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A Reliability Evaluation of Lifeline Systems Effects on Fire Rescue

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Abstract:

In the process of actual fire rescue, the timeliness and success rate of fire rescues will be affected when only one lifeline system is considered and not considered the relationship among other lifeline systems. However, little research was paid attention to the relationship among different lifeline systems and the most of studies was focused on a single lifeline system. Therefore, it is important and significant to study on the interaction of different lifeline systems during the fire rescues. In this paper, a rescue model is built to evaluate the reliability of the effect of lifeline systems on the fire rescues. Many factors are considered including water system, traffic system, rescue workers, equipment and so on. The reliability of the influence factors are also presented. The reliability of fire rescue can be described and characterized efficiently by this model.

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Keywords: lifeline system, reliability, fire rescue, evaluation

Nomenclature

ϕ	rescue function	w	water source
r	roads	pm	rescue workers and materials
P_{pipe}	the property of pipeline and water supply	P	rescue workers
m	goods and materials;	r_c	roads connectivity;
s_{min}	the shortest path.	k_{wi}	Important coefficient of i -th water source
R_w	the reliability of the water source	R_{iws}	water supply capacity of the i -th water source
R_{ws}	actual output of supplying water of the water source	R_{wn}	Water needed in disasters
R_p	reliability of rescue workers	R_m	The reliability of equipment and goods
R_{pm}	the total reliability of rescue workers and materials	R_s	the traffic reliability
R_{rj}	the reliability probability of connection from j -th rescue spot to the fire scene	l_{rj}	the coefficient of importance of path from j -th rescue spot to the fire scene
$R_{jrescue}$	the rescue ability of the j -th rescue station	Q	The output of supplying water, L/s
D	diameter of the pipeline, in	V	The equivalent velocity of the pipeline, m/s
C_i	construction factors	O_i	application of the building,
X_i	it is exposed to fire	$S_{combustion}$	burning area
NFF_i	the needed fire water, gal/min	k	The type of fire engines

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$S_{control}$	the fire area controlled	R_{pi}	the reliability of the No. i fireman
K_{pi}	important degree of the No. i fireman	R_{rpi}	the actual reliability of fire rescue workers,
N_e	education background	N_F	number of fight
N_h	Health degree	R_r	The connectivity reliability of the roads
P_r	route connecting probability	R_{pmj}	Reliability of supplies in j -th rescue station
P_i	the communication of the buildings, such as connection coefficient or fire separation between the chosen buildings	S_{ijk}	the fire area controlled by the No. j fire engine whose type is k from No. i fire station, $i=1,2,\dots,n, j=1,2,\dots,m$

1. Introduction

Lifeline systems generally include the systems of traffic, communication, water supply, power supply, air supply and some other systems supplying social services, which are considered as the key component of the infrastructure in a city. After fire disasters, it is crucial that whether the emergency rescues can be carry out immediately and effectively, and the rescues are the most important part. In the process of rescues, the effectiveness of fire rescue can be affected by the traffic and water supply systems and the smooth progress of fire rescue is safeguarded through the high personal quality and sufficient equipment, goods and materials. Some single systems have been studied, such as the water, traffic, fire-fighters, materials, and so on.

In the aspect of water supply system, Chen and his co-workers [1] have proposed a method to evaluate the municipal water supply capacity through the municipal fire hydrant, which is applied to some problems of production, fire protection and so on in daily life. Wang [2] has expounded some factors through some actual cases which should be considered during the process of the municipal water supply capacity test of pipelines. Afterwards, a method to determine fire flow in a city was presented after many methods used in developed countries are studied by Chen [3].

In the aspect of traffic, Steven D. et al. [4] have summarized the contingency plan about traffic after the earthquake happened in Los Angeles in 1994 and they studied the management of traffic system after emergency from the aspect of operation and management of traffic system. Thomas, et al. [5] proposed that the main reasons of traffic jams during the evacuation were the interweaving and conflict of the traffic flow at the intersections. A network model based upon the lanes was also proposed in order to choose the optimum path in the complicated road network for urgent evacuation. Zilla S.S., et al. [6] proposed that evacuation time of road network can be affected greatly by the interactions between pedestrians and the traffic through microscopic traffic simulation model based on the behaviour. Liu, et al.[7] have put forward a model to calculate the journey time of fire trucks and obtained the importance degree of some factors which have influence on the journey time.

In the aspect of fire-fighting equipment, Zhu, et al. [8] got an evaluation method for the fire fighting and rescue ability after they researched on the personnel, equipment, water supply, and road in regional rescue. An algorithm optimization was given by Liu [9] based on the actual fire-fighting work. It can simplify complexity of Dijkstra model and then improve the operational efficiency greatly.

In the aspect of overall planning during fire fighting, Zhu, et al. [10] have suggested that regional rescue should be established to handle the transregional disaster accident rapidly and effectively. And a mathematical model was also built to calculate the circle radius and it can be optimized according to the investment increase after the regional rescue was carried out. A new math model based on integration of several variables to calculate the average driving distance of the fire station was proposed by Tian [11]. An information system of fire prevention was established based upon the CAD system.

In the above research, only one lifeline system has been considered during fire rescues. However, study on the interaction of several lifeline systems was little. So the interactions among different lifeline system in fire rescues should be taken into account. In this paper, the rescue model is built to evaluate the reliability of fire rescue affected by the lifeline systems. Not only two lifeline systems, water and traffic system, are considered in the model, but also rescue workers, goods and materials and so on are also considered.

2. Theoretical model

The factors that affected the rescue process mainly include 2 aspects: (a) the time needed which rescue workers arrive at the disaster scenes and (b) the rescue technologies [12]. The former aspect can be influenced by the distance between the rescuers and the scenes, the traffic conditions and the traffic management technologies. The latter aspect can be affected by the rescue materials and equipment and the responding speeds and abilities of commanders and executants.

The disasters rescue process is closely related to water sources, roads and the equipping of rescue workers and materials. The water source is greatly related with the water network in the lifeline system, which means the reliability of water source is determined by the reliability of water network. The roads are influenced by roads connectivity and the minimum path. The feasibility of rescue work and the effectiveness of rescue work can be affected by roads connectivity and the minimum path, respectively. The sufficient personnel and materials are the essential conditions to ensure the rescue work carrying out effectively, and it determined whether the loss can be reduced substantially. According to the relationship among fire rescues and the effect factors, the rescue function ϕ is presented in Eq. (1).

$$\phi = \phi(w, r, pm) \tag{1}$$

In the equation above, the parameters include water source (w), roads (r) and the equipping of personnel and materials (pm) are considered. The parameters above can be obtained by the follow equations:

Water source:

$$w = w(p_{pipe}) \tag{2}$$

Personnel and materials:

$$pm = \varphi(p, m) \tag{3}$$

Roads:

$$r = r(r_c, s_{min}) \tag{4}$$

Where,

p_{pipe} - the property of pipeline and water supply; p - rescue people; m - goods and materials; r_c - roads connectivity; s_{min} - shortest path.

Thus, Eq. (1) can be modified as follows:

$$\phi = \phi(w(p_{pipe}), r(r_c, s_{min}), \varphi(p, m)) \tag{5}$$

In this paper, the reliability of fire rescue is used as the function to evaluate the rescue process, so the function can be expressed by the reliability parameters of the factors listed above. Further analysis for the reliability of each factor will be conducted in the following sections.

2.1. Water source

In this paper F was used for a certain fire, and there are n water sources which can be used around it. We supposed that the corresponding importance coefficient is k_{wi} ($i = 1, 2, \dots, n$), the reliability of the water source is R_w and the water supply capacity of the i -th water source is R_{wis} . According to the assumption above, the actual output of supplying water of the water source (R_{ws}) can be obtained by the following equation:

$$R_{ws} = \sum_{i=1}^n k_{wi} R_{wis} \quad (i = 1, 2, \dots, n) \tag{6}$$

The reliability of water source (R_w) can be expressed by the specific value of actual output of supplying water (R_{ws}) and the water needed in disaster (R_{wn}), as shown in Eq. (7).

$$R_w = R_{ws} / R_{wn} \tag{7}$$

2.2. Rescue people, equipment and materials

In this section, there are two aspects, rescue workers and rescue equipment and materials. The reliability of rescue

workers and equipment and goods are expressed by R_p and R_m , respectively and the total reliability of the two aspects is R_{pm} .

Because the reliability of the equipment and goods and that of rescue workers have little impact on each other, they can be considered as isolate and the reliability of supplies can be expressed with the multiplication of reliability of equipment supplies and the reliability of human supplies. Equation (8) will be obtained.

$$R_{pm} = R_m \times R_p \tag{8}$$

2.3. Traffic

Assuming that the quantity of rescue stations is m ; the traffic reliability is R_s ; the reliability probability of connection from j -th rescue spot to the fire scene is $R_{rj} (j = 1, 2, \dots, m)$; the coefficient of importance of path from j -th rescue spot to the fire scene is supposed by $l_{rj} (j = 1, 2, \dots, m)$; and the rescue ability of the j -th rescue station is $R_{jrescue} (j = 1, 2, \dots, m)$.

Thus, R_s can be obtained through the following equation.

$$R_s = \sum_{j=1}^m R_{rj} l_{rj} R_{jrescue} \tag{9}$$

Based upon the parameters mentioned above and the reliability of each parameter, after Eq. (7), (8), (9) were plugged into the Eq. (5), the reliability function Eq. (5) can be changed to Eq. (10).

$$\phi = R_w \times R_{pm} \times R_s \tag{10}$$

3. The calculation of the elements in the model

3.1. Water

For a fire accident, the success or failure of fire extinguishing can be affected greatly by water source directly. Thence, the reliability of the water source is crucial for fire rescues.

As mentioned above in the section 2.1, the important degree of different water source (k_{wi}) can be obtained through Delphi method.

During the calculation of fire fighting force, the output of supplying water can be determined by Eq. (11).

$$Q = 0.5 \bullet D^2 \bullet V \tag{11}$$

Where,

Q - The output of supplying water, L/s; D -diameter of the pipeline, in;

V - The equivalent velocity of the pipeline, m/s. It is worth mentioning that in the branch network of pipes, the equivalent velocity is 1 m/s, while the value is 1.5 m/s in ringed piping network.

Thence, the water supply capacity of the i -th water source (R_{wvs}) can be calculated by the following equation.

$$R_{wvs} = 0.5 \bullet D_i^2 \bullet V (i = 1, 2, \dots, n) \tag{12}$$

In the current ‘Fire Suppression Rating Schedule’^[13], the needed fire water can be calculated by Eq. (13) and (14).

$$NFF_i = C_i O_i (X + P)_i \tag{13}$$

$$(X + P)_i = 1.0 + \sum_1^n (X_i + P_i) (i = 1, 2, \dots, n) \tag{14}$$

In the equations above, C_i -construction factors, O_i - application of the building, X_i - it is exposed to fire, P_i - the communication of the buildings, such as connection coefficient or fire separation between the chosen buildings and NFF_i – the needed fire water, gal/min.

On account of the conversion as 1gal equal to 4.546 L (UK) or 3.785L (USA), R_{wn} can be listed as Eq. (15) and Eq. (16).

$$R_{wn} = 0.06308NFF_i(USA) \quad (15)$$

$$R_{wn} = 0.07577NFF_i(UK) \quad (16)$$

3.2. The supplies

The supplies can be divided into rescue people and equipment. Their reliability can be obtained through the reliability analysis of these two aspects.

3.2.1 The calculation of the reliability of supplies

Set a fire F, its burning area is $S_{combustion}$ and the type is F_{type} . There are n fire stations around it, and each fire station is equipped with m fire engines whose type is k. And the fire area controlled by an engine is S_{ijk} (S_{ijk} is the fire area controlled by the No. j fire engine whose type is k from No. i fire station, $i=1,2,\dots,n, j=1,2,\dots,m$).

Thence, the fire area controlled ($S_{control}$) can be obtained as follows:

$$S_{control} = \sum S_{ijk} \quad (17)$$

And then the equipment reliability can be expressed as Eq. (18).

$$R_n = S_{control}/S_{combustion} \quad (18)$$

3.2.1.1 The controlled fire areas

The controlled fire area can be expressed by the Eq. (19).

$$S = A \bullet N \quad (19)$$

Where,

S - The total controlled fire areas, m^2 ; N -the number of fire engines; A -The fire area controlled by a fire engine, m^2 .

3.2.1.2 Burning area

Burning area of fire ground can be obtained by field commanders through visual calculation, referring to the drawings information, consulting insider or other ways.

3.2.2 Human reliability

A good fire fighting commander should be knowledgeable, healthy and have psychological quality in order to put out the fire quickly and effectively.

Knowledge is the basic conditions in all work. For firemen, they should master professional knowledge and scientific and cultural knowledge. Psychological quality is also important. Fire-fighters who have calm temperament, good personality and a strong will, can work well at the complex and dangerous conditions. Good physical quality of fire-fighters can make them have a good adaptive capacity and work a long time when fires occurred.

Set a fire F. There are n firemen during the process of fire fighting, and assuming that the reliability of the No. i fireman is $R_{pi}(i=1,2,\dots,n)$, and his important degree is $K_{pi}(i=1,2,\dots,n)$. R_p is the total reliability of the fire soldiers.

Each person plays a different role in fire fighting. The commanders' personal quality is the premise of quick and effective rescue. Firemen are the basis. Thence, the important degree of commander and firemen are different. In this paper, the actual reliability of fire rescue workers, $R_{Fpi}(i=1,2,\dots,n)$, are reliability of rescue workers multiplying their important degree and it can be described by Eq. (20).

$$R_{Fpi} = K_{pi} \times R_{pi} \tag{20}$$

Assuming that in the process of fire rescue, the rescue was not reliable until all the fire rescue workers were not reliable. Thus, the total reliability of the fire rescue workers can be illustrated as follows:

$$R_p = 1 - \prod_{i=1}^n (1 - R_{Fpi}) = 1 - \prod_{i=1}^n (1 - k_{pi} \bullet R_{pi}) (i = 1, 2, \dots, n) \tag{21}$$

At the scene of disasters, rescue workers are divided into commanders and fire fighters on the spot. Commanders can be divided into field commander in chief, deputy commander, rescue squadron leader and experts, while fire-fighters can be divide into public security fire brigade, full time fire brigade and obligatory fire brigade in china.

Political quality, professional quality, knowledge quality, psychological quality and physical qualities have effects on the quality of fire rescue workers. For rescues, the political quality and psychological quality of most of workers are qualified, so in the paper, the political quality and psychological quality are not considered. Professional quality and knowledge quality are related to education and training and the experience of participating in the fire rescue, thus these two qualities are expressed by education and the number of participating in the fire rescue. Physical quality is the basis of quick and effective rescue, and in the paper, it will be characterized as healthy or not. The total score of the above-mentioned indexes are 10 points.

Education and training is a discontinuous function and here it can be divided into below vocational school, vocational school, junior college, bachelor, master and doctor. The number of rescue is associated with the experience of the rescue workers and people’s experience and knowledge tend to saturation and don’t increase after reaching a certain number of rescues, N_f (For example, suppose $N_f = 20$ [14]). Thus, we can define the experience of people who have taken certain times of rescue as full marks, 10 points. If less than this value, it can be expressed by the ratio of the fight number N to the Times N_f multiplying a full score 10 points.

According to the mentioned above all, the rescue workers’ reliability can be described as in table 1, 2, 3.

Table 1. The influence factors of different rescue workers

first-grade index	second-grade index	third-grade index	fourth-grade index	calculating
factors	factors	factors	proportion	scores
humans	commanders	The commander in chief	Experience	
			Knowledge	
		The deputy director	Experience	
			Knowledge	
		Squadron leader	Experience	
			Knowledge	
	fighters	experts	Experience	
			Knowledge	
		Full time fire brigade	Experience	
			Knowledge	
		Obligatory fire brigade	Physical quality	
			Experience	
Public security fire brigades	Knowledge			
	Physical quality			

Table 2. The influence factors of education background

Education background	Below vocational school	vocational school	Junior college	bachelor	master	doctor
scores						

The value of education background are 1,3,5,7,9,10 from Below vocational school to doctor, respectively.

Table 3. The influence factors of physical quality

Health degree	Very healthy	Healthy	ill
scores			

The value of physical quality can be defined as 5, 7, and 9, respectively.

Set the education background, number of fight and Health degree as N_e , N_f and N_h , respectively. Thus, the reliability of No. i fireman is that:

$$R_{pi} = \begin{cases} \frac{1}{20}(N_e + \frac{N_f}{N_f} \times 10) & \text{commanders} \\ \frac{1}{30}(N_e + N_h + \frac{N_f}{N_f} \times 10) & \text{firefighters} \end{cases} \quad (22)$$

3.3 Calculation of traffic reliability

Assuming: the number of rescue spots are m around the fire; the reliability of rescue site arriving to fire scene is R_{rj} ($j=1,2,\dots,m$); the important degree coefficient of each route to disaster site is l_{rj} ($j=1,2,\dots,m$); the rescue capabilities of each rescue spot is $R_{jrescue}$ ($j=1,2,\dots,m$), and then the traffic reliability can be obtained as Eq. (23).

$$R_s = \sum_{j=1}^m R_{rj} l_{rj} R_{jrescue} \quad (j = 1, 2, \dots, m) \quad (23)$$

3.3.1 The rescue capability

The rescue ability of each rescue spot is closely related to rescue workers, equipment and goods. Therefore, the rescue capabilities is directly equal to its supplies of fire rescue spot.

Because in the section 3.2, reliability of supplies is used to evaluate it, here reliability is also used to evaluate the capability of rescue spots. And then the following equation is got.

$$R_{jrescue} = R_{pmj} \quad (j = 1, 2, \dots, m) \quad (24)$$

And the traffic reliability can be obtained as Eq. (25).

$$R_s = \sum_{j=1}^m R_{rj} l_{rj} R_{pmj} \quad (j = 1, 2, \dots, m) \quad (25)$$

The important degree of different rescue spot are also obtained through Delphi method.

3.3.2 Road connectivity and connectivity probability

The connectivity reliability of the roads (R_r) can be described as Eq. (26) through the method of Monte Carlo.

$$R_r = k/P \quad (26)$$

Set route connecting probability as P_r and then the reliability of connectivity probability, R_{r_j} is showed in Eq. (27).

$$R_{r_j} = P_r \bullet R_r (j = 1, 2, \dots, m) \quad (27)$$

Finally, the traffic reliability can be calculated as shown in Eq. (28).

$$R_s = \sum_{j=1}^m P_r R_r I_{r_j} R_{pmj} (j = 1, 2, \dots, m) \quad (28)$$

4. Conclusions

In this paper, some lifeline systems which have effects on fire rescues have been analysed and a reliability model is presented. The concrete conclusions are drawn as follows:

- A lot of factors have been considered in the reliability model including water system, traffic system, fire rescue workers, equipment and goods.
- A reliability model of water source has been proposed. The basic factors of constructions have been introduced during the calculation of water reliability and the influence of different important degree of water source are also considered in the model.
- A Reliability model of rescue workers and equipment are also presented. In this model, the influence factors of rescue workers have been analysed detailed. The influence factors included different role of rescue workers, education background, physical quality and experience.
- In this paper the rescue ability of each rescue spot is expressed by the reliability of supplies and different important degree of fire rescue spots are also considered. The influence factors included the shortest path and road connectivity.

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