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Citation (APA)

Huang, R., Wang, T., Xu, H., Xie, Z., Huo, F., Zhao, X., & Yuan, Y. (2025). Experimental Study on Evacuation Behaviour of Passengers in a Confined Seat Area. In G. Zhang, Z. Lin, C. Chen, J. Liu, S. Ou, & Q. Yan (Eds.), *CICTP 2025: Transportation, Artificial Intelligence, and Energy* American Society of Civil Engineers (ASCE).
<https://doi.org/10.1061/9780784486269.121>

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Experimental Study on Evacuation Behaviour of Passengers in a Confined Seat Area

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ABSTRACT

High-speed trains play an increasingly crucial role in mass transportation systems in China. Due to the confined space and high-density crowds in the train seat area, evacuation from trains is a critically risky event during emergencies, but has not yet been fully understood. To fill this gap, well-controlled passenger evacuation experiments in the confined seat area were conducted, based on which microscopic trajectories, evacuation times, flow rates and typical evacuation behaviours were collected and systematically analyzed. The results suggest that the narrow aisle is a significant bottleneck that impedes passenger evacuation. The evacuation time of passengers increases with the number of seat rows. Furthermore, the instantaneous flow rate can be well captured by the Loglogistic distribution. Also, some typical phenomena including overtaking and pushing behaviours are observed and analyzed. The empirical findings of this study are conducive to deepening the understanding of train passengers' evacuation behaviour in the seat area.

Keywords: Train; Passenger evacuation; Evacuation experiment; Evacuation behaviour; Seat area.

INTRODUCTION

In China, trains, especially high-speed trains, are the most widely used mode of passenger transportation, making safety a critical concern. In emergencies, such as fires, the confined seat area presents significant challenges for passenger evacuation behaviour. High crowd densities in these cramped spaces create bottlenecks, increasing the risk of stampedes, crush injuries, and other accidents. This issue is largely attributed to the train's design, which features one narrow aisle and multiple seat rows on each side, creating limited spaces for large populations and resulting in congestion during evacuation (Huang et al., 2018a). Consequently, the confined seat

area within train carriages serves as a typical bottleneck that hinders passenger evacuation. An in-depth investigation of this issue is essential for enhancing passenger evacuation safety.

Existing studies on seat area evacuation have primarily focused on large-scale seat areas in buildings or other facilities. The train seat area, a natural bottleneck that significantly restricts pedestrian flow, has also attracted extensive attention from the academic community. Existing empirical studies have highlighted significant challenges related to evacuating from trains (Huang et al., 2018b), coaches (Huang et al., 2021; Huang et al., 2022), and aircraft (Fang et al., 2016; Fang et al., 2014). Huang et al. (2021) and Huang et al. (2022) quantitatively observed crowd dynamics in seat areas, which primarily focused on the impact of different evacuation conditions. Similarly, while Huang et al. (2018b) identified the seat area as a critical bottleneck, second only to carriage doors, their work lacks a detailed quantitative and qualitative analysis of crowd behaviours. To address this knowledge gap, this study conducted well-controlled experiments examining passenger evacuation in confined seat areas to systematically investigate passenger evacuation behaviour characteristics within train carriages.

This paper provides empirical data sets and behavioural insights to enhance understanding of passenger evacuation in train carriages, particularly in confined seat areas. The main contributions are as follows: First, we for the first time present empirical data sets on passenger evacuation behaviour, collected from three well-controlled experiments, which are available for further research and model validation. Second, through statistical comparisons of five candidate distributions, this paper identifies that the Loglogistic distribution well captures the characteristics of the instantaneous flow sample. Third, the paper explores typical evacuation behaviours and their impact on overall evacuation efficiency. This study uniquely analyzes the data under specified conditions, highlighting important behavioural characteristics not previously discussed.

The remainder of this paper is organized as follows. The first section details the experiment setup, including scenarios, participant characteristics, and experimental procedures. The second section presents an analysis plan of trajectories, evacuation time, flow rate, and typical evacuation behaviours. The third section discusses the results of the study. Finally, the concluding remarks are given in the last section.

EXPERIMENT SETUP

As shown in the introduction, aisle width is an important factors that affect the evacuation behaviours of passengers in the confined seat area of a train. This study was dedicated to investigating evacuation behaviour under the condition of a 0.6-m aisle width, which accords with the train design regulation issued by the International Union of Railways (2004). To this end, a total of three groups of repeated experiments were designed and carried out.

Scenarios

These experiments simulate scenarios occurring during the event of fires. The fire causes the rear carriage door to malfunction. As a result, passengers from the rear carriage (referred to as “aisle participants” hereafter) must merge with passengers from

the front carriage (referred to as “seat participants” hereafter) through the connecting passageway and evacuate simultaneously through the door of the front carriage. The experimental layouts are shown in **Figures 1 and 2**.

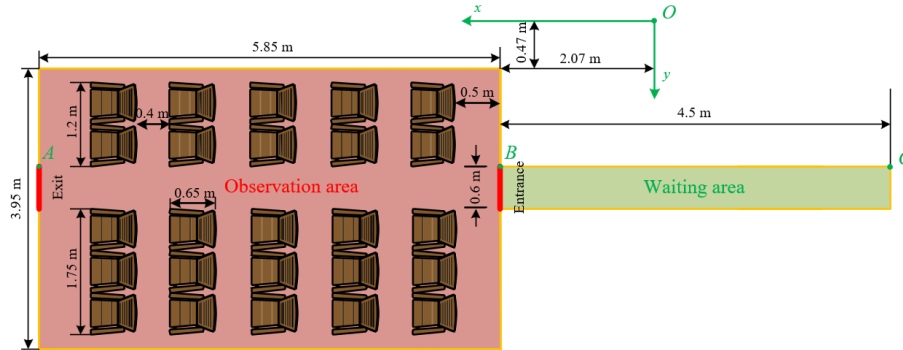


Figure 1. Schematic diagram of the layout of the experiment scenario (top view).



Figure 2. Snapshot of the experiment.

The confined seat area simulates the layout inside a high-speed train carriage in a general condition. The pink rectangle represents the experimental seat area. This paper aims to study the characteristics of seat participants’ evacuation behaviour, so the whole seat area is the main observation area in the experiment (Huang et al., 2018a). Participants are considered to have successfully evacuated once they have completely crossed the line (Huang et al., 2018b). aisle BC behind the seat area is the connecting passageway between two adjacent carriages where aisle participants wait here before the experiment begins. The seat area and aisle BC together form the experimental area, with the boundary enclosed by retractable barriers, shown in **Figures 1 and 2**.

A Dji Osmo Pocket camera (model OT110) was mounted on a building (a height of more than 11 m) next to the experimental site, with a high resolution of 1920×1080 pixels and a frame rate of 25 frames/s. Each participant wore a hat with a white square sticker on it, bearing their own number, to facilitate identification and location tracking from the video. Aisle participants wore red hats, while seat participants wore blue hats. The Tracker software was used to identify the white stickers on the participants’ hats, and their evacuation trajectories were semi-automatically extracted. Moreover, to minimize the influence of randomness, the experiment was repeated three times.

Participants

The experiments were performed at the automobile testing field at Chang 'an University in April, 2024. 45 experimental participants who are physically fit were recruited from the young undergraduate population at the university. They were all divided into two groups: one group consisted of 20 aisle participants standing in the aisle, and the other group consisted of seat participants sitting in the seat area. The aisle group included 10 males (50%) and 10 females (50%), while the seat group involved 13 males (52%) and 12 females (48%). The participants' ages ranged from 17 to 23 years old, with an average age of 19 years. Their heights ranged from 155 cm to 188 cm, with an average of 171 cm.

Experimental Procedures

Before the experiment began, for ethical reasons, participants were informed that they should evacuate as quickly as possible through the door at the front of the carriage (i.e., the exit marked in red on the left, shown in **Figure 1**) in the event of a fire. Aside from this, they were not provided with any detailed information about the experiment setting. Furthermore, In different repeated experiments, each participant in the seat area was randomly assigned to a different position, thus reducing the impact of the learning behaviour (Huang et al., 2021).

Initially, the aisle participants stood and waited in a single file in the connecting passageway (aisle BC) in a random order, while the seat participants sat in the seat area in a specific order according to the instructions of the staff. The aisle participants began evacuating as soon as the countdown started, while the seat participants began evacuating 5 s after the countdown. After the completion of one experiment, the aisle participants returned to aisle BC in random order, while each of the seat participants would be assigned a specific seat by the staff.

DATA PROCESSING AND ANALYSIS PLAN

The data for these experiments were semi-automatically extracted from experimental videos recorded by a camera at the frequency of 25 frames/s (Huang et al., 2021), based on which the evacuation time and flow rate were calculated. In addition, it is worth noting that this paper focuses on studying the evacuation behaviour characteristics of the seat participants, so the remaining sections, when introducing the data extraction methods and analysis, only consider the seat participants.

Trajectories

The pixel coordinates of participants' heads are extracted by a commonly used movement tracking software, i.e., Tracker (<http://physlets.org/tracker/>). Because the recording camera is not perpendicular to the ground, a direct linear transformation method is deployed to accurately convert the pixel coordinates to the real-world coordinates (DeWitt et al., 2000). The results indicate that the maximum error between the measured real-world coordinates and the estimated ones is less than 6 cm, which evidences the accuracy of the used method (Boltes et al., 2013). In this way, the movement trajectories of all participants are obtained.

Evacuation Time

Evacuation time is the most important parameter for assessing evacuation efficiency (Huang et al., 2021) and can be divided into individual evacuation time and total evacuation time. The former refers to the time consumed by each participant from the start of the evacuation to completely leaving the exit, while the latter refers to the total time consumed from the start of evacuation until the last participant completely leaves the exit.

Using the video recorded by the camera and the aforementioned trajectory extraction method, the coordinates of each participant's location in every frame during the experiment will be recorded and imported into a spreadsheet.

Flow Rate

In our experiment, it can be observed that the instantaneous flow rate varies greatly. According to Huang et al. (2021), a probabilistic method comprehensively considering the variations is used. Therefore, a random variable is used to generate the flow distribution of the participants (Cuesta et al., 2017).

In this study, the flow rate is defined as the number of participants who complete the evacuation per unit of time. Correspondingly, the definition of the instantaneous flow rate F_s (per/s) is shown in **Eq. 1**, reflecting the time headway between two consecutive participants leaving the exit.

$$F_s = \frac{f}{\Delta G(i, i-1)} = \frac{1}{\Delta t(i, i-1)} \quad (1.)$$

Where f is also the frame rate (25 frames/s in this study), $\Delta G(i, i-1)$ is the frame difference between the two seat participants consecutively leaving the exit, and $\Delta t(i, i-1)$ is the time difference between the two seat participants consecutively leaving the exit.

Typical Behaviour

In addition to the aforementioned microscopic indicators for studying this evacuation, some typical evacuation behaviours were also observed in this study, including overtaking behaviour, pushing behaviour, and serious congestion, as shown in **Figure 3**. These behaviours would significantly affect the evacuation time and flow rate of the participants, so studying these typical behaviours can help better explain the characteristics of the entire evacuation process.



Figure 3. Examples of typical evacuation behaviour. (a), (b), and (c) are three

snapshots of the experimental videos. In snapshot (a), participant ① is overtaking participant ②. In snapshot (b), ③ is pushing participant ④. In snapshot (c), the serious congestion phenomenon is shown.

RESULTS

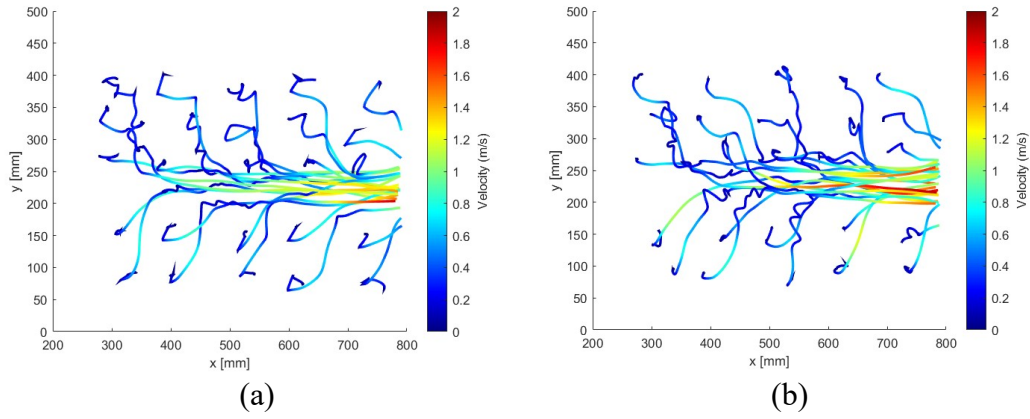
In this section, the trajectory, evacuation time, flow rate and typical behaviour data collected in the previous section will be introduced and analyzed sequentially to illustrate the characteristics of seat participants' evacuation behaviour under the conditions of 0.6-m aisle width.

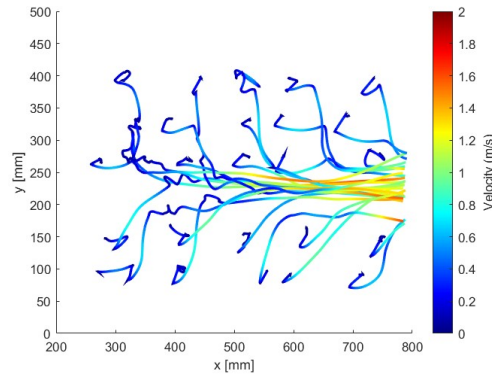
Trajectories

Figure 4 respectively displays the smoothed evacuation trajectories. Additionally, to better describe the movement characteristics of participants, these figures also present the instantaneous velocity. The instantaneous velocity $v_i(t)$ (m/s) is calculated using Eq. 2.

$$v_i(t) = \frac{\sqrt{\left[x_i(t + \Delta t/2) - x_i(t - \Delta t/2) \right]^2 + \left[y_i(t + \Delta t/2) - y_i(t - \Delta t/2) \right]^2}}{\Delta t} \quad (2)$$

Where $x_i(t)$ is the horizontal coordinate of the i -th seat participant at time t , $y_i(t)$ is the vertical coordinate of the i -th seat participant at time t . And Δt represents the time interval, where $\Delta t = 0.4$ s in this paper.





(c)

Figure 4. Evacuation trajectories of participants.

It can be seen that the trajectory shapes from the three repeated experiments are roughly river-like. From the trajectories, evacuation velocities of participants in the upstream part of the process are relatively slow, while in the downstream part, near the exit, participant's velocities are faster. This could be because seat participants in the upstream part merge with the aisle participants in the aisle on a large scale, leading to serious congestion, as shown in **Figure 3** (c). In contrast, the seat participants in the downstream area either already got out of the congestion or were initially in the front rows and were not affected by the congestion.

Interestingly, the trajectories of seat participants in the two columns adjacent to the central aisle on either side exhibit the following phenomenon: the trajectories of participants on the left side of the aisle are closer to the aisle boundary than those on the right side of the aisle, as also shown in **Figure 4**. Through the detailed video observations, this phenomenon should be because that to enter the aisle, participants on the left side typically counterclockwise rotate their body and then move sideways toward the right-hand side, whereas those on the right side do not use the leftward sideways movement manner but moves diagonally. The different entering behaviours could be ascribed to the rather low movement efficiency of the leftward sideways movement (Tan et al., 2024), and thus the right-side passengers adopt another way instead.

Evacuation Time

The cumulative evacuation time curve of three repeated experiments is shown in **Figure 5**. The total evacuation time of each experiment was 17.76 s, 15.52 s and 16.8 s, respectively. Also, to show the trend of evacuation time more intuitively, the average evacuation time is also shown in **Figure 5**.

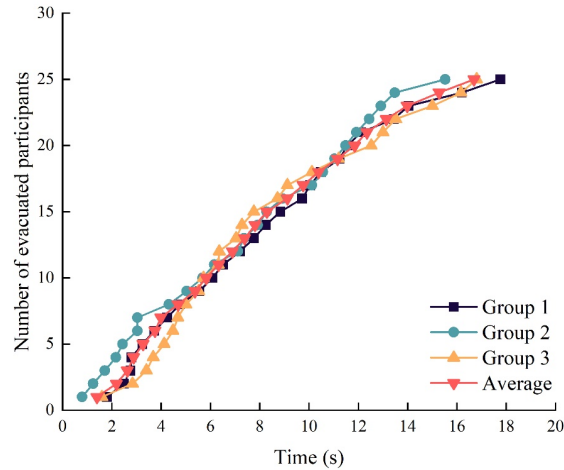


Figure 5. Cumulative evacuation time curves.

It can be seen that the cumulative evacuation time curves of the three experiments exhibit strong nonlinearity and similar shapes, which indicates good consistency of the curves and strong reliability of our experiments. Furthermore, the evacuation behaviour of the seat participant in the train carriage shows distinct phased characteristics, namely reaction, acceleration, fluctuation, and saturation phases (Gu et al., 2016). Therefore, the presence of acceleration and saturation phases leads to the nonlinearity of the cumulative curves (Huang et al., 2022). These four phases not only describe the entire evacuation process of the participants but also reflect the trend of changes in the average cumulative evacuation time curve. In the average cumulative curve of **Figure 5**, no participants have completed the evacuation during the reaction period. Then, the curve has a steep slope, indicating the beginning of the acceleration phase. Subsequently, the curve generally shows a stable upward trend, but there are still some minor fluctuations, which are typical characteristics of the fluctuation phase. Finally, as the curve's slope further decreases, it indicates that most of the participants have completed the evacuation, and the process has entered the final saturation phase.

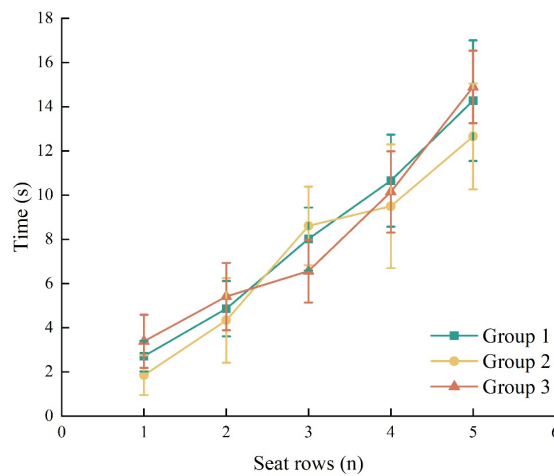


Figure 6. Evacuation time of passengers in different seat rows.

Furthermore, in this experiment, the seat participants were assigned to five seat rows, with varying distances to the exit. Therefore, the row number of the participants' seats has a significant impact on the evacuation time, and the following analysis will further examine this influence.

Figure 6 shows the changes in average evacuation time for each row of seat participants as the seat row increases (Huang et al., 2021). The error bars represent the sample standard deviation of evacuation times for each row. As demonstrated in **Figure 6**, the average evacuation time for each row of seat participants increases with the number of seat rows, indicating that participants in the front rows have a natural and significant advantage over those in the back rows in the evacuation process, and are more likely to complete the evacuation in a shorter time. However, the magnitude of this increase in time varies among different seat rows. This conclusion also can be further substantiated by the four-phase theory of evacuation mentioned before.

Flow Rate

The instantaneous flow rate samples from the three repeated experiments were calculated using the formula **Eq.1**, and the relevant parameters of their descriptive statistics are shown in **Table 1**. It is worth noting that, given that the three repeated experiments were conducted under the same conditions, all experimental data were merged into one group to increase the sample size and reduce the impact of random factors. Therefore, the descriptive statistical parameters for all samples are also listed in **Table 1**.

It can be seen that the instantaneous flow rate values of the seat participants passing through the exit ranged between 0.46 and 3.57 per/s, with the average value (i.e., the average flow rate) for each group of experiments being around 1.8 per/s. At the same time, the coefficients of variation for the three repeated experiments are around 40%, which are much greater than 15%. This indicates that there are significant fluctuations in our instantaneous flow rate samples, making the use of probability distribution methods to study the characteristics of flow rate reliable (Huang et al., 2022).

Table 1. Statistical Parameters of the Instantaneous Flow Rate Samples.

Group	Min (per/s)	Max (per/s)	Mean (per/s)	S.D. (per/s)	Coefficient of Variation
1	0.46	3.57	1.83	0.77	42.1%
2	0.49	3.57	1.86	0.69	37.1%
3	0.68	3.57	1.75	0.81	46.3%
All	0.46	3.57	1.81	0.76	42.0%

Gamma, Loglogistic, Lognormal, Weibull, and Burr are five distributions commonly used for fitting empirical distributions. Therefore, they were used to fit the combined instantaneous flow rate sample. Based on the calculated results of the five distribution fitting parameters, the fitting goodness of all candidate distributions to the empirical distribution was visualized, as shown in **Figure 7**. It is found that only the Loglogistic distribution has a Chi-square value of 24.46, which is less than the critical

value of 25.00 for this case. This indicates that the Loglogistic distribution is statistically significantly close to the empirical distribution.

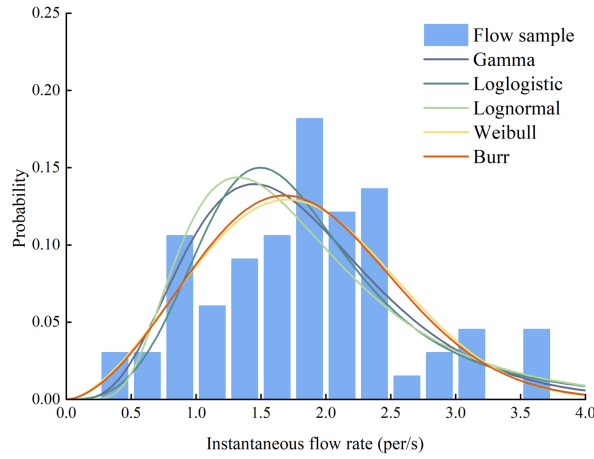


Figure 7. The empirical and estimated distributions of the combined flow rate sample.

Typical Behaviour

According to the typical evacuation behaviour defined before, the frequency of each typical behaviour in the three repeated experiments was obtained by observing the video, as shown in **Table 2**.

Table 2. Number of Typical Evacuation Behaviours.

Group	Overtaking (times)	Pushing (times)	Congestion (existence or not)
1	2	1	√
2	2	2	√
3	3	1	√
All	7	4	-

It can be seen that the frequency of these typical evacuation behaviours in this experimental scenario is relatively low. Overtaking behaviour occurred a total of 7 times, pushing behaviour occurred a total of 4 times, and serious congestion occurred in all three groups of experiments. These typical evacuation behaviours are often attributed to the urgent mentality of seat participants wanting to complete the evacuation as quickly as possible and have a negative impact on the evacuation process (Song et al., 2023).

- 1) *Overtaking behaviour*. Typical overtaking behaviour often occurs in the downstream area of the aisle, and most of the initiators of this behaviour are participants who have just left the congestion.
- 2) *Pushing behaviour*. Typical pushing behaviour often occurs in the middle area of the aisle and in the congestion area. During this evacuation process, pushing behaviour exerts pressure on the participants ahead, which is detrimental to the rapid and safe execution of the evacuation.

- 3) *Serious congestion*. Serious congestion occurred in every repeated experiment, mainly in the upstream area of the aisle. This phenomenon promotes an urgent mentality among participants, leading to more overtaking and pushing behaviours, and increasing the probability of accidents.

CONCLUSION

In this paper, three well-controlled repeated experiments were conducted under the condition of the 0.6-m aisle width to investigate passenger evacuation behavioural characteristics in the confined seat area. Specifically, the evacuation trajectories, evacuation times, instantaneous flow rates, and typical evacuation behaviours are collected and analyzed.

The results indicate that the microscopic trajectories of passengers are roughly river-like, and they generally exhibit slower evacuation velocities in the upstream of the aisle and faster velocities as they approach the downstream exit. The evacuation behaviour of the seat passengers conforms to a four-phase pattern (i.e., reaction, acceleration, fluctuation, and saturation phases), and passengers in the front rows have a significant advantage in evacuation. It is found that the Loglogistic distribution can well describe the instantaneous flow rate distribution characteristic of passengers. Moreover, typical evacuation behaviours, such as overtaking and pushing, were observed and analyzed.

Therefore, we recommend that the operating departments of high-speed trains should strengthen education and training on passenger evacuation knowledge to reduce irrational behaviours, such as pushing, which would be detrimental to passenger evacuation.

ACKNOWLEDGEMENTS

This work was supported by the Postdoctoral Fellowship Program of CPSF under Grant Number GZC20241449 and the Fundamental Research Funds for the Central Universities (CHD) under Grant Number 300102224102.

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