論文の内容の要旨

論文題目　　Modeling and Analysis on Bottlenecks in Airplanes and Airports towards Achievement of Smoother Pedestrian Flow
（航空機と空港におけるスムーズな歩行者流実現に向けたボトルネックのモデル化と解析）

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In this thesis, we have modeled two major bottlenecks in airplanes and airports, which are exits and queues, by using cellular automata and queueing theory. The models are analyzed by both simulation and theoretical analysis to establish new methods to achieve smoother pedestrian flow. Their validities are also verified by experiments with real pedestrians.

In the first half of the thesis, we focus on pedestrian outflow through an exit. It is one of the most important indexes in evaluating pedestrian and evacuation dynamics. In order to study the outflow in detail, the floor field model, which is a crowd model using cellular automata, is extended by taking account of realistic behavior of pedestrians around an exit. The model is studied by both numerical simulations and cluster analysis to obtain a theoretical expression for the average pedestrian outflow through an exit. It is investigated quantitatively that the effects of exit-door width, wall, and pedestrians' mood (competition or cooperation) significantly influences the pedestrian outflow. The results show that there is appropriate pedestrians' mood to evacuate smoothly according to the width and the position of an exit.

Two important factors which affect the pedestrian outflow at a bottleneck significantly are also studied in detail to analyze the effect of an obstacle setup in front of an exit. One is a conflict at an exit when pedestrians evacuate from a room. In the floor field model, conflicts have been conventionally taken into account by the friction parameter; however, it is so far a constant and does not depend on the number of pedestrians conflicting at the same time. Thus, we have improved the friction parameter by the frictional function, which is a function of the number of pedestrians involved in a conflict. Second, we have presented the cost of turning of pedestrians at an exit. Since pedestrians have inertia, their walking speeds decrease when they turn, and the pedestrian outflow decreases. The validity of the extended model, which includes the frictional function and the turning function, is supported by the comparison of a mean-field theory and real experiments. Moreover, we have observed that the pedestrian outflow increases when we put an obstacle in front of an exit in our real experiments. The analytical results clearly explain the mechanism of the effect of the obstacle, i.e., the obstacle blocks pedestrians moving to the exit and decreases the average number of pedestrians involved in the conflict. Our theoretical results also indicate that an obstacle works more effectively when we shift it from the center since pedestrians can go through an exit with less turning.

In the latter half of the thesis, queueing systems are studied in detail. We have introduced the excluded-volume effect, which is a significant factor to model a pedestrian queue in the real world, into the queueing theory. The model is exactly solved, and the probability distributions of the physical quantities such as number of waiting pedestrians, length of a queue, and waiting time, are obtained in simple form. In the normal queueing theory, the length of a queue is represented by the number of pedestrians; however, due to the excluded-volume effect, the length becomes longer by the interval distance between pedestrians in our new model. Moreover, when the ratio of the arrival probability to the service probability remains constant, the mean length of a queue increases as the two probabilities increase since pedestrians take time to close up a queue. Furthermore, the mean waiting time does not increase monotonically with the increase in service time, and the minimum could be reached instead. We have performed the queueing experiments with real pedestrians and succeeded to observe the phenomena which are expected from our theoretical study.

We have also considered queueing systems with multiple service windows. By introducing the effect of delay in walking from the head of a queue to service windows into the queueing theory, we have obtained the suitable type of queueing system under various conditions. When there are multiple service windows, the normal queueing theory indicates that a fork-type queueing system, which collects people into a single queue, is more efficient than a parallel-type queueing system, i.e., queues for each service windows. However, in our walking-distance introduced queueing model, we have discovered that the parallel-type queueing system is more efficient when sufficiently many people are waiting in a queue, and the ratio of service time to walking time is small. In the fork-type queueing system, a pedestrian at the head of a queue, which is usually set at the end of the system, starts to move when one of the service windows become vacant. Since this walking time from the head of a queue to the windows increases the waiting time, we propose to set the head of a queue at the center of a queueing system and keep one pedestrian waiting at each service window when it is occupied by other pedestrians. The validities of these methods are examined by the theoretical analysis, simulations, and experiments. The situation where there are two kinds of pedestrians, whose service time is short and long, is also studied. It turns out that dynamical transformation of a queueing system decreases the mean waiting time of each pedestrian.

Our studies in this thesis mainly focus on indexes of average values such as the pedestrian outflow and the mean waiting time. Thus, they are in the viewpoint of facility operator who wants to maximize total efficiency of the system; however, for each individual pedestrian, waiting time of him/her is much more important. Hence, further studies are needed to satisfy the demand of all pedestrians.

We would like to emphasize that one of the main characteristics of our study is the firm theoretical analysis. There are many studies on pedestrian dynamics with computer simulations, and a number of successful results have been obtained from them; however, theoretical analysis has two advantages over simulations. First, simple theoretical expressions are easy to apply since we can calculate physical quantities with little time. Second, we can understand the mechanism of models in detail by analyzing the mathematical expressions. Therefore, our study on pedestrian outflow through an exit and queueing systems is useful to analyze egress process from airplanes and many queueing systems in airports, respectively. If smoother pedestrian flow is achieved by proposed methods in this thesis, air-traffic system will become much more efficient in the future.