealistic, however, because they do not include any time penalty for the sharing of knowledge. Additionally, the group model used by Tsai et al. is for families where the children do not participate in the decision-making process.

# 3 OUR MODEL

Our research study is performed using the Pedestrian Leadership and Egress Assistance Simulation Environment (PLEASE), which we developed for this purpose. PLEASE is built upon the multi-agent modeling paradigm where each pedestrian is represented as an individually rational agent capable of perceiving the environment and reacting to it. In PLEASE, pedestrian agents can perceive obstacles, hazards, routes, and other agents. The agents are capable of basic communication to allow for the formation and dissolution of coalitions and the sharing of knowledge. The agents use a two tier navigational module to control their movement within the simulation environment. The high-level tier evaluates available routes and selects a destination goal. The low-level tier, based on the social force model (Helbing and Johansson, 2009), performs basic navigation and collision avoidance. The social force model is selected for the low-level tactical navigation for four main reasons: it is simple to understand and implement, it is widely used in many simulation models, it successfully reproduces many crowd phenomena, and it has been validated using actual pedestrian data (Kretz et al., 2008; Helbing and Johansson, 2009; Moussaïd et al., 2010; Luber et al., 2010). Due to space constraints, we do not go into the details of the social force model here but refer the readers to (Feuz, 2011; Helbing and Johansson, 2009; Moussaïd et al., 2010)

## 3.1 Route Selection

PLEASE uses the concept of decision points to facilitate pedestrian route navigation. A *decision point* is defined as a point in the building at which an agent must decide upon the next location in the route. These points may be placed at arbitrary locations, but typically decision points are placed at doorways and intersections. When exiting from a building, pedestrians navigate from one decision point to another. By only placing decision points at doorways and intersections, the placement of the decision point does not require the pedestrian to pass through an area which they would not normally pass through when navigating from one area of the building to another.

Several different route selection algorithms are implemented in PLEASE. For this paper, we focus on two different route selection algorithms, a local route selection algorithm (Feuz and Allan, 2012a) and a trained route selection algorithm (Feuz and Allan, 2012b) which are explained below. We use these two route selection techniques to compare differences in egress times when pedestrians have different amounts of knowledge about the building. The local route selection algorithm does not require any prior knowledge of the building as it uses only locally observable information. The training algorithm allows pedestrians to know the route costs for decision points with which they are familiar. This knowledge can then potentially be shared with other pedestrians.

#### 3.1.1 Local Route Selection

The local route selection algorithm estimates the cost of exiting via a given decision point based upon several locally observable characteristics of the point. In this paper, we use the distance, corridor width, room signs, and congestion characteristics when estimating costs. These characteristics have been found to work well for a variety of building layouts (Feuz, 2011).

#### 3.1.2 Trained Route Selection

The training algorithm allows agents to experience multiple simulation runs in a building during which time the agents may learn the expected costs to different decision points. This information is stored in the agent's model of the building. More training provides agents with more knowledge about the building, allowing for more effective route planning. In this study, we restrict the learning to distance information. This is done to facilitate the sharing of knowledge between group members by enforcing a common cost metric, as discussed in section 3.4.

### 3.2 Group Formation

PLEASE allows for pedestrians to walk in groups. These groups may be formed to share knowledge, request aid, relieve stress, or interact socially. In PLEASE, groups are more than just individuals moving in the same direction. Being a member of a group implies communication, agreement, and a desire to remain close together. Pedestrian groups may be of a static or dynamic nature.

Similar to (Qiu, 2010; Moussaïd et al., 2010), we represent groups using an additional cohesive force applied between group members. Pedestrians in a group seek to maintain a certain proximity to visible group members. This makes sense because one pedestrian cannot maintain a certain proximity to another pedestrian unless the location of the other pedestrian is known. When turning the corner pedestrians might temporarily lose sight of one another. When this happens, they continue in the same direction and as the other pedestrians also turn the corner they are able to reconnect.

#### 3.2.1 Static Group Formation

Static groups can be formed at the beginning of the pedestrian simulation. These groups represent relationships, which are defined outside of the simulation such as family, friend, or business relationships. Static groups do not change throughout the simulation: new members cannot be added and current members are only removed when they exit the building. Rather than require the user to define each group manually, PLEASE uses user-defined parameters to automatically create groups at the start of the simulation. Empirical studies have found that pedestrian group sizes tend to be small and follow a zero-truncated Poisson distribution (Moussaïd et al., 2010). This distribution can be approximated by adjusting the parameters controlling group formation.

#### 3.2.2 Dynamic Group Formation

Dynamic groups can be formed throughout the simulation. An agent may seek to join or leave a group at any time during the simulation, but joining a group requires the consensus of the group members. Pedestrian agents use utility theory when deciding whether to join a group and whether to accept new group members. The two actions each have separate utility functions. We refer to the utility of joining a group as the agent's individual utility function. We refer to the utility of accepting new group members as the group utility function. PLEASE is built to be extensible, so the exact utility functions used may be easily changed.

In describing the group formation process, we will use the following notation.

- $A$ - The set of agents in the simulation
- $G$ - The set of groups of agents in the simulation.
- $S$ - The set of agents in a group.
- $S_x$ - The group of which agent $x$ is a member.

- $L_s$ - The leader of $S$

Initially $\forall x \in A$, $S_x = \{x\}$ and $L_x = x$. This states that at the start of the simulation, each agent in the simulation is the leader of a group consisting only of the individual agent. The group formation process is divided into four steps, do nothing, request admission, extend invitation, accept/reject invitation. Any agent may request admission into any nearby group. Any agent may accept any received invitation. Only group leaders may extend invitations to other agents. At every time step $t$, $\forall x \in A$, agent x evaluates its utility function and then either does nothing, requests admission or accepts/rejects invitations to nearby groups based upon the expected utility. $\forall S \in G$, $L_s$ evaluates its group utility function and can then choose whether or not to extend invitations based upon the expected utility.

## 3.3 Route Consensus

The PLEASE model allows groups to use three different route consensus mechanisms, which incorporate suggestions from group members to different degrees. The route consensus mechanisms are least-cost route (LC), most-common route (MC), or dictator. The dictator mechanism simply chooses the decision point proposed by the group leader. This method serves as a benchmark to measure the effectiveness of groups. Most other simulators do not consider route consensus for groups and are thus using a dictator-like mechanism (Qiu and Hu, 2010; Tsai et al., 2011).

LC and MC require each pedestrian in the group to submit a preferred decision point and an associated route cost estimate. From the proposed routes, the LC mechanism then selects the route with the least cost (as identified by group members). In order for the LC mechanism to work successfully, group members must use the same scale to measure cost. The group members are assumed to be reliable, that is to say, they report their true perception of route costs and do not lie.

The MC mechanism selects the route which was proposed most frequently. Ties are broken by average route cost. The MC mechanism mitigates the problems inherent in comparing costs computed by various means as it chooses the most commonly proposed route. The group members can have completely different route cost functions and a minority of group members could be unreliable without affecting the route selected by the group. However, this mechanism is unable to take full advantage of the special knowledge which any particular agent may have.

## 3.4 Information Sharing

When using the training route selection algorithm, agents are allowed to share expected route cost information. Current simulation models assume that pedestrian knowledge is not shared among group members. This is a valid assumption for many situations. It represents pedestrian groups choosing an egress route without prior discussion as to which route is the most efficient or effective. However, pedestrian groups might also first discuss the benefits and drawbacks to a particular route before deciding on an egress route. PLEASE allows for either scenario, and in this paper, we consider the effects of both.

In PLEASE, expected route-cost information may either be public or private. If the information is public, then, at the beginning of the simulation, group members may share all the route cost information for each decision point learned during the training runs. Each agent has access to the models of other group members to integrate into its own model. Currently, all model information is treated equally so costs are integrated as an average of the other agents' costs. A more complex model might allow for issues such as trust and reliability to affect the weight that each agent applies to other agents' models while integrating the costs into their own model.

Sharing information requires communication costs. In an actual situation, sharing information may take anywhere from a few seconds to a few minutes. To account for this fact, PLEASE has a sharing cost parameter which is the time, in seconds, an agent spends sharing the route information with other group members. Larger groups will thus require more time to share route information than smaller groups. While route information is being shared, no member of the group moves towards any goal location. If group information is private, then the group members do not share complete route-cost information. Hence there is no associated communication cost.

As the route consensus techniques are combined with different information sharing techniques, understanding exactly what information is shared can be confusing. To help clarify, we state explicitly what information is shared for the various combinations. Using the LC consensus mechanism with public knowledge results in agents sharing all their respective knowledge for each decision point at the beginning of the simulation. As the simulation proceeds, at every decision point, each agent will propose their preferred next decision point and estimate of the total route cost via that decision point. The cheapest proposed decision point will be selected. Using the MC consensus mechanism with public knowledge results in agents sharing all their respective knowledge for each decision point at the beginning of the simulation. As the simulation proceeds, at every decision point, each agent will propose their preferred next decision point and estimate of the total route cost via that decision point. The most commonly proposed decision point will be selected. Because all the information has been shared previously, the only difference between these mechanisms is in the individual perspectives of the agents. One agent might have a clearer view of congestion then another agent, or one route might be closer to one agent but further away for another agent so the best next point varies.

With the LC consensus mechanism and private knowledge, no knowledge is shared between agents at the beginning of the simulation. As the simulation proceeds, at every decision point, each agent will propose their preferred next decision point and estimate of the total route cost via that decision point. The cheapest proposed decision point will be selected. With the MC consensus mechanism and private knowledge, no knowledge is shared between agents at the beginning of the simulation. As the simulation proceeds, at every decision point, each agent will propose their preferred next decision point and estimate of the total route cost via that decision point. The most commonly proposed decision point will be selected. In this case, considerable differences exist between these mechanisms as each agent has unique knowledge.

# 4 EXPERIMENTAL RESULTS

In this research, we consider the effects of static grouping on pedestrian egress times. Various experiments control the route selection algorithm used, the route consensus mechanism, and the knowledge sharing available to pedestrians. Egress times are calculated with 100 agents per simulation. Tests are repeated 20 times to put error bars into acceptable ranges. To quantify differences between the performances of the different mechanisms, we define efficiency as the amount of time taken to evacuate a given percentage of pedestrians. We will use this definition of efficiency throughout our discussion of these experiments.

## 4.1 Static Groups

In the first experiment, we compare the results of static group formation when pedestrians use the heuristic route selection with and without group formation. The group consensus mechanism and knowledge sharing mechanism have little effect on the egress time, because in this test, none of the pedestrians have prior knowledge of the building and they all use the same heuristic function. The purpose of this experiment is to verify that pedestrian groups have a negative impact on egress time and to quantify that impact when no knowledge is shared between pedestrians. As can be seen in Figure 1, forming static pedestrian groups without sharing knowledge has a negative impact on egress times. The average time taken to evacuate 50% of the pedestrians is 29% greater when pedestrians form groups than when no groups are formed. Group formation is 35% less efficient at the 70% mark and 69% less efficient at the 90% mark.

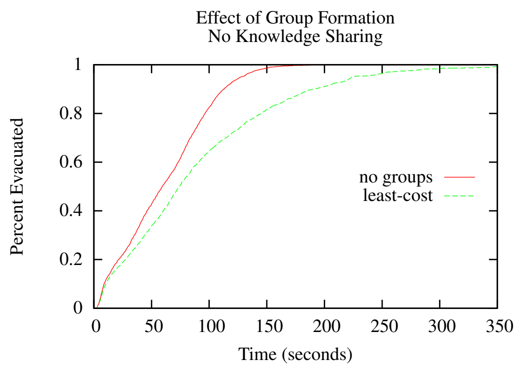


Figure 1: Comparison of static group formation on egress times when pedestrians have no prior knowledge of route costs. Groups use the least-cost route consensus mechanism

In the second experiment, we show that group formation has a negative impact on egress times when pedestrians have individualized knowledge of the building (acquired through training) but do not share that knowledge. To do this we compare the egress times using no groups versus using a dictatorship for pedestrians, which have learned route-distances over the period of 15 training runs. Due to space constraints, the results are not shown here but they are similar to the results shown in Figure 1.

The last experiment for static groups compares the egress times of pedestrian egress when group formation occurs and knowledge sharing is allowed. The route consensus mechanisms are tested pair-wise with the knowledge sharing mechanisms so we have the following combinations: 1) No Groups, 2) Dictator, 3) Least-cost, Private information (cost-prvt), 4) Least-cost, Public Information (cost-pblc, 5) Most-common, Private Information (common-prvt), and 6) Most-common, Public Information (common-pblc). As with the previous test, the pedestrians use the training route selection algorithm and have been trained 15 times in the building. This means that most agents will know one or two exits and several ways to get there. As the cost of communication is likely to vary depending upon the circumstances, we consider two different communication costs, free (0 seconds per agent) and cheap (10 seconds per agent). As will be seen from the experiments, communication costs which are much greater than 10 seconds per agent are no longer effective, so we do not consider them.

Figure 2 compares the resulting egress times when knowledge sharing is free. When group members have their route-cost knowledge public, group formation leads to decreased egress times compared to no groups. Because all the route information is public between group members, the consensus mechanism has little effect on the egress time and only the cost-pblc mechanism is shown in the results. When group members keep their knowledge private, then the consensus mechanism has a greater effect upon egress times. If the group uses the least-cost consensus mechanism, then the egress performance is nearly as good as if the group had route-costs public among them and outperforms the egress time of individuals who do not form groups. If the group uses the most common consensus mechanism, then egress performance is actually worse than not forming groups, as the common consensus mechanism is unable to capitalize on the information that may be had by only a minority of the group members. These results show that when knowledge is shared for free among group members, group formation is transformed from having a negative effect on egress times to having a positive effect on egress times.

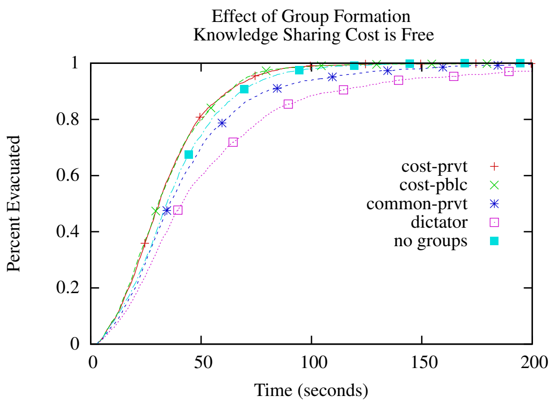


Figure 2: Static group formation and egress times using: 1) No Groups, 2) Dictator, 3) Least-cost, Private information (cost-prvt), 4) Least-cost, Public Information (cost-pblc), and 5) Most-common, Private Information (common-prvt). Sharing is free.

We also consider the case when sharing knowledge is associated with a communication time penalty of 10 seconds per group member (see Figure 3). Under this assumption, having knowledge public among group members is no longer the most efficient solution. However, it can still improve the efficiency of egress as compared to no knowledge sharing. One might expect that a dictatorship would be more effective than taking the time to first share knowledge as this avoids the cost of communication. In the beginning of the simulation, this is true, but as the simulation progresses, the knowledge sharing technique begins to overtake the dictator method in terms of percent of pedestrians evacuated. Sharing knowledge improves the efficiency with which pedestrians exit as compared to the dictator mechanism after the 70% evacuated mark, and it improves efficiency for the last 6% of pedestrians as compared to the common-consensus mechanism without knowledge sharing.

Under the assumption of communication costs, using the least-cost route consensus mechanism with private knowledge (cost-prvt) is the most efficient technique for pedestrian egress. It does not incur the communication costs of publicly sharing all route knowledge but is still able to benefit from the individual knowledge of each pedestrian. In these experiments, cost-prvt is even more efficient than no groups. This is significant because it indicates that group formation does not always have to have a negative effect on egress times. If the knowledge can be used without explicitly being shared, then the whole group can benefit.

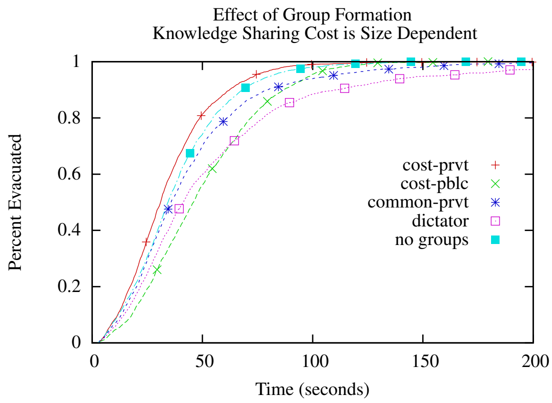


Figure 3: Static group formation and egress times using: 1) No Groups, 2) Dictator, 3) Least-cost, Private information (cost-prvt), 4) Least-cost, Public Information (cost-pblc), and 5) Most-common, Private Information (common-prvt). Sharing costs 10 seconds per group member.

Besides the efficiency of each mechanism, we also consider several other statistics which indicate how well static groups maintain a close proximity (see Table 1). The two most relevant statistics deal with the spatial and temporal proximity maintained by groups while exiting the building. Spatial proximity is calcu-

Table 1: Ranking of route consensus and knowledge sharing mechanisms by spatial proximity

| Rank | Mechanism | Temporal Proximity of Finish Point | Spatial Proximity of Finish Point |
|---|---|---|---|
| 1 | cost-pblc | 7.08 s | 2.33 m |
| 2 | common-pblc | 7.52 s | 2.74 m |
| 3 | cost-prvt | 7.95 s | 5.11 m |
| 4 | common-prvt | 12.04 s | 5.43 m |
| 5 | dicator | 11.95 s | 6.00 m |
| 6 | no group | 26.82 s | 26.63 m |

lated as the average pair-wise distance between the locations at which each group member finishes. Temporal proximity is defined as the amount of time elapsed between the successful egress of the first pedestrian of the group and the successful egress of the last pedestrian of the group. These two measures reflect how well group members maintain a close formation in both time and space.

Table 1 shows the average spatial and temporal proximities for each combination of mechanisms considered. Actively maintaining the group formation leads to closer proximities than no groups. Having knowledge information public among group members further increases the proximities group members are able to maintain because each member has the same knowledge, after the initial sharing has occurred. This helps groups maintain proximity even if they are temporarily split apart. Without the shared knowledge, group members are more likely to become lost after being split apart from the others. This might indicate one reason for sharing route information even with an increased communication cost.

## 4.2 Dynamic Groups

We perform similar experiments with dynamic groups to evaluate the effect of dynamic group formation on pedestrian egress time. The results obtained during these experiments indicate that, like static group formation, dynamic group formation tends to lead to slower egress times. The degree to which egress time is affected is dependent upon the number and size of the groups which form. When only a few small groups form, egress time is not significantly affected. However, as more groups are formed and as group size increases, the negative impact on egress times also increase. When the egress times for the stress and knowledge utility functions are compared, there did not seem to be a significant difference. The factor with the largest impact on egress times is the number and size of groups formed.

It is important to note here that this does not mean it is not beneficial for an individual to join a group as a means of compensating for a lack of knowledge or as a means of relieving stress. Indeed, some individual agents experience improved egress times by joining a group. However, the overall effect on the system is that when too many groups form or the groups become too large congestion ensues and egress times slow down.

# 5 CONCLUSIONS AND FUTURE WORK

Pedestrian simulation is an important area of research with many applications. Until recently, group formation in pedestrian egress has largely been ignored. However, recent work has begun to address the issues that arise with group formation. In this paper, we have implemented a novel dynamic group formation technique which allows pedestrian groups to communicate, share knowledge and reach a consensus regarding route selection. To our knowledge, this is the first such simulation model to address the issues of knowledge sharing with time penalties and group consensus in pedestrian egress. As future work, we suggest that the communication costs for sharing route knowledge be investigated further and that issues of trust and reliability be incorporated into the simulation model.

We have shown that, although recent literature emphasizes the negative impacts group formation can have upon egress times, positive incentives to group formation exist. Our simulation model predicts that sharing knowledge in pedestrian groups can help pedestrian maintain closer temporal and spatial proximity with greater ease as well as improve egress times, compared to group formation without the sharing of knowledge. This is true even when the increased communication costs of sharing knowledge is considered.

Dynamic group formation has impacts on egress times similar to those found with static group formation. Pedestrians can form groups to compensate for a lack of knowledge or as a means to reduce stress, but both reasons have similar impacts on total egress times. The type of consensus mechanism used, the amount of knowledge shared, and the cost of sharing knowledge are all shown to have a significant impact on the overall egress times predicted by the simulation and are therefore important factors to include when designing a realistic pedestrian simulator.

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