A CELLULAR AUTOMATON MODEL FOR EVACUATION RESILIENCE PERFORMANCE IN TUNNEL FIRE

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ABSTRACT

Tunnels connect traffic from on the ground and underground, and play a crucial role to solve traffic overload and congestion. During the operation, fire is a huge threat resulting from vehicle collisions or self-ignition to occupants and their evacuation is one of the main issues to solve these years. Though several technical installations, control systems and smart firefighting technologies are applied to guide and protect evacuation safety, it is not completely clear how to measure the evacuation safety scientifically and accurately especially when more elements are to be considered in the whole evacuation systems. To fill this gap, the concept of evacuation resilience is proposed in this study. The evacuation resilience presents the ability of evacuation from the threat of fire and could be measured by the total evacuation time, successful percentage compared to the evacuation conditions without fire. To point out, it not only evaluates the initial evacuation performance of occupants but also evaluates the optimized evacuation performance with the help of both external guidance and social influence. To obtain the evacuation resilience performance, a cellular automaton model was built and applied to calculate occupants' evacuation performance in fire as a demonstration. The resilience was then calculated by the comparison of evacuation in fire and without fire and a score was given correspondingly. The study is a fundamental attempt to propose evacuation resilience both qualitatively and quantificationally and is expected to attract more related research in the future to improve evacuation safety furthermore.

INTRODUCTION

Tunnels play a crucial role in transportation in cities to solve traffic overload and congestion to a large extent (Ronchi, 2012). Various vehicles deliver goods and passengers through road tunnels, and the traffic volume experiences an explosive increase recently. The increase brings about growing traffic jam and accidents, which could trigger potential tunnel fire. Once a fire accident happens, the tunnel will suffer from high temperature and be filled with toxic smoke generated from burning gradually. The burning will release large amount of heat and smoke, which would threaten the normal operation of tunnel systems and the lives of occupants inside (Yan et al., 2018). Tunnel fires will worsen if fuel tank leakage and chemical goods are involved. Specifically, the hot temperature, heat radiation and toxic smoke from the fire are all fatal to occupants inside the tunnel. Therefore, the occupants need to evacuate from the tunnel before the condition worsens. The evacuation process could be much more terrible in a tunnel fire evacuation that fires in tunnels burn more fiercely in confined space due to heat feedback (Guo et al., 2022).

Considering those adverse fact in a tunnel fire evacuation, corresponding strategies should be complemented to both suppress the fire development such as water sprinklers, and instruct occupants to evacuate quickly in emergency such as guidance and audio instructions (Zhang et al.,

2021). With the assistance of those strategies, occupants could get a longer time to evacuate before the fire extends and operate a fast and proper evacuation according to instructions. The ability to control fire development and instruct occupants to evacuate to safe places could be named as evacuation resilience. A tunnel system which owns resilience could be called as a resilient tunnel system. The degree of resilience of a tunnel reflects the capacity of a tunnel in case of emergency (fire). Proper strategies are vital to increase the tunnel's resilience.

Previous research has focused on typical strategies and their influence on evacuation. Nilsson (2009) and his colleagues explored the effects of lighting in evacuation and found that flashing lights and strobe lights were more helpful compared to standard emergency exit design, and green lights performed better than blue lights or red lights. More recently, Ronchi et al. (2016) researched lighting via a virtual reality experiment and suggest that green or white light with a flashing rate of 1 and 4 Hz and emitting diode light source as the combination achieves the best performance in guiding evacuation. Kinateder and Warren (2016) tested the social influence during the escaping process in tunnels by providing a virtual agent and found that social influence affected behavior activation and route choice during the evacuation. Those investigations are helpful to optimize assistant strategies and facilities.

However, their attention has been paid to the sole relationship between a strategy as an input and human's choice or movement as an output. Rare research has done about the whole process of evacuation performance and tunnel resilience during the whole evacuation process. In order to investigate the evacuation resilience and how they work on the whole evacuation process. models are put forward to simulate human' evacuation behavior and process from the fire starts till the end of evacuation and to evaluate the evacuation resilience.

Several models are applied to study human behavior and among those microscopic models are popular in research since they consider individuals' characteristic and preference for instance, social force models, lattice gas models cellular automaton models ((Guan et al., 2016)). Those models could describe and explain some typical dynamic phenomena in real evacuation scene in emergency like clogging, collision, faster is slower etc. Among them, CA model has a wide application to study the pedestrian dynamic flow since it offers good simulation process step by step. In addition, CA model is simple and efficient with high calculation speed due to its discrete structures compared to those continuous models. Therefore, it is proper to simulate an evacuation with multi agents in a large tunnel space. It is capable to show the condition of the tunnel and occupants in each time step and how the resilience establishes and come into effect during the evacuation.

In this paper, the evacuation resilience is conceptualized and the evaluation process is put forward via a cellular automaton model. The resilience is then calculated according to the tunnel's evacuation strategies and facilities, and the score was given correspondingly. A tunnel fire demonstration is proposed subsequently. This method is expected to value the resilience of a tunnel system and measure optimal strategies to improve resilience in case of a tunnel fire.

EVACUATION RESILIENCE EVALUATION

Evacuation resilience

Resilience is derived from the Latin word "resillo" and was first defined in the Encyclopaedia Britannica as: (1) the ability to recover from stress; and (2) the ability to recover and adapt during a disaster or change (Palekiene et al., 2015). The concept of resilience has undergone a series of developments in ecological resilience, engineering resilience and socio-ecological resilience. In recent years, the basic meaning of the concept of "resilience" has evolved to two approaches. The first is the ability of a system to maintain its basic structure and function and recover from a disaster through effective resistance, absorption and adaptation. The second pays little attention to the original statement but focuses more on the ability to change to the next stage or condition as long as it is beneficial to the systems. For some systems loading a large number of people, the most important goal in emergency is to ensure the safety of people, so the requirement for resilience has changed

from fast recovery to the organic cooperation of systems to ensure the safety of people, thus, we proposed evacuation resilience in case of tunnel fire herein for tunnel evacuation safety

The evacuation resilience of a tunnel refers to the capability that the tunnel system can quickly demonstrate in a tunnel fire, and its main objective is to guarantee the safety of the evacuation of the crowd. It involves the effective cooperation among environment, the system and the population through effective ways of securing the safety of people including the systems could handle the emergency and occupants could evacuate with the assistance of the systems, see Fig. 1. At the same time, the rapid activation and work of resilience could reduce the damage to the tunnel, which conduce to later rescue and tunnel repair etc.
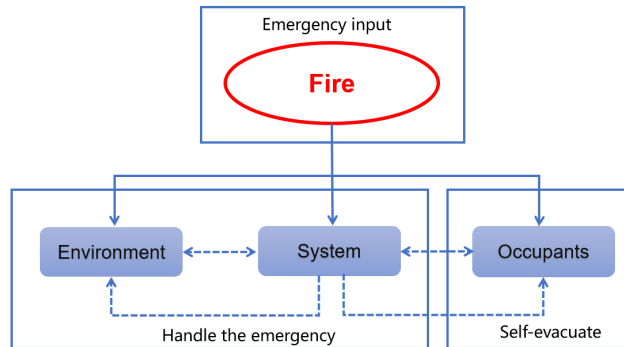

Fig. 1 Characters of evacuation resilience

Resilience working process

When a tunnel is in normal operation, it protects the vehicles and occupants, and it could be called as the "capacity" of the tunnel. The capacity should be larger than the needs of occupants in order to keep the good running of the tunnel, see Fig. 2. In tunnels fire, without any further interventions from the tunnel system, the protection of the tunnel will gradually decline. Specifically, as the fire develops, it may induce the partial collapse of the structure, and great amount of heat and smoke threaten the safety of occupants. Meanwhile, the total resources need from the occupants decreases as more occupants are discovering the fire and starting to evacuate from the tunnel to a safe place. Although this decrease is not uniform, it is simplified here as a uniformly decreasing process. If the capacity of the tunnel is higher than the sum of the crowd's needs at every point of space and time, it ensures that everyone is safe until their evacuation to the designated area. However, if without extra measurement, once the capacity of the tunnel is lower than the needs of the crowd, some trapped occupants at certain place is exposed to potential danger.
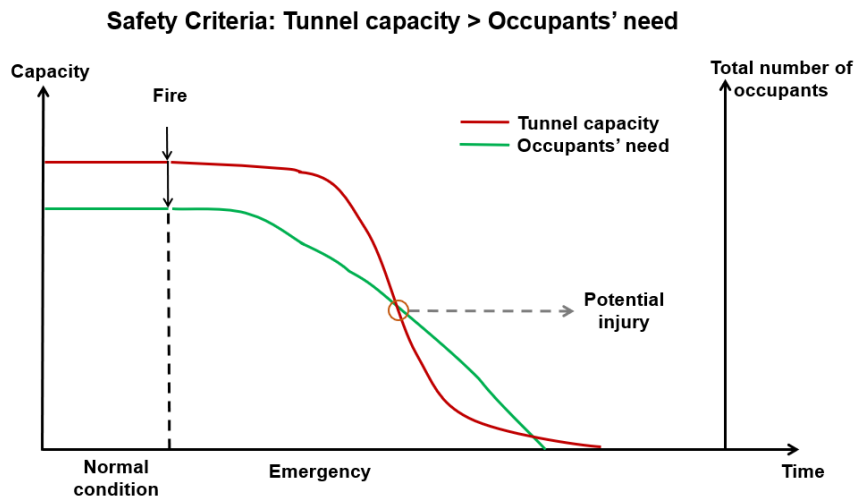
Fig. 2 The development of tunnel and occupants in fire

To avoid the potential injury, the evacuation resilience is introduced in tunnel fire systems see Fig. 3. The resilience is applied to deal with the over-decrease capacity during people's evacuation from two aspects. On the one hand, it slows down the decline of capacity (from red line to reseda), for example, smoke extraction system could exhaust and dust smoke, and limit the smoke generated by the fire within certain ranges through the tunnel, thus allows more space suitable for evacuation. On the other hand, it also guides the occupants' movement and accelerates the evacuation (from yellow line to green line). When the evacuation is faster and more efficient, the needs required by the crowd will be rapidly reduced, thus ensuring that the capacity of the tunnel is higher than the sum of what is required by the crowd at all points of space and time.

In the meantime, it is essential to consider that during the evacuation process, there will be some spontaneous phenomenon that will help the evacuation. For example, the crowd will generate similar social identities in a short period of time, and this identity will help the crowd to create a close connection, share information and risks, and make decisions together, etc. It is also a part of resilience during evacuation
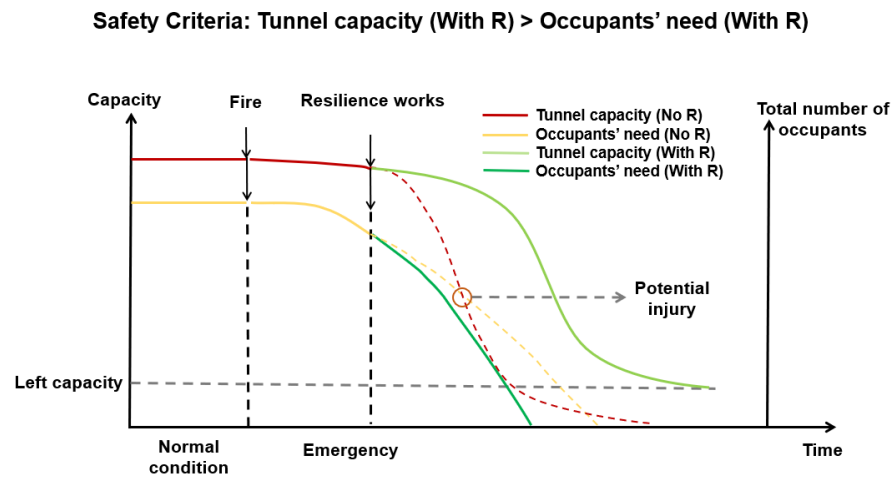
Safety Criteria: Tunnel capacity (With R) > Occupants' need (With R)

Fig. 3 The development of tunnel and occupants in fire after resilience works

Evaluation index

Unlike some simple systems with fixed evaluation index such as speed or accuracy resilience is a relatively complex system and contain multiple elements and factors. It is not easy or scientific to define the resilience with limited index. The process of evaluating the evacuation resilience of a tunnel involves a number of disciplines such as fire science, materials science, computer science, architecture, psychology, sociology and disaster behaviour. Due to the complexity of the process and the number of disciplines involved, a comprehensive evaluation of the resilience of a tunnel evacuation requires the use of appropriate research methods for the different evaluation scales and components. The evaluation index of tunnel evacuation resilience is based on the understanding of tunnel fires development, the evacuation movement process and the working mechanism of tunnel evacuation resilience.

Through the knowledge of tunnel fire incidents, full-size tunnel fire evacuation tests and tunnel firefighting facilities, fundamental concept and index and tunnel evacuation resilience is proposed here as a reference for future research. The key factor of an evacuation is the overall evacuation successful rate of all occupants. In addition, the evacuation speed also matters and instead of each occupant's evacuation speed, the last person who evacuate from the tunnel represents the integral evacuation ability. Moreover, the stability of the evacuation should be taken into consideration along

with the usage of technical facilities, the safety of structures, the fast response of systems and minimum the potential harm. In this paper, we choose the evacuation successful rate and total evacuation time (the last successful occupant) as the principles. To avoid the fluctuation of each evacuation process and show the stability level of the tunnel, repeated calculations are conducted and the standard deviation of rate and time are also considered in the evacuation resilience evaluation.

Evacuation resilience calculation

A method is proposed here to illustrate the evacuation resilience quantitively. Two indexes are chosen namely evacuation time and evacuation progress, see Fig. X. The ideal scenarios are set as the evacuation without fire, as the trapezoid. The x axis refers to the time elapse. T refers to the time when all people evacuate from the tunnel, and T_{lim} refers to the maximum time for people to move through the tunnel. Herein, we introduced the Available safe egress time (ASET) to express T_{lim}. T_{lim} is selected as a constant, 900s, in accordance with the codes of PIARC (1999). The y axis refers to the evacuation progress, specifically, the percentage of evacuated people from the tunnel. The value could be either expressed as 0% to 100% or other forms such as exponent or logarithms of evacuation percentage. The above expression builds a cordoned-off area (S_{id}), and is the maximum resilience of the tunnel, with a score of 100.

Accordingly, a tunnel's evacuation resilience in fire could be expressed as the cordoned-off area (S_{ev}) of evacuation progress with time elapse, and the score is the ratio of S_{ev} and S_{id}. The resilience decreases from Point A to Point B. One limit case is the total evacuation time (T) reaches the maximum of available evacuation time (T_{lim}). It represents the limitation when the last evacuee leaves the tunnel at the last second until the tunnel is not suitable for occupants to move. On top of that, there are chances when some occupants could not evacuate from the tunnel, and Point B will go down, which refers to the decline of successful evacuation percentage.
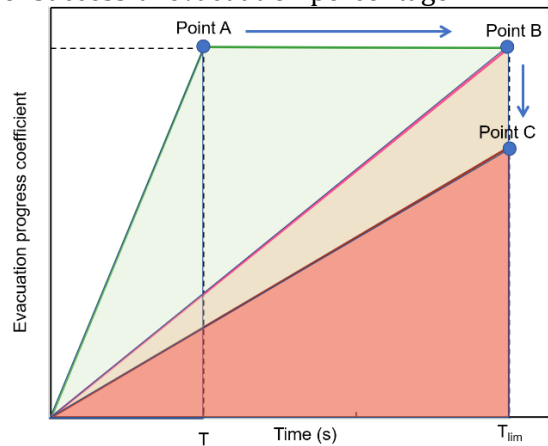

Fig. 4 Evacuation resilience calculation diagram

CELLULAR AUTOMATON MODELS

The concept of cellular automaton models

Cellular automaton (abbreviated as CA) models are a dynamical system consisting of a large number of simple and consistent individuals distributed over homogeneous and consistent lattices through a discrete space composed of local connections, whose lattice can be represented by variables with finite states (Nishinari et al. 1999; Dijlstra et al. 2012). CA models can be viewed as a class of infinite-dimensional dynamical systems characterized by discrete space, time and states, and each variable owns limited choices of states.

The modified CA model depicts an evacuation scene of a tunnel fire in this paper. According to CA models, the tunnel is described as rectangle lattice with 10m*200m in width and length respectively to simulate a standard section of a three-lane tunnel based on local construction codes, and the schematic graph could be referred as Fig. 1. The grids represent the inner space of the tunnel and the tunnel wall does not contain in the grids. The rules and settings are explained as Eq. (1).

$$f : S_i^{t+1} = f(S_i^t, S_N^t) \tag{1}$$

Where:

f is the update/evolution rule;

S_i^t *is the condition of cell i at the step of t;*

S_N^t *is the condition of all N cells at the step of t;*

S_i^{t+1} *is the condition of cell i at the step of t+1.*

Model assumption

According to the average size of human body, each cell is designed as the size of 0.4m*0.4m. Each cell on the lattice has three conditions: "*Empty*" or "*With person*" or be used as exits. Exits are not moveable in the model after the initial setting before each simulation. Apart from cells which are applied as exits, other cells could be either "*Empty*" or "*With person*". Each cell could only occupy one agent at one time.

Each agent will follow specific rules to move towards the exits cell by cell. The velocity of evacuation is 1.35±0.2 m/s according to PIARC (1999). Considering the decisive factor of evacuation efficiency for a large group depends on evacuation route and avoidance of congestion generally rather than fast moving speed for some people, we set the velocity as the mean velocity: 1.35m/s to simplify the calculation and accelerate the computational velocity.

Target choosing rules

Previous studies of CA models involving spatial generations mostly use the model of Moore neighborhood or Von Neumann neighborhood (Zheng et al., 2009). Moore defines the range of one agent's next step as eight cells around him, as shown in Fig. 2(a), and Von Neumann defines as four cells, as shown in Fig. 2(b), and the latter is usually applied with the restriction of physical boundary like streets or blocks.

Considering the tunnel is a huge space with no lineal restriction in movement, an agent is more likely to move along eight stochastic directions during evacuation. Hence, we choose Moore neighborhood as the neighbor cell selection. Following Moore neighborhood, one agent could choose one of eight cells around him as his next step during evacuation. If some cells of neighbors are not available: (a) occupied by other agents; (b) occupied by other obstacles like fire, he will not move to those cells. If all cells are occupied, he will stay still until next generation.

When choosing one cell from the potential targets, there are two general numerical methods which can be used: least-squares estimation (LSE), as shown Eq. (2) and maximum likelihood estimation (MLE), as shown Eq. (3) (Kirchner et al., 1999).

$$L(W) = \sum_{i=1}^N ||\hat{y}_i - y_i|| \tag{2}$$

$$L(W) = P(Y|X, W) = \prod_{i=1}^N P(y_i|x_i, W) \tag{3}$$

Where LSE is to choose the most optimal cell by calculating the sum of each item (i.e. the cell which owns the minimum distance to the exits calculated by the model) whereas MLE is based on maximizing likelihood function and distributes each choice a value considering its location/ability/characteristic etc. (i.e. each potential cell owns a different probability and the agent has a chance to move to any targeted cell following the probability).

A SIMPLIFIED CASE OF A TUNNEL FIRE AND RESILIENCE

A simplified tunnel fire scenario is built as a case study. To start with, numerical modelling using Fire Dynamics Simulator (abbreviated as FDS) was applied to simulate the fire dynamics. Then, a CA model was built to know the evacuation process with human behavior. The FDS model and CA model depict the fire and evacuation development, and contribute to the parameters of resilience calculation. The detailed fire and evacuation modelling could be referred to Zhang's research about a modified cellular automaton model of pedestrian evacuation in a tunnel fire (2022), see Fig. 5.

(a)   *(b)*
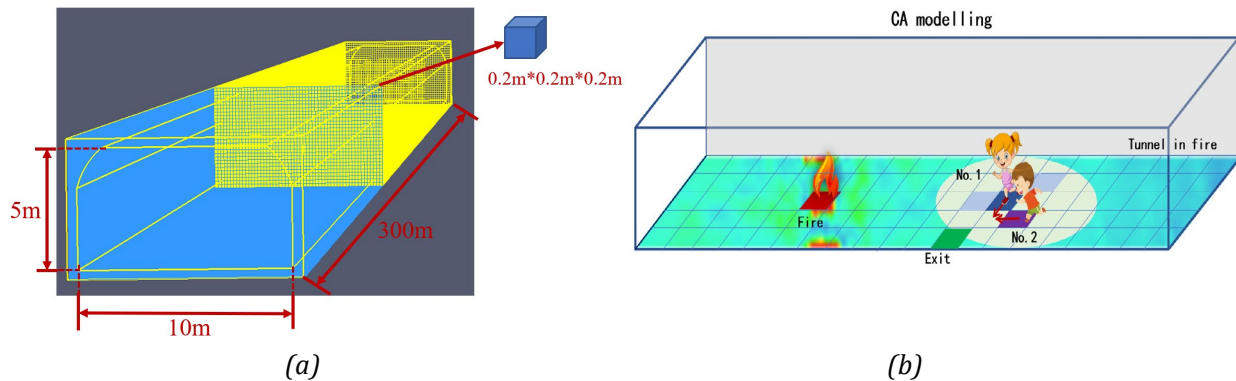
Fig. 5 Tunnel fire and evacuation modelling
(a) FDS modelling, and (b) CA modelling

According to the evacuation results, the evacuation resilience could be drawn, see Fig. 6, and the resilience score is the ratio of yellow area and green area. To point out, the score differs in different fire cases. Moreover, various technical installations could guide evacuation and increase the evacuation speed. Thus, the evacuation process may change. Frankly speaking, though a new quantitative approach of evacuation resilience in each fire scenario, it is entangled to choose one as the standard resilience for one specific tunnel. Thus, more research should be conducted in the future with different modelling cases and evaluation rules.
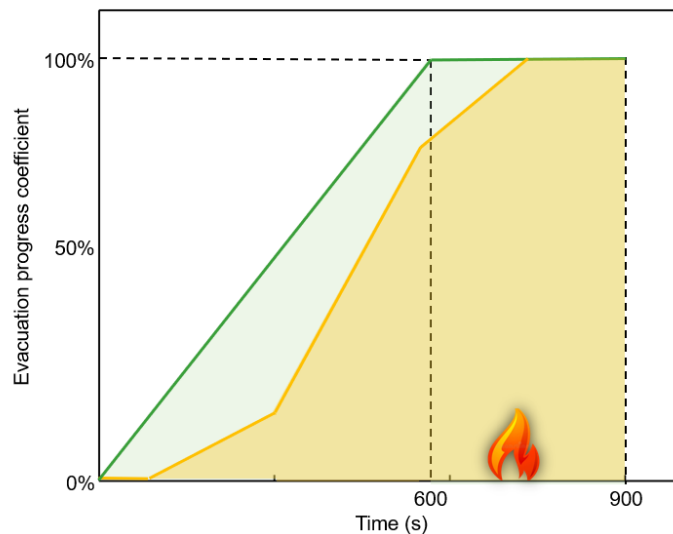

Fig. 6 Evacuation resilience of a simplified tunnel fire

CONCLUSION

It is not completely clear how to measure the evacuation safety scientifically and accurately in a tunnel fire. With the increase of tunnel complexity and elements of tunnel systems, it is necessary to consider and evaluate evacuation safety in tunnel fire systematically. Therefore, the evacuation resilience, as a new concept, is proposed in this study. The evacuation resilience presents the ability of evacuation from the threat of fire and could be measured by the total evacuation time, successful percentage compared to the evacuation conditions without fire. The calculation process is put forward, using FDS modelling and CA modelling together. The resilience was obtained by the comparison of evacuation in fire and without fire and a score was given correspondingly. The study is the first few attempts to introduce resilience into the area of evacuation and hopes to attract more related research to improve evacuation safety in the future.

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