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Self-propelled pedestrian dynamics model: Application to passenger movement and infection propagation in airplanes

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HIGHLIGHTS

- Population contacts in air-travel studied using a pedestrian dynamics model.
- Location dependence on self-propelling momentum in social force model is proposed.
- Model parameters validated using parallel computing and comparison with observed data.
- Air-travel policies that reduce contacts and thus curb infection spread are suggested.

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ABSTRACT

Reducing the number of contacts between passengers on an airplane can potentially curb the spread of infectious diseases. In this paper, a social force based pedestrian movement model is formulated and applied to evaluate the movement and contacts among passengers during boarding and deplaning of an airplane. Within the social force modeling framework, we introduce location dependence on the self-propelling momentum of pedestrian particles. The model parameters are varied over a large design space and the results are compared with experimental observations to validate the model. This model is then used to assess the different approaches to minimize passenger contacts during boarding and deplaning of airplanes. We find that smaller aircrafts are effective in reducing the contacts between passengers. Column wise deplaning and random boarding are found to be two strategies that reduced the number of contacts during passenger movement, and can potentially lower the likelihood of infection spread.

1. Introduction

The main factors determining whether or not transmission will successfully take place in directly transmitted diseases are the ability of the agent to survive in the environment and/or the extent of the contact that occurs between infected and susceptible individuals of the host populations and their mobility within these populations. If a location has extremely

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high densities in a local area, it might pose high risks that may facilitate disease spread. That is, if the host and the agent are in close contact, the transmission of disease can be effected rapidly and easily. Thus, making it essential to estimate contacts for understanding disease dynamics. In 2003–2004 SARS outbreak, it was found that transmission rates fell during the epidemic, primarily as a result of reductions in population contact rates and improved hospital infection control [1]. Contact tracing of symptomatic infecteds has been found to be an effective control program because unidentified infecteds are most likely to be diagnosed under reasonable cost on resources [2]. The success of managing contacts and reducing drastically transmission rates have been directly seen in control of many diseases in the past such as smallpox [3], SARS epidemic [4], foot-and-mouth outbreak [5], and recent outbreak of Ebola [6].

Those who report more frequent social contact should be at a higher risk of infection during an epidemic, baring other considerations such as immunity and differences in susceptibility. There are number of large-scale empirical studies that attempt to estimate contact networks in case of sexually transmitted diseases [7]. However, relatively little effort has been devoted to infections spread by respiratory droplets or close contact. Instead, the contact structure for these infections has been assumed to follow a predetermined pattern governed by a small number of parameters that are then estimated using sero-epidemiological data [8] or using small non-representative populations survey [9]. Contact studies are especially relevant in high density and mobility areas such as in airports and airplanes. To address this lack of empirical knowledge, we develop a pedestrian dynamics model in the context of air-travel and robustly analyze the contact patterns.

There is direct evidence for spread of infection during commercial air-travel for many infectious diseases including influenza [10], SARS [11], tuberculosis [12], measles [13], norovirus [14] and malaria [15]. Several factors affect the infection transmission in the high occupancy enclosed environment of aircraft cabin including: cabin air quality, exposure time and flight duration, passenger contact due to inflight movement. Models of infection transmission during air-travel [16–18] often utilize aggregate analysis based on the Wells–Riley equation [19]. These studies address aerosol based transmission but do not account for discrete human interactions. Computationally intensive agent-based models (*e.g.* EpiSimdemics [20]) and stochastic models [21] include human interactions through behavioral rules. Such models are well suited for modeling simple interactions over large populations and geographical areas like entire urban areas [22]. Air travel however involves a high density of pedestrians over relatively small areas. Passengers move during boarding (ingress), deplaning (egress) and within cabin. Passengers otherwise not exposed to contagion may come into contact with contagion when they are in close proximity of infected passengers or contaminated surfaces during the high mobility phases of passenger entry and exit. Modeling the complete pedestrian trajectories and interactions as travelers move through airports and airplanes can help identify policies and procedures that reduce contacts between passengers and thereby reduce the infection spread.

Movement of passengers within an aircraft is a special case of a more general problem of pedestrian movement. This problem has been addressed using several approaches such as particle dynamics or social force models [23,24], models based on cellular automata [25], fluid flow models [26], and queuing based models [27]. Social force models have specific advantages for studying passenger movement and contacts in airplanes. Each passenger is modeled individually and moves continuously; this enables individual trajectory evolution and estimation of the contacts between pedestrians.

Social force models of pedestrian movement are essentially based on molecular dynamics. In molecular dynamics, atoms are treated as Newtonian particles with forces between atoms described by interatomic potentials [28]. Social force models extend this concept to pedestrian movement. Here the forces are a measure of internal motivations of individual pedestrians to move towards their destination in presence of obstructions like other pedestrians and objects (e.g. chairs). Social force models have been applied to crowd simulations situations in panic [23], traffic dynamics [29], evacuation [30] and animal herding [31]. Algorithmic developments have included generation of force fields using visual analysis of crowd flows [32], explicit collision prediction [33], and collision avoidance [34].

One of the difficulties in modeling pedestrian movement is in estimating the parameters to be used in force fields. We address this problem by two approaches. Firstly, we formulate a local position based input to the self-propelling momentum of pedestrian particles. This modification to the equations of motion reduces the dependence on repulsive force-fields. Secondly, we use parallel computing in conjunction with available experimental data and vary the unknown model parameters over a vast design space to assess validated parameter combinations that explain the observed airplane exit data. We then use this pedestrian dynamics model to assess the optimal boarding and deplaning procedures that reduce contacts between individuals and can potentially reduce the infection spread. The simulations are performed on several airplane models and seating configurations with number of seats varying from 50 to 240.

2. Pedestrian movement model formulation

We model the motion of pedestrians using molecular dynamics based social force model [14]. The force $\bar{f}_i$ acting on ith pedestrian (or particle) can be defined as:

$$\bar{f}_i = \frac{m_i}{\tau}\left(\bar{v}_o^i(t) - \bar{v}^i(t)\right) + \sum_{j \neq i} \bar{f}_{ij}(t) \tag{1}$$

where $\bar{v}_o^i(t)$ is the desired velocity of pedestrian and $\bar{v}^i(t)$ is the actual velocity, m_i is the mass and τ is the time constant. The momentum generated by a pedestrian's intention results in a force that is balanced by a repulsion force $\bar{f}_{ij}(t)$. This force term