International Journal of High-Rise Buildings
December 2018, Vol 7, No 4, 409-415
https://doi.org/10.21022/IJHRB.2018.7.4.409

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Implementation of Occupant Density and Walking Pattern Measurement for Emergency Evacuation and Safety in High-Rise Multi-Purpose Facilities

Myung Sik Lee†

Department of Architectural Engineering, The University of Dongguk, Seoul 04623, Korea

Abstract

Recently, many countries around the world began to show interest in safety against terrorism, fire, and natural disasters. This study aimed to propose a quantitative measurement system for emergency evacuation and safety for various kinds of terrorism and fire within high-rise multi-purpose facilities, which can measure the pedestrians' ordinary walking patterns in the concourse with the highest pedestrian volume out of all the spaces within multi-story buildings, predict pedestrians' evacuation walking lines when a sudden disaster breaks out, and analyze the gait coefficient, occupant density, and evacuation behavior time.

Keywords: High-rise multi-purpose facilities, Emergency evacuation, Walking patterns, Occupant density, Gait Measurement, Evacuation behavior time

1. Introduction

1.1. Purpose and Necessity of Research

The world has seen an increase in man-made calamities, including terrorism, in recent years. Terrorist attacks, in particular, have exhibited an acute surge in the forms of chain attacks, suicidal bombings, and mass shootings since the 9·11 incident in 2001. In response, the anxiety regarding public safety and the skepticism concerning whether South Korea is safe from such attacks have been gaining strength.

The global community has long addressed these apprehensions by making commitments against terrorism and human disasters on a national and administrative level. Nonetheless, most of these measures pertained to the installment of defensive infrastructures, which failed to realize fundamental prevention.

For example, the heavy employment of security checkpoints and surveillance cameras in South Korea's leading high-rise buildings may offer some security, but it is unfit to function as a selective screening measure because predicting and categorizing individual human psychological states through appearance alone is an oversimplified ordeal.

Human psychology becomes even more complex and diverse during a disaster. According to a research that analyzed human behavior in fire emergencies, human behavior shows a tendency to follow a reasonable pattern consistent with fire safety regulations. Hence, one may acknowledge the unconscious prevalence of a dominant normal behavioral pattern even in a crisis (Lee, 1997). Collectively, observing pedestrians to assess the familiar path selection (relying on homing instincts) would be an essential parameter in planning evacuation layouts.

This study was conducted to predict the human escape response in light of a sudden evacuation need, such as the occurrence of a terrorist attack or the breaking out of a fire, with emergency ambulation derived from peak gait mobility. This article proposes occupant density measurement for an effective evacuation safety measurement technique as well as an evacuation route prediction.

1.2. Research Scope and Method

As mentioned above, this study selected high-rise multi-purpose facilities as study models as tall buildings and public infrastructures have been observed to be terrorists' favored targets.

The study method was as follows. First, the previous studies regarding escape and evacuation conducted by domestic and overseas researchers were surveyed to differentiate this research from them. Then the target survey site was physically measured. Based on the amassed information, a gait pattern sheet was produced to analyze the gait pattern, occupant density, and ambulatory intensity so that an emergency evacuation ambulatory route and its analytical method in cases of terrorist attacks and fire can be offered.

2. Analysis of Previous Studies

2.1. Research Trends

The following briefly discusses some past researches

†Corresponding author: Myung Sik Lee
Tel: +82-2-2260-3610; Fax: +82-2-2277-5042
E-mail: mslee@dongguk.edu

regarding safe evacautions, for the purpose of reference and study differentiation.

Nam et al. (2016) utilized the motion modeling software Simulex and Pathfinder to compare the evacuation time, evacuating population, and evacuation conditions in college campus buildings.

Jang (2010) employed the 3D simulation software SIMULEX, EXODUS, EXITT, and Building EXODUS to propose an algorithm for escape simulation that accounts for the temperature and smoke.

Hwang and Youn (2011) researched on and analyzed the occupant densities of the juxtaposing establishments of South Korea's leading skyscrapers and ordinary office buildings to suggest a standard occupant density for high-story offices.

Ma et al. (2017) gathered, through data on the simulation pedestrian density and evacuation time that differed according to the width of the exit, that the evacuation time increases with the rise in the pedestrian density. The researcher also concluded that the evacuation time has an inverse relationship with the width of the exit. Hu et al. (2014) created a 3D evacuation model for ambulatory collision to test the relationships among the evacuation time, the width of the exit, and the pedestrian density. Wang et al. (2015) researched on pedestrian dynamics with an escape scenario involving emergency exits and designated group leaders.

2.3. Research Differentiation

The examination of the previous researches revealed a dichotomy between the domestic and overseas study trends. Whereas the domestic research heavily relied on foreign software to conduct 3D simulation or to draw parallel feasibility experiments, the overseas studies mostly employed 2D-based mathematical modeling and analysis. Overall, algorithms were rapidly developed to convey the prediction, but these models merely reflected mechanical orders and did not address in-depth pedestrian patterns or environmental factors.

Practical complications forced these researchers to maintain some estimation as further experimentation may be unviable due to physical and financial restrictions.

3. High-Rise Multi-Use Building's Pedestrian Measurement

3.1. Analysis of the Study Site

This study targeted high-rise multi-use buildings for its research scope. The study site was composed of three low-floor public spheres: eastern and western public infrastructures and a channel leading to traffic facilities (Fig. 1).

3.2. Overview of the Gait Measurement

A filming was administered for an hour (at 17:00) on November 13th, 2016.

(1) Purpose: Pedestrian pattern and density analysis

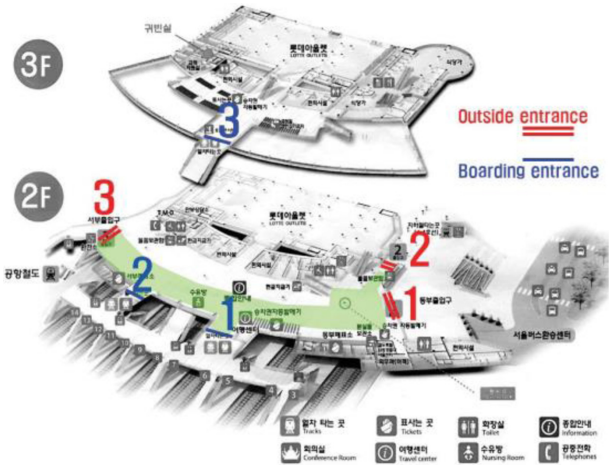


Fig. 1. Status of Each Entrance of the subject Example Building.



Fig. 2. Left (C1), Right (C2) Placement of the Measuring Equipment.

(2) Survey date and time: 17:00~18:00, Sunday of November 13th, 2016

(3) Survey subject: A High-rise multi-use facility's eastern wing concourse walkway of the eastern wing and its low-story infrastructure

(4) Survey method: Filming pedestrians passing by the specific area using a camera.

3.3. Pedestrian Measurement Area

In this study, the gait pattern was measured and analyzed for a secondary analysis within "Eastern Walkway 1 (Fig. 2)," the area with the most activity in the low-floor public facility. To distinguish the area from the rest of the walkway, the connecting void was named "C1" and the walkway itself was named "C2" (Fig. 3-5).

The lower stories of tall buildings are the critical areas that all evacuees pass through. The bottleneck phenomenon is determined by the width of a passage and must be appraised for evacuation evaluation. The C1 zone consists of the left and right passages with locus columns, set as Entrance A and Entrance B, respectively.

4. Measurement Information System

4.1. Zoning of Detailed Survey Zone

The collected video details the basic flow of pedestrian

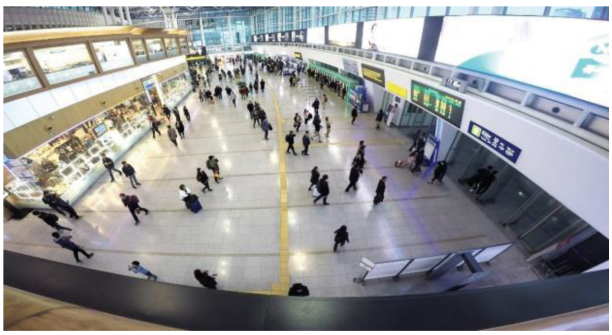


Fig. 3. Field Measurement Range of Example Building.



Fig. 4. C1's Entrance.



Fig. 5. C2's Entrance and Walkway Flow.



Fig. 6. Analysis of C2's Walkway Flow.

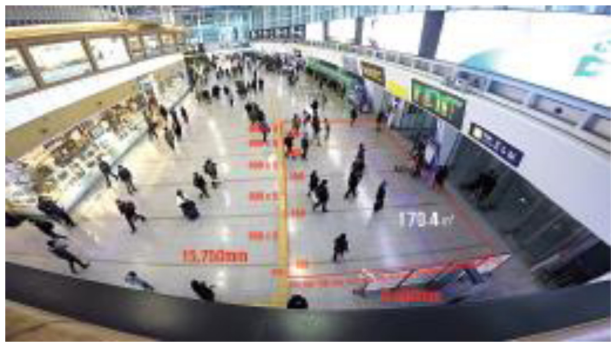


Fig. 7. Setting of the Detailed Investigation Interval of C1.

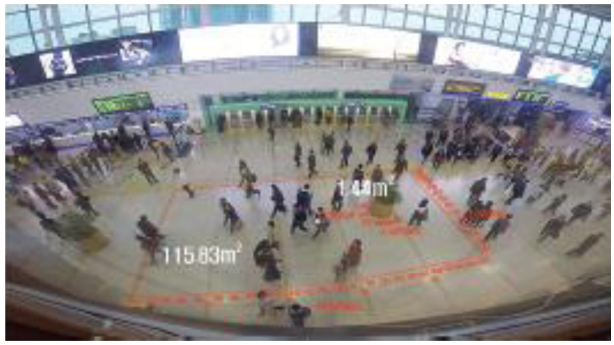


Fig. 8. Setting of the Detailed Investigation Interval of C2.

gaits in survey areas C1 and C2. There are shops in front of C1 and these are surrounded by pedestrians waiting or taking repose.

To examine the safe evacuation gait pattern, the zoning of the detailed survey area was classified as a space from the point of entry to the dispersing of the pedestrian population. The layout was divided vertically in accordance with the perspective of the film recording, and the gait flow came from the left to the right and from the right to the left.

C2 consists of a web of passages that lead away from the lower stories or towards the public facilities. The main pathway vertically divides the space, with the upper half for kiosks and the lower half for shops and the reposing demographic (Fig. 6).

4.2. Area of the Detailed Survey Zone

The floor tile size was inspected in advance to account for the are of the detailed survey zone.

In general, indoor spaces such as the study site study employs standardized tiles which can paly a vital role in comprehending the spatial extent. The 0.3 m × 0.3 m braille block (Ministry of Health and Welfare, 2012) can serve as an ideal measuring device determining the size of the other floor tiles. For its equation Eq. (1).

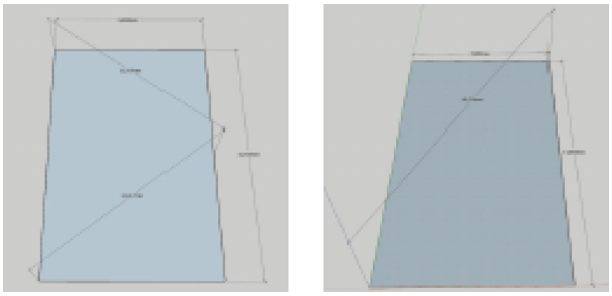


Fig. 9. Left (C1), Right (C2) Measuring Distance.

$$A = Lx \div Ly \quad (1)$$

Where, A: Area (m^2), Lx, Ly: Width, Length (mm)

Thus, C1 was determined to be 9.6 m wide and 15.7 m long, with a total area size of 170.4 m^2 (Fig. 7). C2, on the other hand, was determined to be 14.8 m wide and 7.8 m long, with a total area of 115.83 m^2. C1, however, has a 1.44 m^2 obstacle area. Excluding the compound, C1 was verified to have a 114.39 m^2 total area (Fig. 8).

4.3. Gait Time Settings

According to the average ambulation speed in different age groups, the teenage male group had an average coefficient of 1.3 m/s, and the female group, 1.4 m/s. The males in their 30 s had an average coefficient of 1.49 m/s, and the females, 1.35 m/s. Both the men and women in their 40-50 s showed a speed of 1.41 m/s. The men in their 60 s showed a speed of 1.61 m/s, and the women in their 60 s, 1.32 m/s (Park et al., 2007), respectively. Overall, the average gait speed for the males is 1.45 m/s, and the females, 1.37 m/s. Hence, the average gait speed of the two groups is 1.41 m/s. For the equation, see Eq. (2).

$$N = d \div v \quad (2)$$

Where, N: passage time (sec), v: walking speed (m/sec), d: straight distance (d/m^2)

C1 has a 9.6 m straight-line gait distance and a 12.4 m diagonal distance; C2, on the other hand, has a 14.8 m straight-line gait distance and a 16.7 m diagonal distance. Hence, when either the left or the right edge of the detailed survey section of the filmed image becomes the first departure point, C1 would offer 6.8 seconds for the straight distance and 8.7 seconds or more for the diagonal distance: C2, on the other hand, would offer 10.5 seconds for the straight distance and 11.8 seconds diagonally for a pedestrian to enter and completely deviate from the survey zone (Fig. 9).

In other words, for concise assessment, it would be imperative to adhere to no more than 11 seconds for C1 and 7 seconds for C2 when distinguishing and observing the images of the pedestrians (Oh & Lee, 2013).

The ambulation paths in real life, however, do not consist only of straight lines. Therefore, in this study, the images were captured based on 10 seconds for C1 and 15 seconds for C2. As the diagonal distance of C1 consists of two channels, the walking activity was determined from left and right, with the column as the central divider.

4.4. Analysis Time

This research employs an hour-long pre-recorded footage starting from 17:00. As the peak time for the most activity was confirmed to be five minutes from 17:52:10~17:57:00, this duration was selected for analysis.

4.5. Creating Pedestrian Analysis Sheet

The aim of this research was to come up with a more convenient method of analyzing and measuring the gait pattern and density for safe evacuation. For this, Microsoft Excel was employed.

The design method to acquire an excel sheet that encompasses the same area as the site floor is as follows:

$$=\text{SUM (A1, A14, A27, A40)} \quad (3)$$

The position of the pedestrian was identified while confirming his location by second on the analysis sheet procured from above, and the number "1" was written in the corresponding sheet. The sheets indicating the movement at every second resulted in aggregate seconds, and the aggregate seconds were compiled in a total of 5 aggregate minutes. These five sheets were again analyzed for a 5-minute footage, and three sheets pertaining to seconds and minutes were ultimately created. The gait determinant was verified when the pedestrian's "foot" was filmed.

Through this process, the numbers of pedestrians from C1 and C2 were gathered.

5. Evacuation Analysis for Emergency Evacuation Safety

5.1. Gait Pattern Analysis

The pedestrian analysis sheet created in this study may be visualized in the form of graphs (Fig. 10, 11). These can be used as convenient and expedient quantitative basis for comprehending pedestrian count, usage characteristic, gait pattern and pedestrian coefficient measurement in a given spatial context.

5.2. Analysis of Flow Coefficient

The corridor is divided into the left and right parts, with a column in the middle, where each width stretches 5.4 m long. The 1.5 N person/m·s accepted domestic run-off coefficient was calculated using the data on the occupant density, moving speed, and occupant capacity, for evaluation purposes (Youn et al., 2012). Therefore, it was determined that 8.1 persons/second can access an entrance with a 5.4 m width (see Eq. (4)).

$$P_{per} = W \times 1.5N(\text{person/m}\cdot\text{s}) \quad (4)$$

Where, P_{per}: Flow coefficient, $1.5N$(person/m·s): Run-off coefficient, W: The door wide (m)

In addition, the entry flow populace was assessed to be 321, and the exit outflow totaled 684. The passage time for each outlet was thus estimated at 84.4 persons/second for the exit, and 39.6 persons/second for the entrance (see Eq. (5)).

$$T = P^{A} / P_{per} \quad (5)$$

Where T: person/second (sec), P_{per}: Flow coefficient, P^{A}: Total Passed Person

5.3. Occupant Density Analysis

The flow coefficient was obtained by dividing the total number of personnel analyzed based on the sum of the values divided per seconds into minutes (see Eq. (6)).

$$P_{m/p} = \frac{5_{m/p}}{a_p + b_p + c_p + d_p + e_p} \quad (6)$$

Where $P_{m/p}$: Average flow coefficient (person), a_p~e_p: 1minute (Total number per second) person, $5_{m/p}$: minute (Number of minutes)

It is essential to estimate the number of occupants within a building to determine the evacuation capacity or to design the escape route. The Occupant Load Factor, or OLF was used to estimate the numbers of the general occupants (Seo and Hwang, 2016). The pertaining equation is presented in Eq. (7).

$$P_{OLF} = n_p / A_f \quad (7)$$

Where P_{OLF}: Occupant density (m^2/per), n_p: Number of Occupant (per), A_f: Effective floor area (m^2)

C1: The average number of pedestrians was determined through the measured number of steps in C1. The occupant density for C1 was calculated to be 0.86 m^2/per. The correlating equation is noted in Eq. (8).

$$147.63_{m/p} \div \frac{5_{m/p}}{20.33_p - 34.66_p + 41.83_p + 45.66_p + 25.67_p} \quad (8)$$

C2: The average number of pedestrians was determined through the measured number of steps in C2. The occupant density for C2 was calculated to be 0.79 m^2/per. The correlating equation is noted in (9).

$$91_{m/p} = \frac{5_{m/p}}{19.22_p + 20.75_p + 25.5_p + 28.75_p + 19.5_p} \quad (9)$$

Utilizing the density value, the population flow into lower half of this high-rise infrastructure was determined to be 13 people per second (s). The equation is detailed in Eq. (10).

$$F = S \times D \times W \quad (10)$$

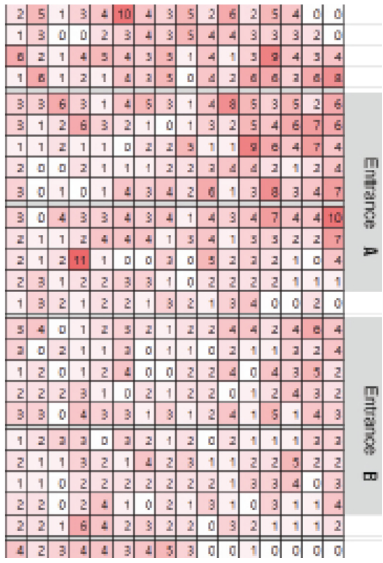


Fig. 10. Analysis of Walking Patterns C1.

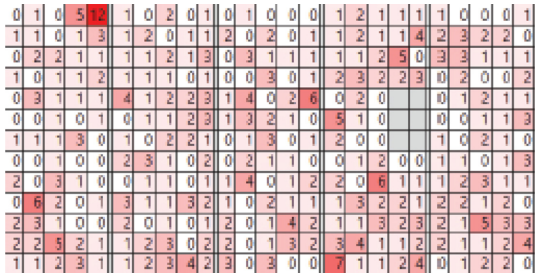


Fig. 11. Analysis of Walking Patterns C2.

Where, F: Population flow, D: population density, S: moving speed, W: Passage width

5.4. Evacuation Time Analysis

Evacuation time analysis refers to a required duration of time needed to make a safe escape from the establishment transiting through the bottleneck section during the time of emergency. The process appears in Eq. (11).

According to the gathered data, the total evacuation time was calculated to be 79.9 seconds.

$$t_s = t_1 + t_2 \quad (11)$$

(1) Evacuation Movement Time: the value of t_1, is expressed as L_x+L_y: the walking distance in x and y axis with 17.9 seconds of duration. The Evacuation Movement Time Equation is introduced in Eq. (12).

$$t_1 = \frac{L_x + L_y}{v} \quad (12)$$

(2) The value of t_2 or the Bottleneck Transit Time is determined by n, the number of evacuees, N, the run-off coefficient where N is (person/n·sec) and W,

the width of the passage in meters. The Bottleneck Transit Time is found to be 62.0 (s). The equation for the Bottleneck Transit is as appears in Eq. (13).

$$t_2 = \frac{n}{N \times W} \tag{13}$$

5.5. Sub-conclusion

The purpose of this research was to predict the human evacuation response in light of a sudden terrorist attack or a fire, and to determine the evacuation route during the peak ambulatory conditions. The prior studies in South Korea and abroad were examined to maintain the unique contribution of this research, then the aggregate coefficients were derived from the target location study. The following conclusions were drawn.

First, for the gait strength, it was verified that the pedestrians exiting from C1 move to disperse towards the eastern end of the study location. The eastern wing of this high-rise building is linked to the transportation hub; this particular passageway would thus have been frequented by the major demographic within the establishment. Therefore, the strong preference for a certain route could be deduced as homing and gathering instincts taking effect even under normal circumstances.

The analysis of the C2 gait pattern revealed that the populace that exited from C1 walked diagonally to disperse, only to regather, rather than to maintain a straight path continuum. Such abnormality was accounted for as an obstacle; as seen from this analysis, obstacles can disrupt the behavioral pattern not just in an emergency but also in the average ambulation. This should be considered an important factor in planning evacuation layouts.

The occupant densities for C1 and C2, respectively, were determined to be 0.8 and 0.7/m^2. The population flow through C1 was evaluated as 12.1 sec. The evacuation time was analyzed by discerning the transit time of the bottleneck section during an emergency and determining the number of evacuees, transit populace, and width of a passageway. Overall, C1 offered 17.9 seconds per gait area, 62 seconds for the bottleneck section, totaling a 79.9-second evacuation time.

6. The Conclusion

The ambulation mobility may be quantitatively described as density, speed, and population flow. When an evacuation situation breaks out, the pedestrians' ambulation is often complicated by physical strain for escape as well as psychological strain, and the individuals may carry out unpredictable and irrational actions or may even panic.

Yet some studies emphasize that an extreme-degree crisis is a rare occasion, and simplifying the actions triggered by survival instincts and other physiological reaction as panic attacks could be a dangerous oversimplification (Park, 2008). Such statement raises inquiries of whether a human evacuation study must be conducted under a psychologically taxing environment.

In this research, the average gait demeanor was considered prime. Normal ambulation was employed as a variable to predict a practical evacuation route and to determine and provide pragmatic and applicable equations through site study.

In South Korea, the dominant research trend was employing 2D or 3D simulation to compare and analyze the outcomes, rather than using equations. It must be noted that there is now no easy way to obtain these software for free. The students used to be offered a free version, but as a recent academic licensed version asks for a US$100 estimate, it appears that the future research may face some financial limitations. As such, it is even more imperative to share the formula for evacuation and evaluation.

The Life Safety Code of the National Fire Protection Association (NFPA) states that "emergency evacuation drills cannot be considered as evacuation routes unless regular evacuation practices are carried out" (Lee, 1997). To revitalize the domestic research, the studies on emergency evacuation safety in light of a terrorist attack and fire must be assessed and analyzed through various ways.

This research aimed to simplify, analyze, and present the gait pattern and quantitative data measurement evaluation method using the Microsoft Excel program derived from the occupant density measurement of the visiting demographic of a high-rise multi-purpose building. While the analogue method may offer a lower error range than the mechanical method, a more precise digital procedure is likely to provide a significant headway. Moreover, as the measurement in this study was done in the confines of the concourse passageway, clear differences from the actual event of a disaster are to be expected. An appropriate experimental method reproduced onsite would be necessary to further study the emergency evacuation safety condition in a large space during a human disaster.

Acknowledgement

This research was supported by a grant (18AUDP-B106327-01) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean Government.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NO.NRF-2017RIE1A1A01074321).

References

Hwang, E. K. and Youn, H. J. (2011) A Basic Survey for the Guideline of the Office Occupant Load. J. Korean Soc. Hazard Mitig., Vol. 11, No. 6, pp. 45-51.

Kiyono, J. and Mori, N. (2004) Simulation of Emergency Evacuation Behavior During a Disaster by Use of Ellptic

Distinct Elements. 13th World Conference on Earthquake Engineering, Paper No. 134, Vancouver, B.C., Canada.

Kachroo, P., Al-nasur, S. J., Wadoo, S. A., and Shende, A. (2008) Pedestrian Dynamics: Feedback Control of Crowd Evacuation. Springer-Veralg, Germany.

Kim, H. Y., Yoo, Y. H., and Rie, D. H. (2017) A Study on the Operation Plan of Evacuation Shelter to Improve Evacuation Performance of Existing Underground Subway Station. J. Korean Soc. Hazard Mitig., Vol. 17, No. 4, pp. 159-164.

Ma, Y., Lee, E. W. M., and Yuen, R. K. K. (2017) Dual Effects of Pedestrian Density on Emergency Evacuation. Physics Letters A, Vol. 381, No. 5, pp. 435-439.

Nam, H. W., Kwak, S. Y., and Jun, C. M. (2016) A Study on Comparison of Improved Floor Field Model and Other Evacuation Models. Journal of the Korea Society for Simulation, Vol. 25, No. 3, pp. 41-51.

Park, S. J., Lee, J. S., Kang, D. S., Jung, E. H., Jun, H. J., and Park, S. B. (2007) A Study on Walking Speed and Stride Length According to Age. Proceedings of Eromonomics Society of Korea 2007 Conference, p. 432.

Son, Y. N., Yoon, S. H., and Yee, J. J. (2009) Basic Study on Analyzing Evacuation Experiment Using Video Analysis Processing. Proceedings of Annual Conference of the Architectural Institute of Korea Planning & Design, Vol. 29, No. 1, pp. 637-640.

Wang, J. H., LI, N., and Zhang, L. (2015) Small Group Behaviors and Their Impacts on Pedestrian Evacuation. 2015 27th Chinese Control and Decision Conference (CCDC), IEEE.

Youn, H. J., Hwang, E. K., and Kim, J. H. (2012) Measurements of Flow-Rate with Korean for Performance Based Egress Safety Design. J. Korean Soc. Hazard Mitig., Vol. 12, No. 2, p. 139.