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Subway Fire Cause Analysis Model Based on System Dynamics: a preliminary model framework

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Abstract

This paper collects typical major subway fire cases in nearly 20 years. Through analysis of these cases, the causes of the fire accidents are summed up. And further the influence factors of these reasons are extracted, including four aspects namely equipment, human, environment and emergency management. On this basis, combined with the relevant principles of system dynamics, the influence of various factors on the happening, spreading and controlling of subway fires are considered. Then, a simulation model of subway fire accident rate is constructed by Vensim. The equations of relevant variables and parameters of the system are given preliminarily.

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Keywords: Subway Fire, Case analysis, System Dynamics, Model

1. Introduction

The world's first subway was built in London in 1863. According to incomplete statistics, subways have been operated in 136 foreign cities, while in China 24 cities have subways. The subway has become the preferred means of transport in cities. It not only brings convenience to the public, but also has strengths such as great capacity, less pollution, etc. However, we must pay great attention to the subway safety since it has many weaknesses, including long and narrow subway tunnels, enclosed subway carriages, high crowd density and so on. In case of subway fires, explosions and other unexpected events, it can easily result in casualties of a large number of passengers. The main factors based on the statistical data inducing the global subway accidents in nearly 20 years are shown in Fig 1.

It can be seen clearly from Figure 1 that the fire accident in all the subway accidents occupies 68%, followed by the explosion, 12%. The rest are the train derailed, poison gas, power cut, floods, earthquakes and other accidents, occupying 7%, 3%, 2%, 2%, 2% and 4%, respectively. Subway fire accident occurred at the highest frequency and it causes the most serious casualties among all the accident types. Therefore, the fire is a major threat to the safe operation of the subway. In order to prevent and control the fire, both emergency mechanism and emergency evacuation are important issues of the metro operation.

For the study of subway fire prevention and emergency management, both the domestic and foreign scholars have done a lot of work. Liu et al. [1] used the improved AHP for subway fire risk evaluation, in which they proposed three-scale-method to determine the judgment matrix, and verified the rationality and reliability of the method with evaluation for subway fire risk; Lu [2] used the method of fault tree to make qualitative analysis on subway fires, and then put forward measures to reduce subway fires. These studies on the subway fire accident are mostly from the static angle, while the occurrence and spread of subway fire accident is a dynamic process. On the basis of the studies above, other scholars have conducted dynamic simulation and analysis. For example, Zhao [3] put forward early warning management mode during the incubation period of major emergencies, who thought the monitoring, guidance and suppression of the factors before outbreak play a decisive role

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in the control of the accident; Jiang et al. [4] used evolution scenario method for unconventional emergencies, according to the time rule of scenario evolution, the unconventional emergency is divided into pre-incident emergency plan formulation phase, the emergency response phase of the incident and the disposal of things in real time and decision-making phase. Virginia [5] used EvacTunnel3.0 software to obtain the total evacuation time and the number of people trapped inside the tunnel, the model considers the effects of smoke and the ventilation method employed and analyses the possible consequences in terms of the number of affected people.

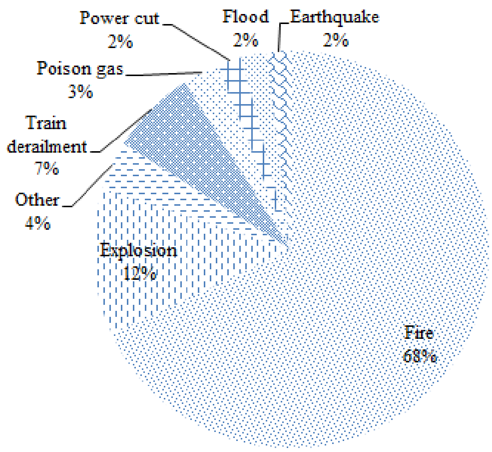

Fig. 1. The proportion of different inducing factors related to subway accidents in China and abroad

System Dynamics [6] is a method which combines qualitative analysis with quantitative analysis. It describes the mechanism of the accident in dynamic view, thereby analyzes the relationships and linkages between various factors of the accident as well as the consequences of these factors on the event during different stages of evolution of the accident. Researchers have already [7] used it into evolution mechanism of unconventional emergencies , and extracted out of the main causes of accident happening and evolution according to the theory of man-machine-environment. They also divide the factors related to unconventional incident system into human factors, equipment factors, environmental factors, and emergency management factors. The complex relationships between factors are studied and comprehensive system of factors is established. Ji [8] used system dynamics simulation software Vensim to simulate the overall process of blowout accident to achieve the dynamic monitoring and early warning of security level of oil and gas wells; Shin [9] and others developed a system dynamics (SD)-based model of construction workers' mental processes that can help analyze the feedback mechanisms and the resultant dynamics regarding the workers' safety attitudes and safe behaviors. Hafida [10] and others used system dynamics methodology to support decisions related to the improvement of industrial safety and the implementation of managerial tools involving organizational, technical and human factors.

Based on the analysis of typical cases of subway fires, this paper aims at using system dynamics to build a model of fire accident rate to simulate the influence of factors on the spread, affecting and control of subway fire.

2. Cause analysis on typical subway fire cases

The factors extracted from the above table which influence the occurrences and development of subway fire accident includes:

(1) Equipment factors: including carriage fire prevention materials, automatic fire water supply system, monitoring system, equipment failure, emergency braking device, fire alarm systems, strong exhaust system, end collision of trains.

(2) Human factor: including illegal operation, weak awareness of prevention, information transmission speed, the rescue efforts, subway staff training, subway staff negligence, subway staff quality, passengers panic, security staff, psychological quality, equipment maintenance.

(3) Environmental factors: including poisonous smoke, high temperature.

(4) Emergency management factors: including emergency plans, emergency evacuation guidance, hindered rescue, emergency evacuation drills, safety supervision, safety inspection measures.

Table 1. Typical cases of subway fire

Accident time	Location	Casualties	The direct cause of the fire	Factors obtained from accident investigation	Extracted influencing factors
1995.4	Daegu	103died, 230 injured	Subway expansion construction, gas pipeline explosion	Illegal operations; Illegal command; Contingency plans defects; Incomplete emergency evacuation; Slow escape messaging ; Passenger panic	Illegal operation; Weak awareness; Information transfer rate; Psychological quality; Contingency plans; Emergency evacuation guide
1995.10	Baku, Azerbaijan	558 died, 269 injured	The circuit was aging, Underground got fire in a tunnel between two stations	Decorate carriages with flammable synthetic materials; Unreliable exhaust system; Rescue forces; Lack of rescue equipment; Ineffective rescue measures; Lack of lighting	Equipment maintenance; Carriage fire prevention materials; Strong exhaust system; Rescue efforts; Fire Water System; Emergency evacuation guide
1999.8	Cologne, Germany	67 injured	Subway Collision	Lack of fireproof material; Staff illegal operation	Motorcycle rear-end; Illegal operation; Carriage fire prevention materials; Emergency braking; Metro staff training
1999.10	Seoul, Korea	55 died	Arson	Metro staff slow access to information; Gas and smoke	Monitoring System; Metro staff neglection; Rescue blocked; Strong exhaust system
2000.11	Austria	155 died, 18 injured	Electric heating and air conditioning overheating	Metro maintenance is not in place; Fire consciousness; Equipment failure	Equipment failure; Equipment maintenance; Emergency evacuation drill; Poisonous smoke
2003.1	London	32 injured	Train derailment rush to platform	Driver training, motorcycle maintenance is not in place	Equipment failure; Equipment maintenance; Emergency braking device
2003.2	Daegu	198 died, 147 injured	Arson	Driver's compartment does not open in time due to fear of toxic gases; Poor staff psychological quality; Invalid exhaust system; Mostly elderly and children; Inadequate safety supervision; Fireproof materials have gas after combustion	Metro staff training; Psychological Quality; Automatic fire alarm system; Metro Staff Quality; Emergency evacuation guide; Safety Supervision; Emergency plan drills; Strong exhaust system
2004.2	Moscow	40 died , 120 injured	Rush hour explosion; Suicide terror attacks	Extremist retaliation; Government lack of intelligence-gathering and analysis of the terrorist ; Inadequate crackdown	Monitoring systems; Security checks and measures; Safety supervision; Passengers panic; Emergency evacuation guide
2005.2	Daegu	126 died, 146 injured	Arson	Sprinklers and emergency lightings not work after power failure; Lack of security awareness; Security staff shortage; Incomplete communication	Emergency evacuation guide; Security service; Automatic fire alarm system; Enforced exhaust system; Fire water supply system; Safety supervision
2005.7	London	45 died, thousands injured	Terrorist attack	Terrorists take revenge on society; The explosion caused a network outage; Get information slow	Monitoring systems, security checks and measures; Automatic fire alarm system; Passengers panic
2006.7	Chicago	152 injured	Cars derailed	Slow information transmission of escape; Contingency plans defect; Car exhaust system not work	High temperature; Information transfer rate; Emergency plan drills; Fire extinguishing system with forced exhaust system; Passengers panic
2011.4	Belarus	15 died, more than 200 injured	Terrorist attack Arson	Site monitoring is not in place ; Slow transmission of information	Monitoring systems; Security checks and measures; Automatic fire alarm system; Safety awareness

3. System Dynamics Modeling

3.1 Subway fire causes tree and flow diagram

As a system dynamics simulation software, Vensim is used to establish the causes tree with the above fire factors combined with accident-causing theory. As shown in Fig. 2, 3, 4 and 5, the following subsystem that includes environment, equipment, man-made and emergency management were established by Vensim.

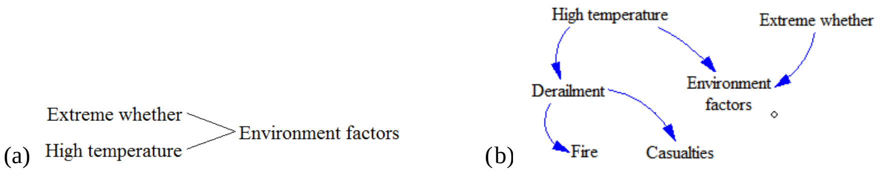

Fig. 2. The (a) causes tree and (b) subsystem of environment factors

In Fig 2, the extreme weather and high temperatures may cause the occurrence of subway fire accidents, such as earthquakes or high temperature, they may cause short circuit, rail deformation or even train derailment.

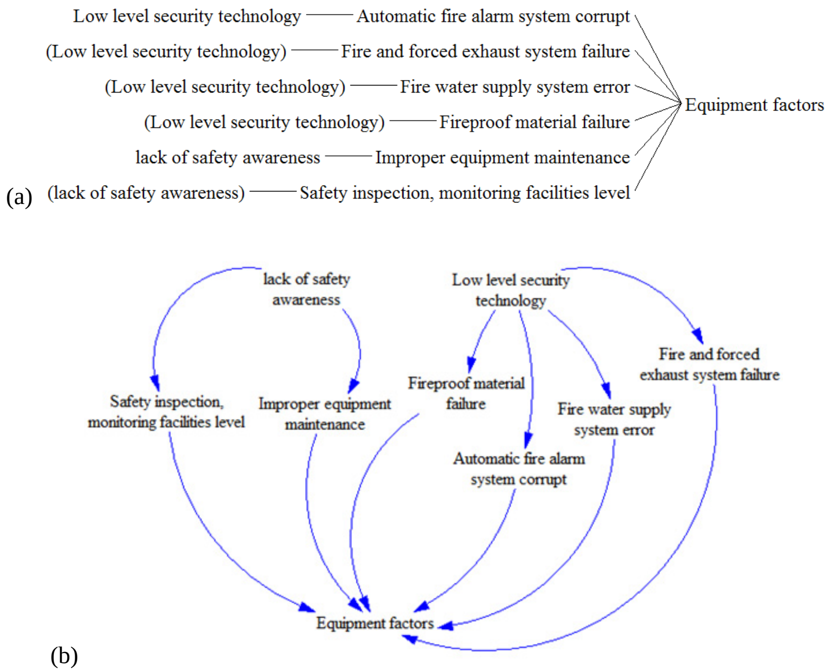

Fig. 3. The (a) causes tree and (b) subsystem of equipment factors

In Fig 3, lack of safety awareness will reduce the level of equipment maintenance and safety investment to equipments, and the low level of security technologies will cause poor reliability of automatic fire alarm system, forced exhaust systems, fire water supply, fire prevention materials and other equipment in case of fire.

In Fig 4, the weak awareness of fire prevention may lead to passengers carry inflammable and explosive materials illegally. If the transmission of information is not timely, it may cause passengers panic. Important human factors in the emergency evacuation system contain subway staff quality, psychological quality and passenger safety awareness.

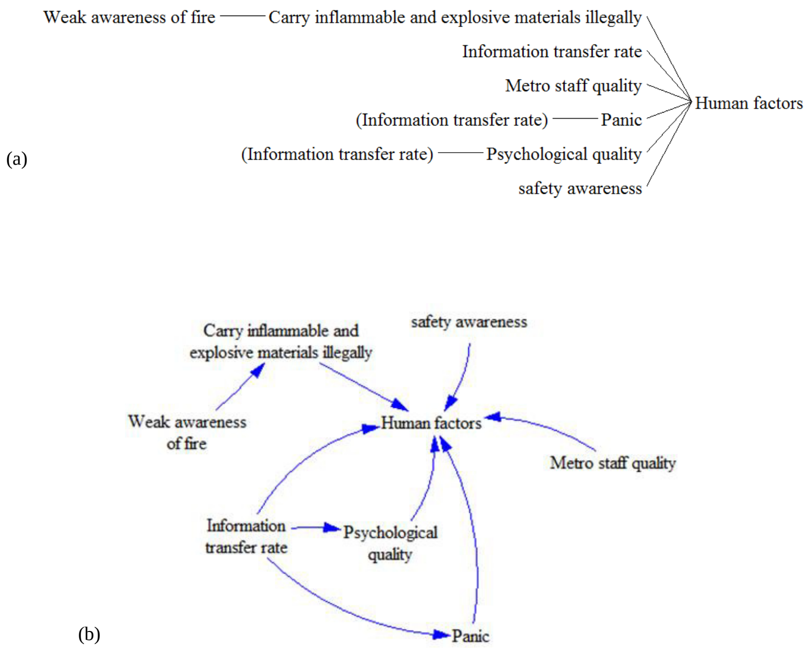

Fig. 4. The (a) causes tree and (b) subsystem of human factors

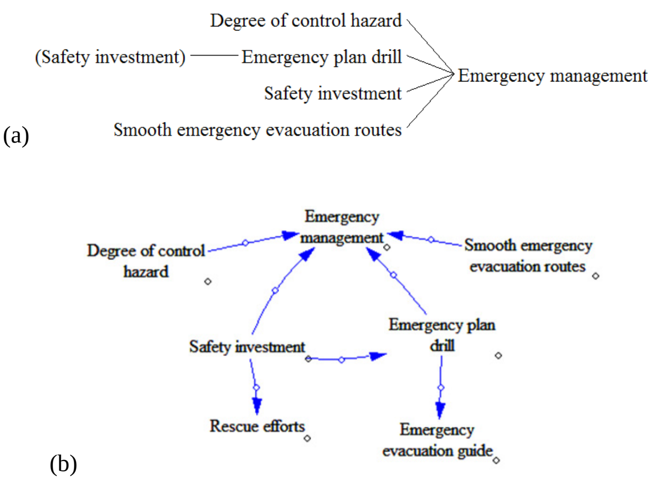

Fig. 5. The (a) causes tree and (b) subsystem of emergency management factors

In Fig 5, the emergency management factors include the degree of hazard control, emergency evacuation drills, as well as subway security investment and smooth evacuation routes, etc. Adequate investment not only ensures the emergency evacuation drills, but also determines the extent of the rescue efforts.

The first three subsystems have decisive role for the probability and severity of subway fire accidents, while emergency management can reduce accident losses. The entire flow diagram of system dynamics model of subway fire system is shown in Fig 6.

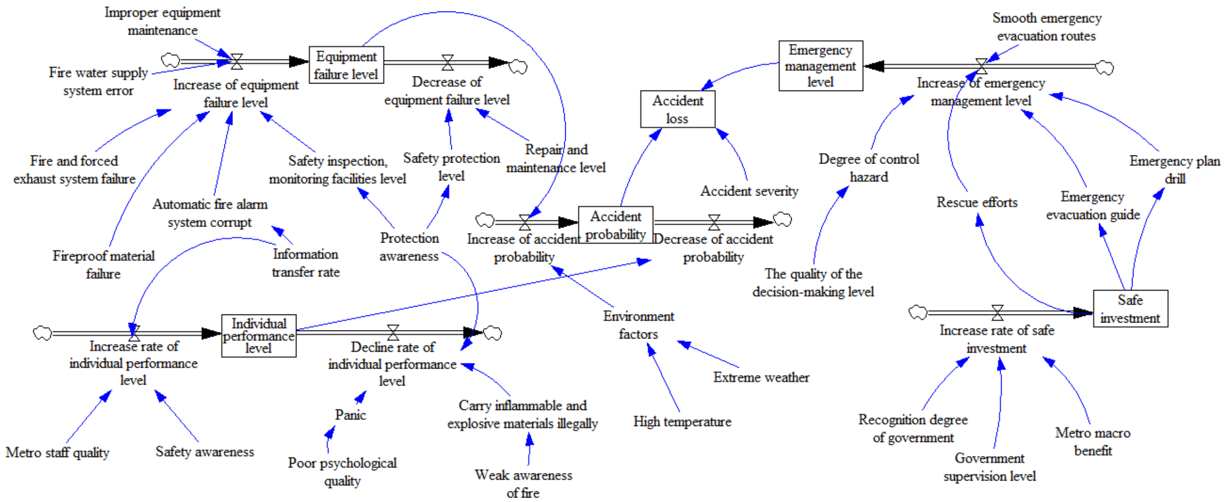

Fig. 6. System dynamics model of subway fire system

3.2 System variables and parameter equations

Based on the system flow diagram shown in Fig 6, in order to simplify the system-related variable name, the corresponding variable symbols are listed in Table 2.

Table 2. System related variables

Box variables	Rate variables	Auxiliary variables	Constant
B1: Equipment failure level	R1: Increase of equipment failure level	A1: Improper equipment maintenance	C1：Information transfer rate
B2: Individual performance level	R2: Decrease of equipment failure level	A2: Fire water supply system error	C2：Protection awareness
B3: Emergency management level	R3: Increase rate of individual performance level	A3: Fire and forced exhaust system failure	C3：Emergency evacuation guide
B4: Safe investment	R4: Decline rate of individual performance level	A4: Fireproof material failure	C4：Emergency plan drill
B5: Accident probability	R5: Increase of emergency management level	A5：Automatic fire alarm system corrupt	
B6: Accident loss	R6: Increase rate of safe investment	A6：Safety inspection, monitoring facilities level	
	R7: Increase of accident probability	A7：Safety protection level	
	R8: Decrease of accident probability	A8：Repair and maintenance level	
		A9：Metro staff quality	
		A10：Safety awareness	
		A11：Panic A12：Poor psychological quality	
		A13：Weak awareness of fire A14：Carry inflammable and explosive materials illegally	
		A15：Smooth emergency evacuation routes	
		A16：The quality of the decision-making level	
		A17：Degree of control hazard A18: Rescue efforts	
		A19：Recognition degree of government A20：Government supervision level	
		A21：Metro macro benefit A22: Accident severity	
		A23: High temperature A24: Extreme weather	
		A25: Environment factors	

The main parameters of the system equation is as follows:

(1)Box variables:

B1=R1-R2

B2=R3-R4

B3=INTEG(R5,B3 initial)
B4= INTEG(R6,B4 initial)
B5=R7-R8
B6=B5*A22-B3
(2)Rate variables:
R1= influence coefficient of A1 to R1*A1+ influence coefficient of A2 to R1*A2+ influence coefficient of A3 to R1*A3+ influence coefficient of A4 to R1*A4+ influence coefficient of A5 to R1*A5+ influence coefficient of A6 to R1*A6
R2= influence coefficient of A7 to R2*A7+ influence coefficient of A8 to R2*A8
R3=influence coefficient of A9 to R3*A9+ influence coefficient of A10 to R3*A10+ influence coefficient of C1 to R3*C1
R4= influence coefficient of A11 to R4*A11+ influence coefficient of A14 to R4*A14
R5= influence coefficient of A15 to R5*A15+ influence coefficient of A17 to R5*A17+ influence coefficient of A18 to R5*A18+ influence coefficient of C3 to R5*C3+ influence coefficient of C4 to R5*C4
R6= influence coefficient of A19 to R6*A19+ influence coefficient of A20 to R6*A20+ influence coefficient of A21 to R6*A21
R7=B1+A25
R8=B2
(3)Auxiliary variables:
A5= WITHLOOKUP(C1,(0,0)-(a10,b10)],(a1,b10),(a2,b2),(a3,b3),…(a10,b10)))
A6= WITHLOOKUP(C2,0,0)-(a10,b10)],(a1,b10),(a2,b2),(a3,b3),…(a10,b10)))
A7= WITHLOOKUP(C2,0,0)-(a10,b10)],(a1,b10),(a2,b2),(a3,b3),…(a10,b10)))
A11=ACTIVE INTIAL(0.6×A12,A11 initial)
A14=ACTIVE INTIAL(0.0001×A13,A14 initial)
A17= ACTIVE INTIAL(0.4×A16, A17 initial)
A25= influence coefficient of A23 to A25*A23+ influence coefficient of A24 to A25*A24
(4)Constant:
C3=WITHLOOKUP(0,0)-(a10,b10)],(a1,b10),(a2,b2),(a3,b3),…(a10,b10)))
C4=WITHLOOKUP(0,0)-(a10,b10)],(a1,b10),(a2,b2),(a3,b3),…(a10,b10)))

4. Conclusions

This paper analyzes the typical cases of subway fires over past 20 years. Based on the case analysis, the influential factors are extracted into four levels, namely environmental factors, equipment factors, human factors and emergency factors. The simulation platform Vensim is used to establish the four subsystems and the whole system flow diagram. Based on this flow diagram, the relevant equations reflecting the relationship between variables are given. In future work, a detailed analysis of specific case will be introduced. In order to simulate the occurrence and spread of fire influenced by related factors, we will bring specific parameters and equations to simulate the subway fire risk. The data and conclusions we obtained can provide guidance for prevention and response measures of subway fires.

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