# Spatial and Temporal Analysis of Pedestrian Egress Behavior and Efficiency[1]

Atsushi Nara
School of Geographical Sciences
Arizona State University
600 E. Orange St. SCOB Rm330
Tempe, AZ 85287–0104
1 – (480) 965 – 7533
atsushi.nara at asu dot edu

Paul M. Torrens
School of Geographical Sciences
Arizona State University
600 E. Orange St. SCOB Rm330
Tempe, AZ 85287–0104
1 – (480) 965 – 7533
torrens at geosimulation dot com

## ABSTRACT
This research reports on exploring analytical methodologies for spatio-temporal data of pedestrian egress dynamics in a crowded environment. The research objective is to spatially and temporally quantify, visualize, and examine pedestrian egress behaviors and efficiency. The data of pedestrian dynamics on four different egress scenarios were collected with the use of Global Positioning System. The data were spatially analyzed with the measurement of tortuosity, which is a property of a movement path being tortuous. Specifically, fractal analysis was employed for quantifying tortuosity of movement paths and answering two specific research questions; 1) how does the structure of egress route affect the egress efficiency; 2) how does the pedestrian mode impact the egress efficiency? In terms of spatio-temporal analysis, the data of each path were visualized as a 3D space-time path, which is an individual trajectory starting from its origin and ending at its destination when using two-dimensional plain to show geographical positions and use perpendicular dimension to represent the time. Providing the 3D visualization of space-time paths helps to qualitatively and quantitatively analyze the spatio-temporal patterns and tendencies for pedestrian egress dynamics.

## 1. INTRODUCTION
Designing pedestrian facilities is not only an art but also requires the efficiency of pedestrian flows, in particular when many people meet at one place, for example, airport terminals, stadia, or theaters [1]. Safety is another important concern for such as planning safe egress routes. During the emergency evacuation, an extreme case of egression, pedestrian crowds have a chance to encounter secondary disasters, the impact of which may cause serious injuries and fatalities. Potential factors are overcrowding and crushing caused by, for example, human stampede behaviors and structural problems of pedestrian facilities. In fact, such pedestrian crowds incidents have been reported numerous times [2]. In order to design effective and safe pedestrian facilities and egress routes, it is important to spatially and temporally understand pedestrian egress behaviors and efficiency.

This study reports on exploring analytical methodologies for spatio-temporal data of pedestrian egress dynamics in a crowded environment. Specifically, fractal analysis and 3D space-time path analysis were employed for answering the question of what are distinct characteristics of pedestrian movements and the egress efficiency in relation to space and time.

## 2. RELATED STUDIES
Designing efficient and safe egress routes is a key factor for pedestrian facilities. In recent years, advancements in geospatial technologies allow us to collect rich and reliable pedestrian movement data with relatively reasonable cost compared to the past. For example, experimental evacuation data can be acquired from devices such as Global Positioning System (GPS), Radio Frequency Identification (RFID), and video recorders. Moreover, real emergency evacuation data can be obtained since urban spaces have become digitally equipped with such data capturing devices. Not many studies, however, have focused on quantitatively analyzing such data. The current demand for pedestrian egress studies is, therefore, to establish useful frameworks of analytical methodologies for spatio-temporal data.

To spatially quantify and analyze the egress efficiency of pedestrian movements on an egress route, we consider tortuosity, a property of path being tortuous or crooked. It is a pure measurement of a path structure, and we assume that the more the pedestrian egression is efficient, the more its movement path should be close to a straight line from the start point to the goal. To estimate tortuosity, we apply fractal analysis, the idea of which has been spread by Mandelbrot [3]. The fractal dimension is non-integer and always greater than the ordinary Euclidean dimension for a given object. The fractal dimension provides a measure of how densely an object fills space or how many parts of an object are observed as measurement resolution becomes finer. In the case of linear feature, the fractal dimension lies between 1 and 2, where 1.0 represents a straight path and 2.0 indicates that a path is so tortuous as to completely fill a plane.

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Calculating the fractal dimension is a useful approach for studying how animal behavioral movements change in their response to their environment with changes in spatial scale [4]. This is because such movements are spatially dependent meaning that behaviors like animals exhibit various spatial patterns in different spatial scales. Fractal analysis has been used in various types of studies of animal movements and habitats, for example, the landscape perceptions of grasshoppers [5], habitat selection at different spatial scales of marten [6], and scale-dependent movements of seabirds [7]. In spite of the advantage of fractal analysis, which potentially reveals various features of movement paths in relation to various spatial scales, there are few studies applying it for pedestrian dynamics. In this research, we use fractal analysis to measure the egress efficiency of pedestrian movements on egress routes for better understandings of pedestrian egress behaviors and efficiency.

In terms of the spatio-temporal aspect, 3D space-time path analysis was applied. It is based on Hagerstrand's time-geographic concept that individual movements over time can be represented by an individual trajectory [8]. The space-time trajectory resides in a 3D space where the X and Y axis represent geographic positions and the Z axis, a perpendicular dimension, represents time. Space-time trajectories provide an event-oriented framework for analyzing individual's activities based on spatial and temporal change with space and time constraints [8]. Moreover, the 3D visualization of space-time trajectory in Geographic Information Systems (GIS) provides an interactive environment for human activity exploration and helps to visualize, quantify, and analyze the geographical patterns and tendencies in relation to time. Thus, providing the 3D visualization of space-time paths helps to qualitatively and quantitatively detect spatio-temporal behaviors and patterns for pedestrian egress dynamics.

The research objective is to examine primary field data of individual pedestrian movements in egression. The data were acquired in the Phoenix Zoo during the ZooLights, which is a light up event during the winter season. In terms of spatial analysis, fractal analysis was employed for quantifying tortuosity of movement paths and answering two specific research questions; 1) how does the structure of egress route affect the egress efficiency; 2) how does the pedestrian mode impact the egress efficiency? In terms of spatio-temporal analysis, the data of each path were visualized as a 3D space-time path and they were qualitatively and qualitatively examined and analyzed. Both analyses are useful for understanding pedestrian behaviors and their relation to space and times. Ultimately, such analyses contribute to the planning of pedestrian facilities in the aspect of designing efficient and safe egress routes.

# 3. METHODOLOGY

## 3.1 Study Area and Data

With a GPS receiver, four qualitatively different individual pedestrian movement paths in egression were acquired in the Phoenix Zoo during the ZooLights event, which opens 45 days in the winter season and more than 250,000 people visits during the period. All data were collected after 6 p.m. on the Saturday night of December 23, 2006, when the pedestrian crowd density was very high. All egress routes started from the furthest point from the main entrance located at the south edge of the main lake and ended at the exit (Figure 1). Starting from 6 p.m., the temporal order of data collection is Path1, Path2, Path3, and Path4.

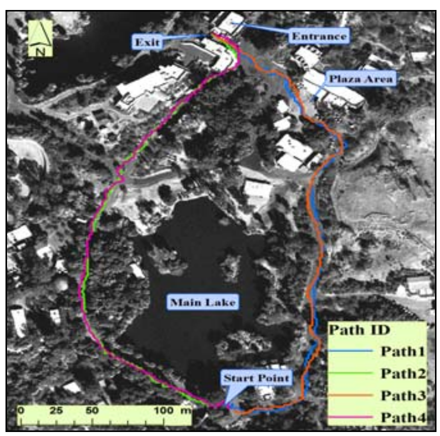


Figure 1. Study Area and Path Data

To acquire data of pedestrian movements in egression, the GPS receiver of GARMIN GPSMAP 60CS, a 12-parallel-channel receiver that continuously tracks and uses up to 12 satellites to compute and update information, was used. To obtain temporally detail data, the update rate was set to 1/second. To increase the accuracy of measurements, Wide Area Augmentation System (WAAS), which is a Federal Aviation Administration funded program for use in precision flight approaches, was enabled. With WAAS, the GPS accuracy on position errors increased from < 15 meters (95% typical) to < 3 meters (95% typical). The data were collected by an individual walking with a normal speed for Path1 and Path2 and with a quick step for Path3 and Path4. Since the main focus was not on the issue of data quality but the exploration of spatio and temporal analytical methodologies, all field data were collected by the author of this paper. To minimize the subjectivity, one premise was made: When the data collector hit the crowd, the observer tries to avoid queuing if there was enough space in a close distance, otherwise queuing.

## 3.2 Fractal Analysis

Fractal analysis was applied to quantitatively examine the tortuosity of pedestrian movement paths during different egress scenarios. A fractal dimension (*D*) is the continuous analogue of discrete geometric dimensions [3]. To estimate the value of *D*, a conventional approach is the dividers method. The basis of the method is to measure the length of the curve by approximating it with a number of straight-line segments, called steps. The calculated length of the curve is the product of the number of steps and the length of the step itself. As the step size is decreased, the straight-line segments can follow the curve more closely, smaller-scale structure becomes more significant, and the calculated length of the curve increases. Plotting the logarithm of the step length versus the logarithm of the corresponding curve length, a Mandelbrot-Richardson plot is obtained. The slope of a line fitted to these points is related to the degree of complexity of the curve being analyzed. The value of the slope is equal to, or less than 0. In the case of a curve, the fractal dimension is estimated by (1 – Slope). This yields one overall estimate for *D* over a range of scales, the value of which lies between 1 and 2.

There are two potential problems with the divider methods [4]. The first is a problem affecting the accuracy. The last divider step rarely falls directly on the end of the path causing underestimate or truncation of the path length. The underestimate would be greater at larger scales, leading to a steeper relationship between the logarithm of the step length versus the logarithm of the corresponding curve length so that *D* is overestimated. The other is a problem affecting precision. As the dividers walk along the path, at some locations they may land right on the middle of the bend of a curve, and at other locations they may bypass over a curve. Whether they land in a curve depends on the starting point. Thus the estimated gross distance is sensitive to the starting point of the dividers increasing potential variation in *D*.

To improve the precision, we applied the *FMean* estimator proposed by Nams [4]. In the *FMean* method, *D* is calculated twice, once going forwards along the path starting at the first point, and once going backwards starting at the last point. When the dividers reach the beginning/end point, but do not reach it exactly, the extra distance is estimated as the straight-line distance between the end of the last divider step and the end/beginning point of the path respectively. Then, the mean of these two *D*-values is calculated for improving precision.

We also applied the *VFractal* approach proposed by Nams [9] in order to statistically test for changes in *D* with various spatial scales. *VFractal* considers a movement path to be a series of turning angles for each scale. For each V formed by turning angle, various statistics are calculated, and then *D* is estimated from the mean of these statistics over the whole path. Equation 1 gives an estimate of *D* for the V formed by one pair of steps.

$$D = \frac{\log(2)}{\log\left(\frac{Net}{s}\right)} = \frac{\theta}{1 + \log_2(\cos\theta + 1)} \qquad \text{(Eq. 1)}$$

where, s is size of one step, *Net* is the net distance from start of one step to the end of the second step, and $\theta$ is the turning angle between the two steps. To estimate *D* for the whole path, Nams [9] proposed four different estimators.

(1) *DMean(V)*: Estimated D for each V, and then find the mean *D* for the whole path.

(2) *Net(V)*: Estimate the mean Net over the whole path, and then estimate overall fractal D by Equation 7, but with using $\overline{Net}$ instead of *Net*.

(3) *Cos*: Estimate the mean cos( $\theta$ ) over the whole path, and then estimate overall D by the equations described as follows.

$$D = \frac{\theta}{1 + \log_2(\overline{\cos\theta} + 1)} \qquad \theta < 90 \qquad \text{(Eq. 2)}$$

$$D = 2 \qquad \theta \geq 90 \qquad \text{(Eq. 3)}$$

(4) *NetCos*: The mean of the estimators of *Net(V)* and *Cos*.

Among four estimators, Nams [9] found that *NetCos* is the most accurate estimator. Unlike the traditional divider method, confidence intervals for *D* with these *VFractal* estimators can be estimated, and thus changes in *D* can be statistically tested.

In this research, fractal dimensions for each pedestrian movement path were calculated with two estimators, *FMean* for estimating fractal dimension of overall path, and *NetCos* for analyzing how fractal dimensions change with various spatial scales.

## 3.3 3D Space-Time Path Analysis and Toolkit

For spatio-temporal analysis of pedestrian egress behaviors and efficiency, we applied 3D space-time path analysis. In order to build Space-Time Paths (STPs) in the GIS environment, we developed the STP toolkit under the ArcGIS 9.x environment using Visual Basic for Applications. Interacting with ArcGIS, tasks involve not only converting raw data of multiple mobile objects into polyline shape files for qualitative representation of spatio-temporal trajectories, but also calculating measurements of STPs for quantitative analysis, which includes length, speed, slope, direction, and straightness index. Providing the 3D visualization of STPs helps to qualitatively and quantitatively analyze spatio-temporal patterns and tendencies for movement data including pedestrian dynamics. For examining the spatio-temporal egress efficiency, we specifically used a measurement of space-time slope, which indicates spatial traveling cost with respect to time.

## 3.4 Egress Scenarios

For answering two specific research questions (Section 2), four egress scenarios were examined corresponding with collected pedestrian movement data in a high crowd density environment. The first (Path1) and second (Path2) scenarios investigate the egress efficiency in a different curve structure of egress routes. In the first scenario, the route structure is crooked. In addition, the route passes through the plaza area, where the highest crowd density was created by amusement facilities, food stalls, and other street objects including trees, signboards, and garbage cans. Comparing with the first route, at a large view, the second route is less crooked and the width is narrower. The third (Path3) and fourth (Path4) scenarios examine the egress efficiency in an urgent mode. In these two scenarios, the speed of pedestrian was increased. The egress route direction in the third scenario is same as in the first scenario, while that in the fourth scenarios is same as in the second scenario.

# 4. RESULTS

## 4.1 Fractal Analysis

The result of *FMean* estimator for Path1, Path2, Path3, and Path4 were 1.04, 1.03, 1.04, and 1.03 respectively. For all scenarios, *FMean* is close to 1 indicating straight movement paths and efficient egressions; however, *FMean* for overall path hide how fractal dimension changes with various spatial scales.

Figure 2 represents fractal dimensions with various spatial scales for each path estimated by the *NetCos* estimator. The result shows that, at large spatial scales, Path1 and Path3 have higher fractal dimensions than Path2 and Path4. This result can be explained by the influence of egress route structure because scenario 1 and 3 both have crooked route structure in large spatial views comparing to scenario 2 and 4. Thus, the response to the first research question is that the egress route with more complex structure is less efficient on pedestrian egress at large spatial scales. In contrast with this result, Path1 and Path2 have higher fractal dimensions than Path3 and Path4 at small spatial scales. Because pedestrian modes in both scenario 3 and 4 are quick speed while those in scenario 1 and 2 are normal speed, the outcome can be interpreted as the impact of pedestrian speed. Thus, for the answer toward the second research question, we can imply that pedestrian with quick speed has more efficient on egress at small spatial scales. This outcome is explained by such pedestrian behaviors that pedestrian with quick speed has smoother steering behaviors to avoid collisions, whereas pedestrian with normal speed can have rough pedestrian behaviors like suddenly changing walking direction and speed.

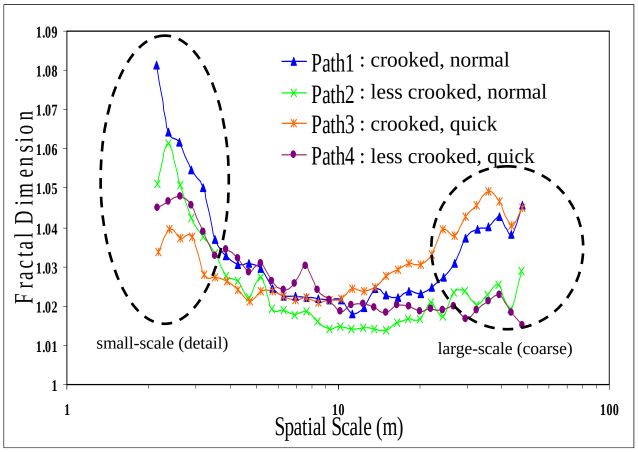


Figure 2. Fractal dimension using *NetCos* estimator

## 4.2 3D Space-Time Path Analysis

3D space-time path analysis provided useful information of pedestrian behaviors and egress efficiency in terms of spatio-temporal aspects. With the STP tool kit, we calculated and visualized space-time slopes for each segment in each path.

Figure 3 represents 3D space-time slopes of four paths, where slopes in higher values reveal the queuing behavior. In our field data, we were able to capture the queuing behavior on Path2 around time 100. Moreover, fragmented red dots on movement paths reveal pedestrian stampede behaviors. The visualization of STPs together with quantitative analysis is significantly effective to find out where and when pedestrian bottlenecked.

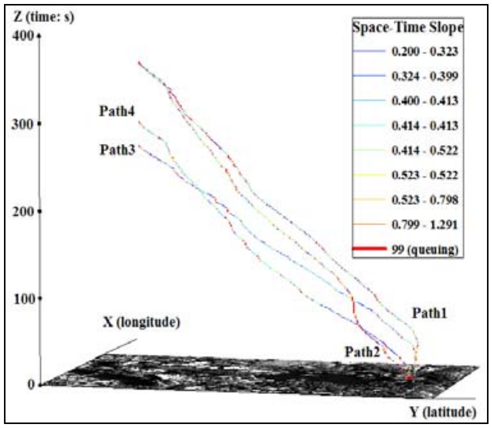


Figure 3. 3D space-time slopes

## 5. CONCLUSION

Our results exhibit practical and useful methodologies for spatial and temporal analysis of pedestrian behaviors and egress efficiency. The significance of this research is to integrate various techniques including GPS, GIS, and spatio-temporal analyses to examine spatio-temporal data of human behavior, which is a somewhat unique case study. Fractal analysis is a strong method to examine spatial behaviors of pedestrian dynamics, especially by looking at their behaviors in different spatial scales; thus, it has a capability to capture various pedestrian behaviors in different spatial scales; however, it only considers a spatial property of pedestrian dynamics despite the fact that such dynamics have a spatio-temporal property. 3D space-time path analysis, on the other hand, inquires spatio-temporal behaviors of pedestrian dynamics. The combination of two analyses enables us to better understandings of pedestrian dynamics in different aspects.

As future directions of this research, first of all, we consider that it is necessary to gather pedestrian data from various groups such as age, gender, body shape, and ethnicity for better explanation and generalization of pedestrian dynamics. Second, because calculating a fractal dimension of tracking data in 2D can only detect the spatial egress efficiency but not spatio-temporal, we need to consider estimating a fractal dimension of those data as a 3D space-time trajectory in order to measure the spatio-temporal efficiency. Lastly, we are planning to add more functionalities into the STP tool kit for enhancing the qualitative and quantitative capability of representing spatio-temporal behaviors and patterns of various moving objects.

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