



Fire spread simulation using GIS: Aiming at urban natural gas pipeline



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ABSTRACT

With the increasing use and complexity of urban natural gas pipelines, the occurrence of accidents owing to leakage, fire, explosion, etc. has increased. To analyze the scope of impacts of single-point fires associated with urban natural gas pipelines and the spread of urban fires caused thereby, this study analyzes single-point fires and the dynamic spread of fires by using a natural gas pipeline network fire model and a framework for an urban fire spread model by using GIS spatial analysis technology. Experiments show that by using the proposed method, we can easily determine key urban areas that are impacted by natural gas pipelines and where fire spread may occur. This study should be of great significance in preventing and controlling hazardous fires, deploying firefighting forces, planning urban construction, etc. We hope that the analysis results for hazardous areas from the viewpoint of urban pipelines using the proposed modules can be directly applied to urban safety planning.

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1. Introduction

With the increasing use and complexity of urban natural gas pipelines, the occurrence of accidents owing to leakage, fire, explosion, etc. has increased (Jo and Ahn, 2005). For example, on August 2, 2004, an explosion of natural gas pipelines in Asuncion, Paraguay, caused a fire and led to the death of 250 people; on April 6, 2007, a natural gas pipeline in East Nanjing Street, Shenyang, China, was broken during an excavation, causing a widespread suspension of the gas supply; and on November 22, 2013, an oil pipeline in Huangdao District, Qingdao, China, leaked and exploded, leaving 62 persons dead, 136 persons injured, and direct losses of RMB 750 million Yuan. Fires are more likely to spread and cause casualties, property losses, and large-scale environmental damage in old towns/cities dominated by wooden structures, because of the poor firefighting infrastructure and relatively narrow roads (Ohgai et al., 2007). For example, in 2014, a fire broke out in Shangri-La, an ancient town, from an inn, causing destruction to more than 100 buildings and serious economic and cultural losses in the town; and on May 9, 2009, a natural gas pipeline in Moscow,

Russia, leaked and exploded, causing the largest urban fire in Moscow since the end of World War II (Han and Weng, 2011).

The above mentioned incidents suggest that urban natural gas pipelines pose a huge risk to life and property. In China, most large- and medium-sized cities have complicated pipelines, closely spaced buildings, and extremely high population density. Furthermore, they respond to accidents by paying more attention to post-accident treatment but less to pre-accident prevention, as a result of which any accident will likely have serious consequences (Fu, 2009). Therefore, there is a strong need for a pre-warning system for forecasting and simulating natural gas pipeline accidents (Ma et al., 2013a,b; Ma and Li, 2010). Although secondary disasters (e.g., fire) have a low possibility of occurrence, they can cause serious impacts and losses, and therefore, they should be strongly focused on in the simulation as well.

Toward this end, this study establishes a natural gas pipeline network quantitative risk analysis model and the urban fire spread model. Furthermore, it employs GIS spatial analysis technology to determine areas where fires can spread easily so as to take preventive measures for the same. By focusing on Leshan, Sichuan, as the study site, this study analyzes the impacts of accidents relating to urban natural gas pipelines and dynamic fire simulation; summarizes previous models; simplifies and improves them; develops a framework for the combined analysis of the impacts of fires or explosions related to natural gas pipelines and simulation of the spread of urban fires; proposes methods to determine the direct

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impacts of natural gas fires or explosions and the locations where accidents occur; and simulates the possible spread of the fires. This study visualizes the analysis of fire impacts and simulation of fire spread by employing powerful GIS spatial analysis and image display technologies (Zhao, 2011). The pre-warning system can not only serve as an important reference for related decision-making departments in formulating contingency plans but also assist in related planning management departments in conducting prevention, control, publicity, and education regarding areas with potential safety hazards before any accident happens; furthermore, it can contribute toward the secondary planning and reconstruction of a city so as to nip any potential risks in the bud (Han and Weng, 2010).

2. Related works

2.1. Analysis of impacts of natural gas accidents

Researchers, both domestically and internationally, have extensively studied the impacts of accidents related to natural gas pipelines. In the 1970s, the US started conducting risk assessments of oil and gas pipelines and identified 22 fundamental factors that endanger pipelines (ASME, 2001). Subsequently, researchers used qualitative research methods such as analytic hierarchy process (AHP), fuzzy mathematics (FM), fault tree analysis (FTA), and data envelopment analysis (DEA) for the risk analysis of natural gas accidents (Cagno et al., 2000; Bonvicini et al., 1998; Yuhua and Datao, 2005; Hawdon, 2003). By summarizing existing studies, Muhlbauer (2004) wrote the *Pipeline Risk Management Manual*, which is the first report to contain a quantitative risk assessment of oil pipelines. This manual is widely accepted worldwide and is considered a standard for developing risk assessment software. It has been successfully applied to the development of several systems and has been used continuously for more than 10 years (Han and Weng, 2011). In the early 1990s, Canada established a special pipeline risk assessment committee responsible for implementation schemes for the development of pipeline risk assessment management technology (Brian and Mike, 1995). Between 1997 and 2000, the Gas Transportation Committee of the International Gas Union (IGU) conducted studies on risk assessment; in their concluding report in 2000, they presented methods for risk assessment and identification, risk assessment, risk control, environmental risk assessment, etc. (Fever, 2000). In 2000, Southwest Petroleum University and PetroChina Southwest Branch jointly researched and developed a gas transportation pipeline risk assessment software and conducted full-line risk analyses and assessments of gas pipelines in Chongqing using this software and an international assessment indicator system (Fu, 2009). In 2008, the China Safety Science Research Institute of Dangerous Chemicals Safety Institute of Technology developed the CASST-QRA software for the quantitative area risk assessment of major hazardous installations V1.0 (CASST-QRA, 2008). Ma and Li (2010) proposed natural gas disaster models, including the fire effect model and the overpressure explosion model. Ma et al. (2013a) established several GIS-based natural gas pipeline network pre-warning systems by employing a quantitative risk assessment method. Many studies and analyses have shown that the quantitative risk assessment method has become one of the important ways for improving the performance of urban natural gas pipelines and avoiding the related risks. However, most currently used analysis models do not take accident types into consideration; instead, they only focus on the consequences of an accident or analyze some link of the accident process, and they do not simulate the further impacts of accidents (e.g., fire spread). To bridge this gap, the present study focuses on these issues.

2.2. Simulation of urban fire spread

Many researchers have simulated fire spread. Relative to the spread of urban fires, current research methods for the spread of forest fires are mature. These include the contiguous cellular model based on cellular automata theory and the volatility transmission model based on the Huygens Principle (Karafyllidis and Thanailakis, 1997; Anderson et al., 1982). Unlike forest fires, the spread mechanism and spread environment of urban fires have distinct characteristics, based on which researchers have built corresponding spread models.

Through statistical analyses of data related to post-earthquake fires, Japanese research groups such as Suzuki and Kinbara (1940), Tokyo Fire Prevention Working Group (1942), Tosabayashi (1947), Hamada (1951), Hishida (1954), Horiuchi (1961), Fujita (1975), and Sakai (1983) have proposed a series of fire spread empirical models (Fire safety science, 1986), among which Hamada's model is considered the most representative. This model is based on an ideal city (all buildings in the city have consistent size, shape, and distance) and related experiences, which provides a method that is relatively easily understood and easily applied and that becomes a basic empirical model with the most extensive scope of application and the greatest influence (Hamada, 1951). Based on Hamada's model, the Federal Emergency Management Agency developed the FFE earthquake secondary fire spread model (HAZUS99 Federal Emergency, 1999). In 2000, Himoto and Tanaka built a physics-based model for fire spread and models for heat radiation and plume spread inside buildings and among buildings based on the mechanism of urban fire spread (Himoto and Tanaka, 2002, 2008). In 2006, Zhao et al. simplified the model for spread inside buildings (Zhao et al., 2006; Zhao, 2010) and divided the entire fire simulation process into in-building spread and building-to-building spread. Cousins et al. (2002) and Ohgai et al. (2007) developed a cellular automata urban fire spread model based on a 3×3 grid; Zhao et al. (2011) improved this model by modifying its form and increasing the cell size to develop an urban fire spread model based on coarse cellular automata. In 2008, Lee et al. compared and summarized existing urban post-earthquake fire spread models in terms of aspects such as the model algorithm, model parameter, result analysis, and model presentation (Lee and Davidson, 2008). In 2010, Selina et al. developed a model for fire spread in a single room, among rooms in a building, and among buildings (Lee and Davidson, 2010). Cheng and Hadjisophocleous (2011) developed a model for horizontally and vertically simulating urban fire spread. Nishino et al. (2012) presented an evaluation method for urban post-earthquake fire risk and simulated the fire spread results using physics-based fire-spread. Recently, Li and Davidson (2013) apply an urban fire simulation model to a case study area and examine the key factors that influence fire spread.

We note that most existing urban fire spread models are proposed based on post-earthquake fires and only analyze the impacts of natural gas fires (Ma et al., 2013a; Ma and Li, 2010) without considering the further spread of fires occurring in areas with many wooden structures. And also less the other application is implemented. Moreover, theoretical models have been used to analyze spread processes based on their mechanisms; however, they are too complicated and need to be simplified and revised so that they can be adapted to macroscopic dynamic simulations. In addition, fire spread shows special characteristics when caused by natural gas pipeline leakages. Based on related studies on the two sectors and conclusions regarding practically available models and in combination with the objectives of this study, this study simplifies, revises, and improves problems such as incomplete consideration of accident types, lack of further simulations of fire spread, complexity of urban fire theoretical models, and lack of analyses of natural gas accidents.

3. Methods

The effective analysis and dynamic simulation of urban natural gas pipeline accidents is complicated. Using GIS, this study combines the effect analysis module of natural gas accidents with the urban fire spread module and develop a pre-warning system, with a specific realization including the following four main steps: (1) Calculation of leakage amount: the calculation of the leakage amount is the basis of physical effect analyses. The failure or leakage of a pipeline will lead to different physical effects. During analyses, appropriate models should be selected based on pipeline parameters and environmental parameters to calculate the leakage amount. (2) Physical effect analysis: Natural gas is flammable, and if the concentration of the gas leaked out falls into the range of a fire limit, under the action of an ignition source, a serious fire (fire ball, jet fire, or flash fire) or explosion accident will be triggered. Different accidents correspond to different physical models, and here the jet fire model is used to calculate the related physical quantity according to the different leakage amounts and related environmental conditions, based on which this study also realizes the effect analysis of accidents related to natural gas leakage point sources. (3) Fire accident effect analysis for ignition from urban gas pipeline: Physical effects and accident impacts caused by failures or leakages of pipeline networks are quantitatively associated. The simulation of fire accident impacting on people or buildings and the analysis of the spatial distribution of high-risk areas can be realized based on different physical effects and their corresponding damage standards. The ignition of building arouse (4) urban fire spread simulation: If a fire due to a leakage of pipeline networks occurs in an area with closely spaced wooden buildings, it is very likely to cause fire spread and have a large-scale impact. Here we propose a multi-objective fire spread model among buildings to estimate overlapping impact. Based on theoretical models and in combination with natural gas fire models, this study makes simplifications and revisions and develops an urban fire spread two-stage model using GIS that considers fire development inside buildings and fire spread among buildings. Taking into account the building ignition conditions, this study also dynamically simulates

fire spread in fire hazard areas. Specific processes regarding the effect analysis and dynamic simulation for urban natural gas pipeline accidents are shown below in Fig. 1.

3.1. Urban natural gas pipeline fire model

3.1.1. Calculation of leakage amount

Among failure modes of pipeline networks, the most common one is leakage. The methods for calculation of the leakage amount of pipelines vary with their diameters. The calculation methods mainly include the small-hole model, pipeline model, and model of other diameters (Ma et al., 2013b). The small-hole model is mainly introduced as follows. Provided that the gas leaked out from small holes conforms to the ideal gas law, according to the Bernoulli equation, the gas leakage amount is calculated as

$$q = C_d p A \sqrt{\frac{2kM}{(k-1)RT} \left[\left(\frac{p_0}{p} \right)^{\frac{2}{k}} - \left(\frac{p_0}{p} \right)^{\frac{k+1}{k}} \right]} \quad (1)$$

where q is the gas leakage amount (kg/s); C_d is the discharge coefficient the value of which depends on the shape of the fracture lips, and if there is a sharp edge like triangle (0.95) or rectangle (0.90) the value will not be 1.0; p , the internal pipeline pressure (Pa); A , the area of the pipeline crack (m^2); M , the molecular weight of the gas in the pipeline (kg/mol); R , the gas constant (8.314 J/(mol K)); T , the temperature of the gas in the pipeline (K); p_0 , the ambient pressure (Pa); and k , the adiabatic exponent, i.e., the ratio of constant pressure specific heat capacity to constant volume specific heat capacity.

3.1.2. Fire and thermal radiation modelling

In the case of a leakage of hazardous substances, a fire will be triggered under the action of an ignition source. High-temperature radiation generated from combustion is the main cause of harm to people and buildings. In this study we mainly focuses on natural gas fires, the introduction to the fire effect model is emphasized upon. Other natural gas disaster models have also been proposed in previous studies (Ma and Li, 2010; Ma et al., 2013a), including

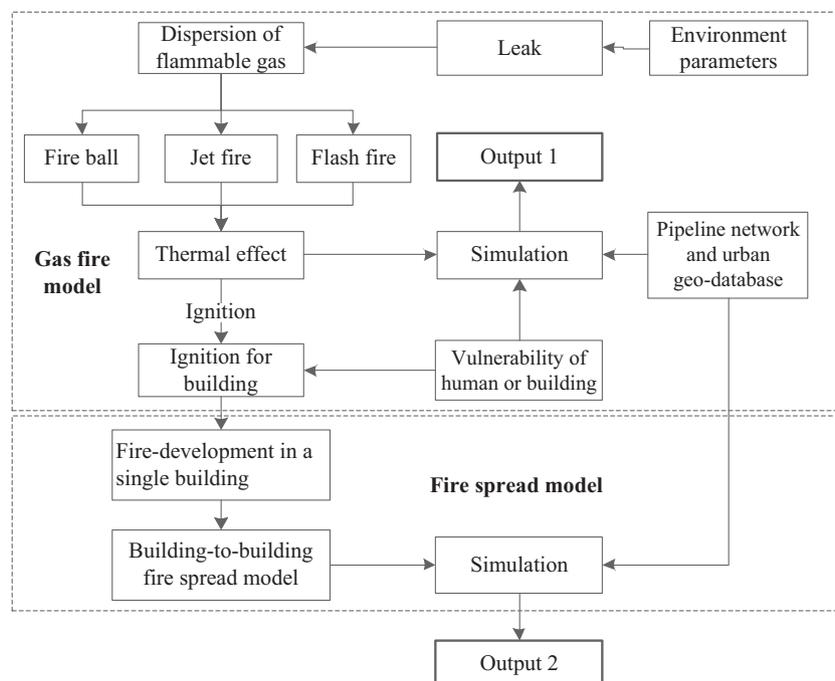


Fig. 1. Research processes.

the overpressure explosion model. According to previous studies, a fire is classified into three types based on the flame shape: fire ball, jet fire, and flash fire (OGP, 2010a,b). The jet fire model of the flame shape is selected to simplify the simulation in GIS. In the jet fire model, the equation of the heat radiation flux an object receives at a specific site is calculated by using (Ma et al., 2013a)

$$I = \frac{\gamma \tau q H_c}{4\pi r^2} \quad (2)$$

where I is the thermal radiation (W/m^2); γ , the radiance coefficient (0.2); τ , the atmospheric transmittance (1); q , the leakage flow (kg/s); H_c , the heat of combustion of the natural gas ($5.56 \times 10^4 \text{ kJ}/\text{kg}$); and r , the distance (m).

3.1.3. Accident impact analysis

When determining the high-risk areas related to fires accidents, we should, based on the calculation formula for heat radiation in the physical effect model, select corresponding heat radiation standards and obtain the radius of damage of different degrees to simulate the multi-level impacts of a specific accident on people and buildings. In addition, we can also extend the model to the entire urban pipeline network and determine the potential hazardous areas of fire accident of different degrees arising from the pipelines by analyzing the danger distance buffer. The impacts of heat radiation from fires on people and buildings/equipment are shown below in Table 1 (OGP, 2010a,b).

Different standards correspond to different damage conditions. The proposed model can simulate the damage conditions at specific points of accidents that have already occurred, pre-analyze the targets that should be well-protected and determine the possible damage to people and buildings, and analyze the danger distance buffer concerning the entire urban natural gas pipeline network to select buildings that are more likely to be affected by pipeline accidents. To analyze the impacts of the entire pipeline network, the model selects the level B and level C damage standard for the impacts of heat radiation on buildings to determine the buildings that are more likely to be affected (most wooden structures). For houses with a higher risk of fire, fire spread can be simulated using the later modules so as to further determine the scope of impacts of secondary disasters due to natural gas fires and pre-analyze the high-risk areas.

In addition, we can also obtain the population density of high-risk areas through statistical data. We can determine the damage radius, predict the death toll, and quantitatively understand the potential or real disaster impacts based on the level A damage standard for impacts on people in areas where fires or explosions occur or are likely to occur.

3.2. Urban fire spread model

Based on theoretical models and in combination with natural gas fire models, this study makes simplifications and revisions

and develops an urban fire spread two-stage model using GIS to consider fire development inside buildings and fire spread among buildings. It also dynamically simulates fire spread in fire hazard areas by considering the conditions for building fires. First, in the natural gas fire impact analysis module, based on the damage standards (shown in Table 1) of heat radiation due to fires in wooden houses, this study selects buildings with higher fire hazards as ignition buildings. In other modules, buildings whose heat radiation, calculated by employing a model for fire development inside buildings and a model for fire spread among buildings, satisfies the conditions for catching a fire are considered ignition buildings.

3.2.1. Model for fire development inside buildings

Because the fire development and spread behaviors inside rooms in a building are very complicated, being impacted by factors such as the building structure, building materials, and building ventilation conditions, a complicated individual building model is not suitable for the macroscopic simulation of the entire city, and therefore, the proposed model does not consider the detailed spread processes of indoor fires. By referring to Zhao et al.'s (Zhao, 2010) simplified model for fire development inside buildings and considering the background regarding the ignition of natural gas, this study selects buildings with greater fire hazards as the initial ignition buildings. The simplified model considers every ignition building an ignition source and divides the fire development process inside buildings into five stages: ignition, flashover, full-development, collapse, and extinguishment (see Table 2). This model considers that when an internal fire develops to the flashover stage, the fire breaks through the limitation of rooms and spreads across stories. When the internal fire develops to the full-development stage, the fire develops to the entire building; the indoor temperature and heat release rate reach the peak values; and the fire likely spreads outward. To simplify the model, based on experts' suggestions, this study roughly estimates the time period from the ignition stage to the full-development stage by only considering the buildings' structural types and basic environmental parameters.

In addition, the average temperature and heat release rate of the building at any moment can be calculated, and the related fire development stage can be judged based on the simplified curves of the individual building fire development. The ranges for peak values of the temperature and heat release rate are $T_{\max} = [800, 1200] \text{ }^\circ\text{C}$ and $Q_{\max} = [40, 50] \text{ MW}$. The simplified curves are shown below in Fig. 2 (Zhao, 2010).

3.2.2. Model for multi-objective fire spread among buildings

When an indoor fire develops to the full-development stage, the fire will spread to adjacent buildings and cause fire spread over a larger scale. This study mainly uses the theoretical models proposed by Himoto and Tanaka and improved by Zhao et al. (Himoto and Tanaka, 2002, 2008; Zhao, 2010) and makes corresponding simplifications and adaptations based on background

Table 1
Impact of heat radiation from fires on people and buildings/equipment.

Radiation intensity (kW/ m^2)	Impact on people	Impact on buildings/equipment	Influence division
37.5	1 min, 100% people die; 10 s, 1% people die	All operating equipment are damaged	A
25	10 s, serious injury	Minimum energy for wood burning with no fire and long radiation	B
12.5	1 min, 1% people suffer serious injury; 10 s, first-degree burn	Minimum energy for plastic melting with flame and wood burning	C
4	Feel pain, even burns, above 20 s	30 min, glass broken	D
1.6	No impacts even over a long time		E

Table 2
Time ranges of stages of individual building fire development model (Zhao, 2010).

Fire stages	Time interval (min)	Structural type		
		Wooden	Fire-proof	Fire-resisting
Ignition → flashover	t_1	[5, 10]	[5, 10]	[5, 10]
Flashover → full-development	t_2	[20, 30]	[30, 50]	[50, 60]
Full-development → collapse	t_3	[50, 60]	[80, 100]	[120, 180]
Collapse → extinguishment	t_4	[240, 300]	[30, 40]	[20, 30]

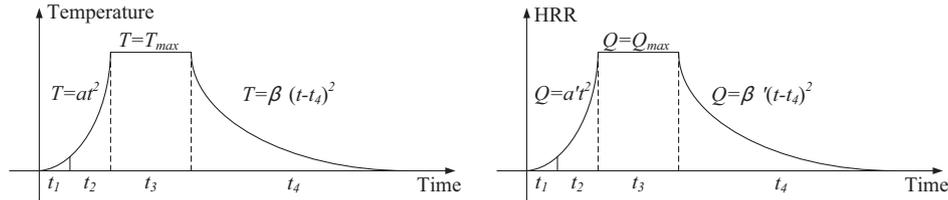


Fig. 2. Simplified curves for development of internal temperature and heat release rate of buildings (Zhao, 2010).

knowledge of natural gas accidents. The model for fire spread among buildings mainly includes the heat radiation spread, heat plume spread, and jump fire spread, among which the heat radiation spread is the main mode of fire spread among buildings and the heat plume spread is the main mode of downwind direction temperature rise. Owing to its uncertainty, jump fire spread is not discussed herein. We also consider the overlapping impact of multi-objective fire building due to multiple fires occur simultaneously.

(1) Heat radiation

Ignition leads to the transmission of heat radiation via indoor exhaust gas, flame ejected from building windows, and exterior walls (see Fig. 3). To simplify the model, the ignition building is seen as an integrated part, and after the ignition sources of the windows and exterior wall radiation are converted, the radiation intensity transmitted by the ignition building may be calculated as (Himoto and Tanaka, 2002)

$$q_R = \frac{q_D A_D + q_W (A_W - A_F) + q_F A_F}{A_D + A_W} = \frac{1}{\varphi} \frac{q_D A_D}{A_D + A_W} = \frac{k}{\varphi} q_D = \frac{k}{\varphi} \sigma T^4 \quad (3)$$

where q_D (kW/m²) is the radiation intensity that indoor exhaust gas emits via windows; A_D (m²), the area of the windows; q_W (kW/m²), the radiation intensity of exterior walls; A_W (m²), the area of exterior walls; q_F (kW/m²), the radiation intensity of the flames ejected; A_F (m²), the area of ignition sources; φ (0.8), the conversion factor regarding the proportion of flame radiation and exterior wall radi-

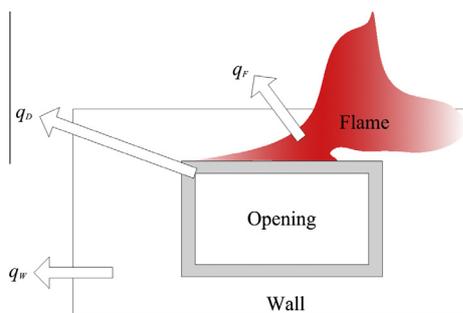


Fig. 3. Intensity of radiation generated by exterior walls of ignition building (Himoto and Tanaka, 2012; Zhao, 2010).

ation in the total radiation; k , the windowing rate of the exterior walls (0.4 for general office buildings, 0.2 for residential buildings); σ (5.6697×10^{-8} kg/s³ K⁴), the Stefan-Boltzmann constant; and T (K), the temperature of indoor exhaust gas.

(2) Heat plume

The model for fire spread among downwind direction buildings is very complicated. Research concerning heat plume features has progressed slowly owing to the insufficiency of experimental data. In contrast, the features of vertical heat plume have been sufficiently researched. This study uses the temperature on the vertical heat plume axis to approximately replace the temperature of the heat plume axis inclined under wind action. The temperature of the heat plume axis (ΔT_0 (K)) is calculated as (Himoto and Tanaka, 2002, 2008)

$$\Delta T_0 = 24 \left(x / Q_0^{2/5} \right)^{-5/3} \quad (4)$$

where x (m) is the distance between any point on the heat plume axis and the center point of the ignition building and Q_0 (kW), the heat release rate of the ignition building. Provided that the symmetric temperature of the heat plume remains unchanged under wind action, the temperature rise owing to the heat plume of a building located in the downwind direction and at a certain distance from the heat plume axis may be calculated as

$$\Delta T(r) / \Delta T_0 = \exp \left[-(r/b)^2 \right] \quad (5)$$

where r (m) is the perpendicular distance between the center point of the building located in the downwind direction and the heat plume axis and b (m), is the radius of the heat plume. Because the wind speed is much higher than the heat plume propagation speed, the possible impacts of the heat plume on the wind speed are not considered. As shown in Fig. 4, to determine the radius (r), the model should first calculate the gradient of the heat plume under wind action with speed U_∞ (m/s). In this study, the gradient is calculated by referring to Yokoi's heat plume experiment formula as

$$\tan \theta = 0.1 \left[U_\infty / (Qg / \rho_\infty C_p T_\infty) \right]^{-3/4} \quad (6)$$

where Q (kW/m) is the heat release rate per unit length calculated by using the formula $Q = Q_0 / \sqrt{A_{\text{floor}}}$. (A_{floor} (m²) is the plane area of the ground floor of the ignition building); ρ_∞ (kg/m³), the density of ambient air; C_p (kJ/kg K), the specific heat of the heat exhaust gas; and T_∞ (K), the ambient environmental temperature.

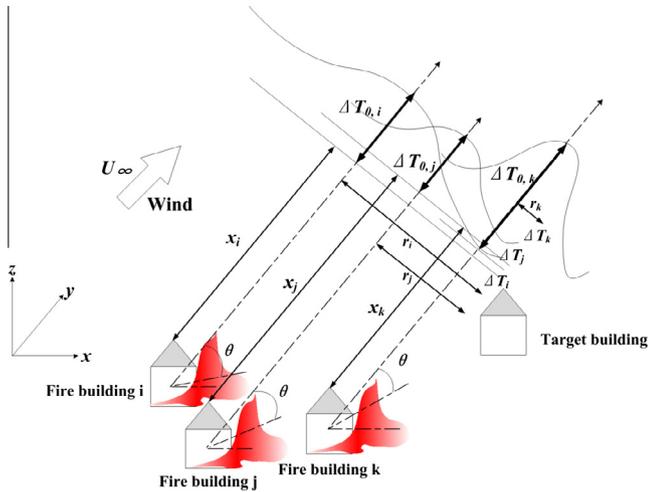


Fig. 4. Heat plume model (Himoto and Tanaka, 2008).

Cities contain many closely spaced buildings, and therefore, an adjacent building may catch fire during fire spread. As a result, downwind buildings are under the joint action of several heat plumes. Because mutual mixture among different plumes is excessively complicated, to simplify the model, this study assumes that the temperature rise of downwind buildings is the superposition of the temperature rises of several heat plumes, based on which a downwind building's temperature rise ΔT (K) under the joint action of several heat plumes is calculated as

$$\Delta T = \left[\sum_{i=1}^n (\Delta T_i)^{3/2} \right]^{2/3} \quad (7)$$

where ΔT_i (K) is the temperature rise under the action of one heat plume and n , the number of heat plumes that impact the building.

(3) Ignition condition

An unignited building receives the combined action of external environmental heat radiation and heat plumes via its exterior walls and windows. Once the heat it receives exceeds the radiation intensity of the ignition limit, this building is considered to have ignited. The circumstances under which a building receives heat radiation are shown in Fig. 5. If an unignited building is a wooden structure, the ignition of its exterior walls always precedes that of its indoor space. Considering practical circumstances, we mainly analyzed the possible disasters of wooden buildings; therefore, in

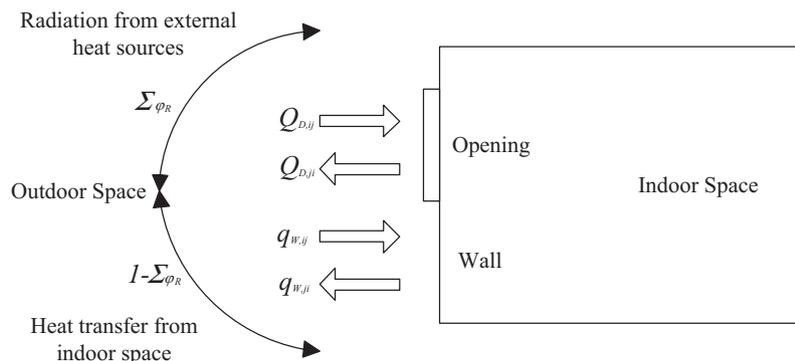


Fig. 5. Schematic diagram of intensity of heat radiation a building receives (Himoto and Tanaka, 2002; Zhao, 2010).

this study, we only discuss the intensity of heat radiation that exterior walls receive.

When a building receives heat radiation via its exterior walls, the intensity of the heat radiation it receives is calculated as (Himoto and Tanaka, 2002)

$$q_w = q_{w,ij} - q_{w,ji} \quad (8)$$

where $q_{w,ij}$ (kW/m^2) is the heat radiation that an unignited building receives via its exterior walls and $q_{w,ji}$ (kW/m^2), the heat radiation the building transfers outward. $q_{w,ij}$ and $q_{w,ji}$ are calculated as

$$\begin{cases} q_{w,ij} = \varepsilon_w \left[(1 - \sum \varphi_R) \sigma T_i^4 + \sum \varphi_R q_R \right] + h_w T_i \\ q_{w,ji} = \varepsilon_w \sigma T_w^4 + h_w T_w \end{cases} \quad (9)$$

where ε_w is the emissivity of the exterior walls (generally, 0.9 for wooden structures); φ_R , the angular coefficient of heat radiation of the exterior walls imposed by the heat source beyond the walls; q_R (kW/m^2), the intensity of heat radiation that the external heat source (ignition building) transmits; h_w , the convective heat transfer coefficient of the walls; T_w (K), the temperature of the walls, calculated via a one-dimensional heat conduction equation that includes humidity; and T_i (K), the temperature beyond the walls, being the temperature increase under the action of heat plumes, namely, $T_\infty + \Delta T$. When the intensity of heat radiation that a building's exterior walls receive exceeds that for the ignition limit (q_c), the building is considered to have ignited. When the intensity of the limit heat radiation for the ignition of wood is considered, according to different water contents (subject to environmental humidity), q_c should range from 10 to 18 kW/m^2 .

In addition, fire spread is also influenced by weather conditions. Among air temperature, humidity, rainfall, wind, and other meteorological conditions, wind has the greatest impact. The wind direction influences the fire spread direction and the wind speed, the fire spread speed. The effects of wind direction and wind speed are appropriately considered in the heat plume model.

4. Results and discussion

4.1. Accident impact analysis

To verify the feasibility of the proposed method, we conducted urban natural gas fire accident analysis and developed a fire spread dynamic simulation module by using special data concerning the complete natural gas pipeline network and the basic geographical database of a city and by integrating the .NET platform (of Microsoft) and the ArcGIS Engine (of ESRI) secondary development module. With regard to a natural gas single-point leakage accident, the degree of harm suffered by people and buildings within a certain area around the accident point may be simulated based on the

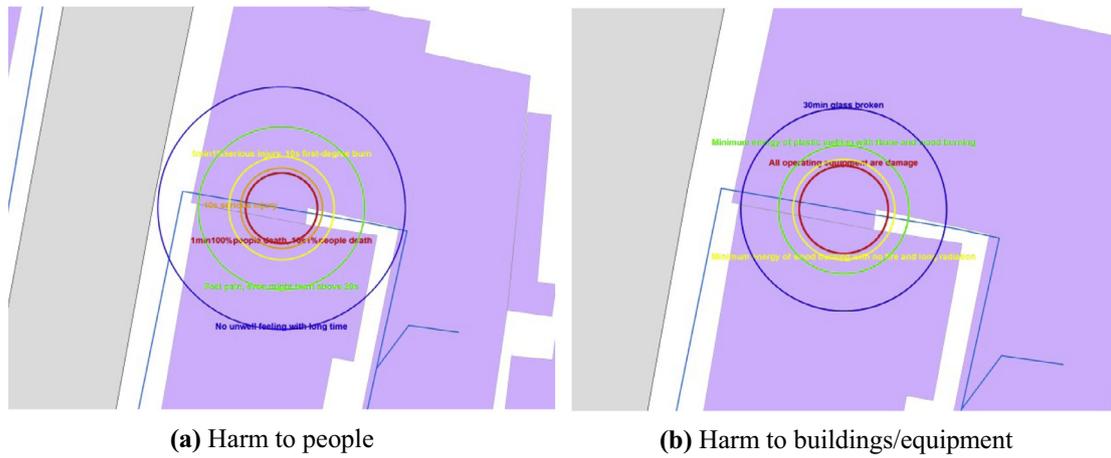


Fig. 6. Fire impact analysis. (a) Harm to people. (b) Harm to buildings/equipment.

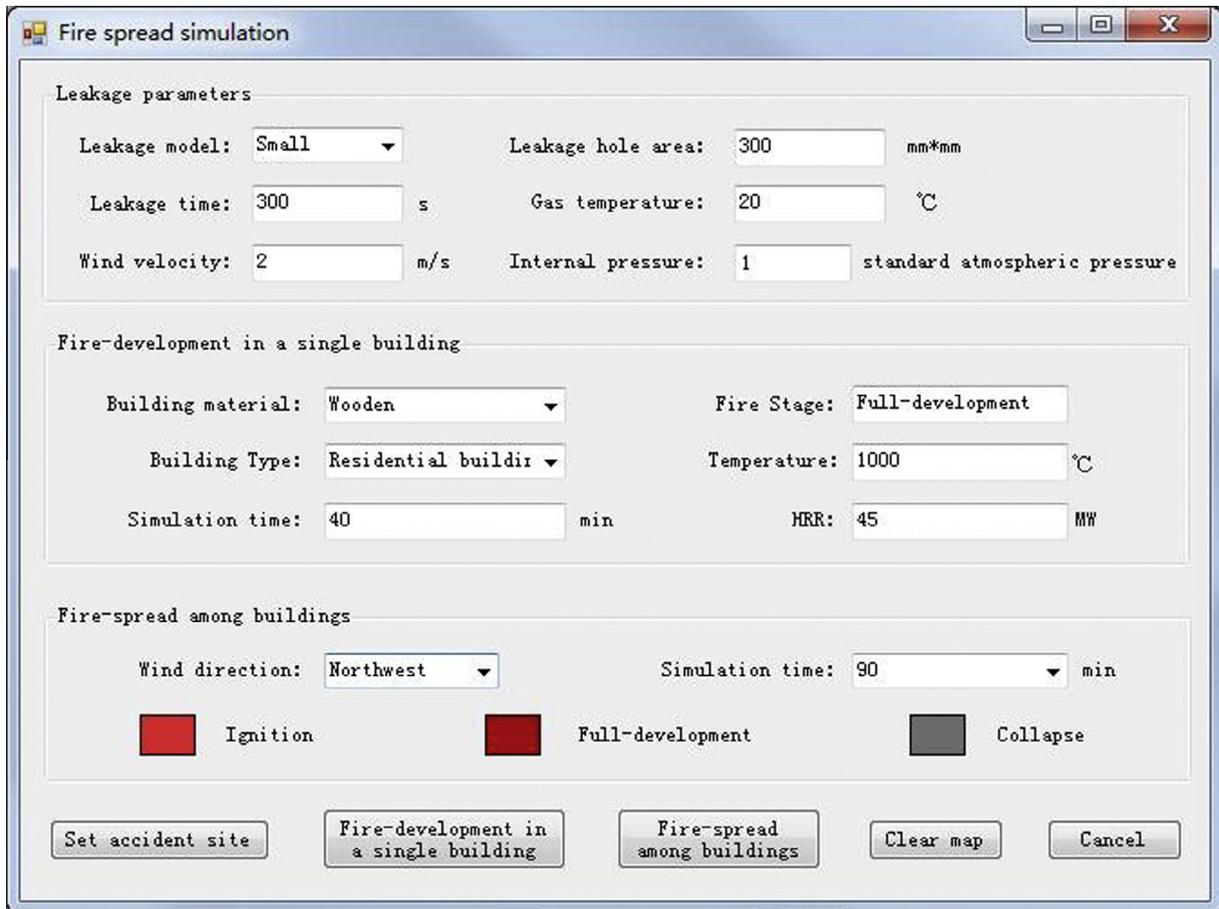


Fig. 7. Fire spread simulation interface.

jet fire model (Section 3.1.2) and by inputting parameters such as leakage area, internal pipe pressure, gas temperature, leakage model, and leakage time. Table 1 lists the five and four levels of impacts of various durations of fire to people and buildings, respectively. Different levels are labeled by different self-defined colors. Under the condition that the leakage opening area is 300 mm², the internal pipe pressure is 0.1 MPa (one time the standard atmospheric pressure), gas temperature is 20 °C, leakage model is the small-hole model, and leakage time is 5 min; then, the harm that a fire does to people and buildings is shown below in Fig. 6.

In 2013, Ma et al. proposed a function for analyzing the impacts of natural gas explosion accidents (Ma et al., 2013a), so unnecessary details are not given here. In particular, for the level-C standard for damage to buildings, namely, the minimum energy for wood burning, if we analyze the buffer of the damage distance of the entire urban pipeline network and select the wooden houses falling into the range of damage, we can determine the wooden buildings that are likely to be ignited under an urban natural gas pipeline network fire (see the initiation of fire spread at 0 min in Fig. 8a), providing a foundation for analyzing the potential fire spread in areas of the city.

The analysis results show that fire hazard buildings are mainly distributed in areas with closely spaced wooden buildings (Fig. 8a) that are extremely likely to cause further fire spread and lead to large-scale hazards. The fire spread simulation module is described below. The urban natural gas management departments, by using fire or explosion impact analysis modules, can not only evaluate the accident impact degree after an accident occurs but also pre-analyze high-risk areas and take key prevention and control measures.

4.2. Fire spread simulation

The system sets fire hazard buildings as ignition buildings and employs the model for fire development inside buildings (Section 3.2.1). When developing to the full-development stage, a fire spreads outwards. At this time, the model for fire spread among buildings (Section 3.2.2) is employed to judge the buildings satisfying the ignition conditions for the ignition state via the temperature rise from heat radiation and heat plumes. Then, the two models are alternatively employed until the total preset simulation time is satisfied. After several alternative uses of the models, the

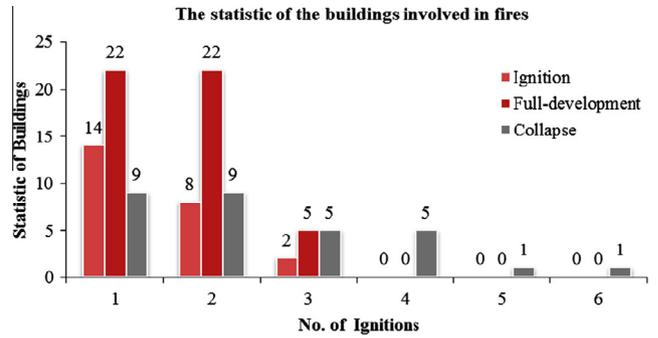


Fig. 9. Comparisons of fire spread buildings at different stages (ignition, full Development, and collapse).

distribution of the fire spread is output to realize the fire spread simulation and analyze the fire hazard areas in urban buildings. Fig. 7 shows the fire spread simulation interface.

The leakage parameters input into the module are the same as those input into the fire impact analysis module. If the leakage

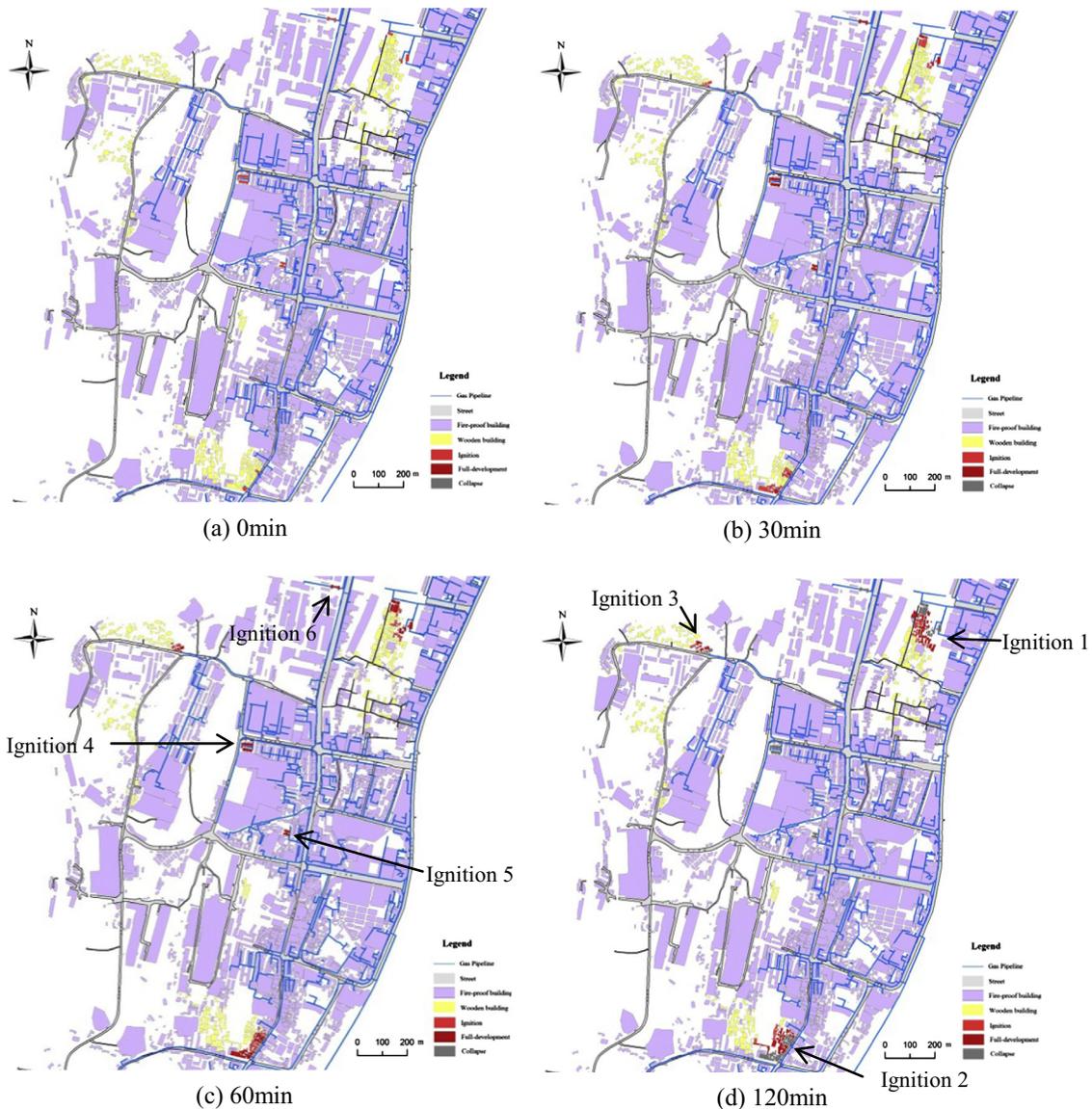


Fig. 8. Fire spread simulation.

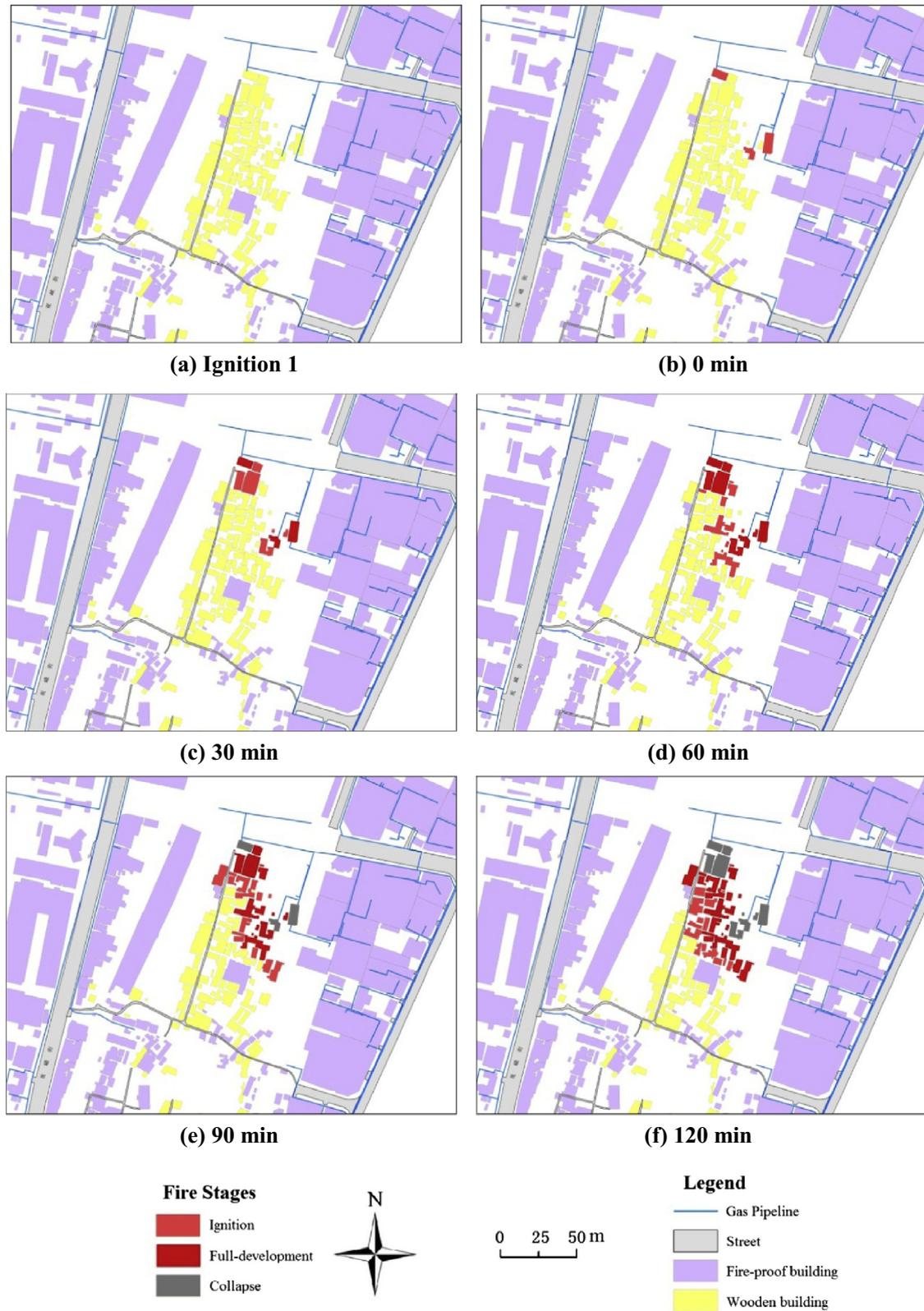


Fig. 10. Fire spread simulation in ignition 1.

opening area is 300 mm², the internal pipe pressure is 0.1 MPa (one time the standard atmospheric pressure), gas temperature is 20 °C, leakage model is the small-hole model, and leakage time is 5 min; if the leakage lasts 5 min, after a quantitative analysis of the leakage and fire accident, the building may be confirmed as a

fire hazard building (see Fig. 8a) or a starting point for the spread of an urban fire. When analyzing a single-building fire development model, we decide the stages of the fire by simulating the building materials, building types, and fire duration; simultaneously, we calculate the thermal radiation and temperature inside

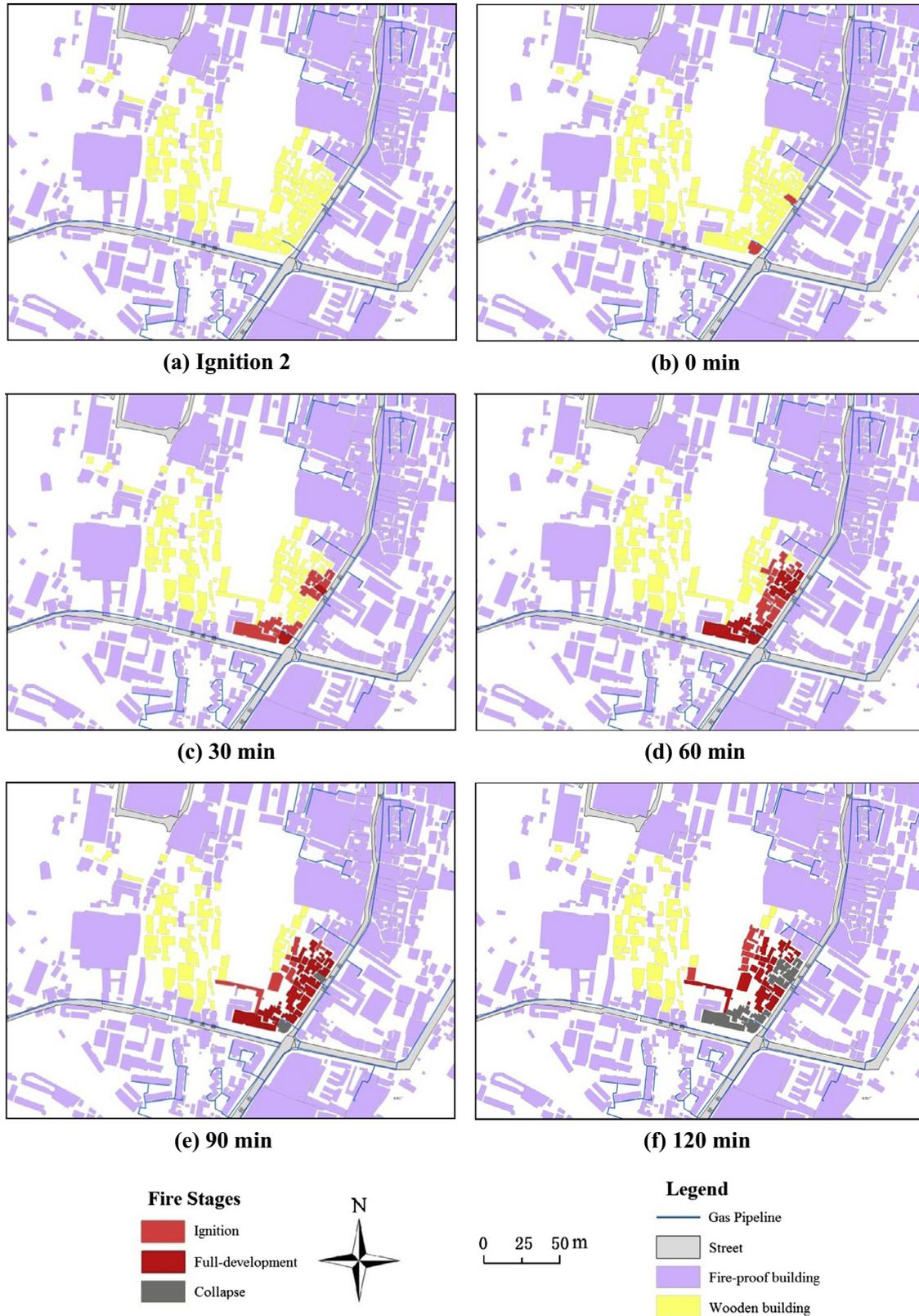


Fig. 11. Fire spread simulation in ignition 2.

the building. If the building is made of wood, if the building is a residential house, and if the fire lasts for 40 min, according to a calculation based on the model for fire development inside buildings, the fire accident is at the full-development stage; at this time, the

temperature inside the building is 1000 °C and heat release rate is 45 MW. When analyzing the model for fire spread among buildings, we dynamically simulate the spread of an urban fire accident by simulating the wind direction and fire duration based on the

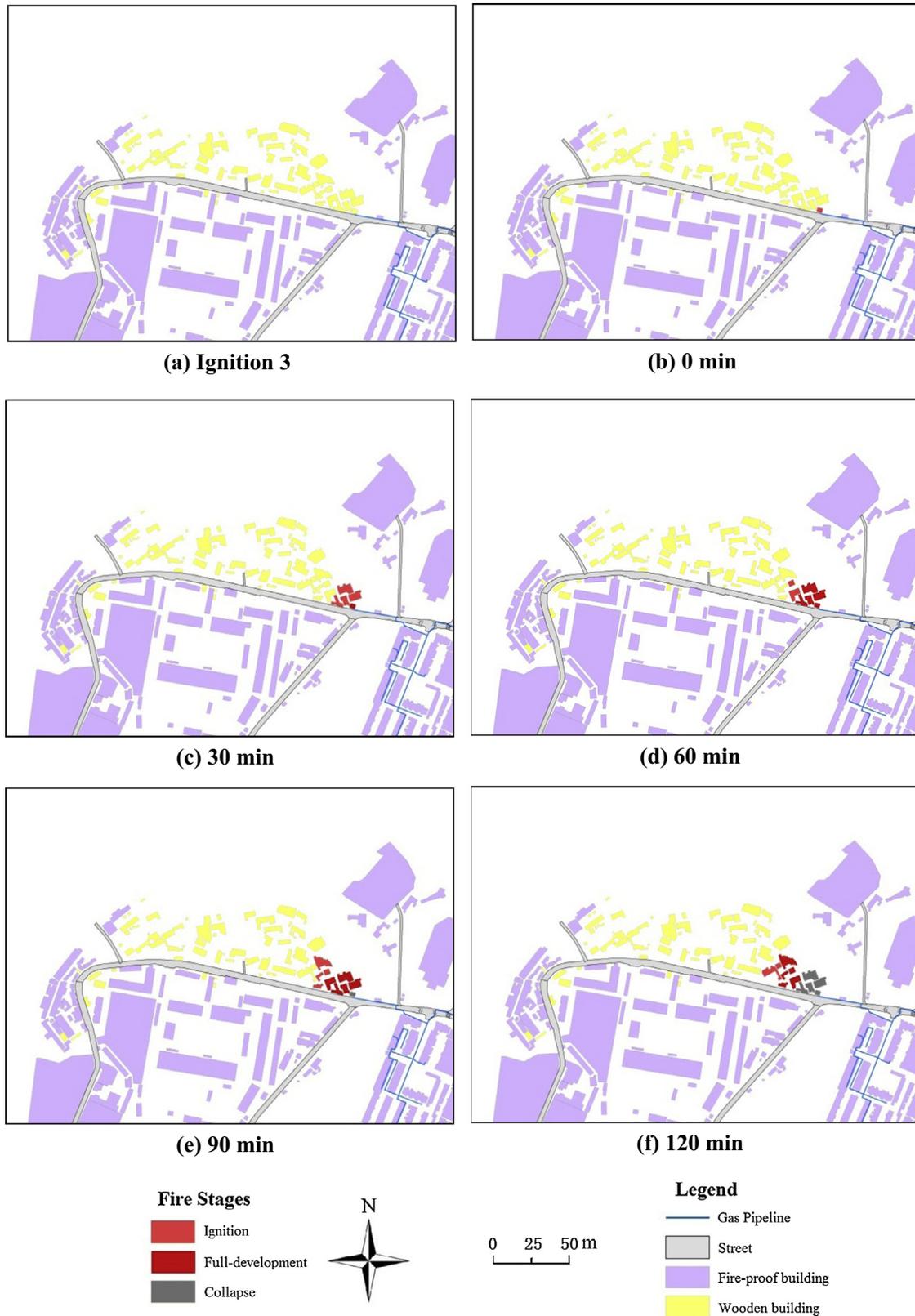


Fig. 12. Fire spread simulation in ignition 3.

abovementioned process. As shown in different colors (see Fig. 8), a building goes through the following stages when it catches fire: ignition, full development, and collapse. As illustrated in Fig. 8a, we dynamically simulate the initiation of fire from a building affected by a natural gas pipeline fire accident based on the above mentioned parameters (leakage parameters are the same as those

used in the fire impacts analysis model). As illustrated in Fig. 8, we take a snapshot of the fire spread at 0, 30, 60, and 120 min.

A comparison of the fire spread simulation results at different time nodes reveals the following: at the initial stage, when the fire spreads slowly, it is best to extinguish the fire; once it spreads, when the fire engulfs an increasing number of buildings, it spreads

increasingly fast; at this time, it is difficult to extinguish the fire. After analyzing the fire spread, we conclude the following: there are six fire-prone spots in the research area, including ignition 1, 2, 3, 4, 5 and 6 (see Fig. 8c and d); among the six fire-prone spots, three are sensitive to the spread of a natural gas fire accident. The simulated results may help the natural gas pipeline network departments or urban planning departments devise secondary plans for pipelines or related areas so that they can nip a fire accident in the bud. As shown in Fig. 9, we statistically analyze the buildings remaining in the six spots across which the fire spreads so that we can further explain the fire impacts.

A statistical analysis of fire spread (see Fig. 9) reveals the following: after a natural gas leakage triggers a fire, the fire spreads expansively; 120 min later, the fire spreads the fastest at Spot 1, where 45 buildings are burning, among which 9 collapse, 22 are in the full-development stage (fire burns ferociously), and 14 are ignited; at Spot 2, 39 buildings are burning, among which 8 collapse, 9 are ignited, and 22 are in the full-development stage; the fire spreads less fast at Spot 3 than at Spots 1 and 2 in that 5 buildings collapse, another 5 are in the full-development stage, and 2 are ignited; at Spot 4, 5 buildings collapse; at Spot 5, 1 building collapses; and at Spot 6, 1 building collapses. From these statistics, we know that the fire spreads the fastest at the first three spots because they are situated in an area where wooden houses are concentrated. The fire then tends to spread further because these wooden houses burn easily, are connected with each other, and are poorly equipped with firefighting facilities. However, because wood materials are less used as building materials in the buildings situated at Spots 4, 5, and 6, and because these buildings are fire-proof or fire-resistant, the fire does not spread across the buildings at these three spots. We respectively illustrate the fire spread at Spots 1, 2, and 3 in Figs. 10–12. At Spot 1 (Fig. 10), 3 buildings may be starting points of the fire triggered by the natural gas leakage; 30 min later, another 6 buildings are ignited; 60 min later, another 9 buildings are ignited; 90 min later, another 12 buildings are ignited and 3 buildings collapse; and finally, 9 buildings collapse, 22 buildings are in the full-development stage, and 14 buildings are ignited. At Spot 2 (Fig. 11), 2 buildings are threatened by the fire; because these buildings are connected with each other and because the natural gas pipelines are densely buried underground, 30 min after the fire breaks out, another 7 buildings are ignited; 60 min later, another 13 buildings are ignited; 90 min later, another 8 buildings are ignited and 2 buildings collapse; and finally, 8 buildings are ignited, 22 buildings are in the full-development stage, and 9 buildings collapse. At Spot 3 (Fig. 12), only 1 building is the starting point for the fire; 30 min later, another 4 buildings are ignited; 60 min later, another 13 buildings are ignited; 90 min later, another 3 buildings are ignited and 1 building collapses; and finally, after 120 min, 5 buildings collapse, another 5 buildings are in the full-development stage, and another 2 buildings are ignited. A comparative analysis of fire spread across the three spots reveals that fire spreads the fastest here because of the closely spaced and interconnected wooden houses; furthermore, fire spreads more easily at Spots 1 and 2 than at Spot 3.

After analyzing fire spread, we understand the importance of the fire spread model for preventing fire accidents. By using the strong spatial analysis and imaging functions of GIS, the fire spread model can provide rich information about a fire accident. It uses the depth of colors to simulate the stages of fire development inside a building as well as the special conditions under which a building collapses. The fire spread model can be used for real-time fire spread simulation when a fire does occur. It exports statistics such as maps, drawings, and sheets. It simulates the fire severity. It can be used to derive many useful conclusions; for example, if between 60 and 90 min, many buildings are ignited and if the wooden houses are concentrated, the fire may spread quickly. By

analyzing a fire accident, predicting where the fire tends to spread across, and providing other related information, this model may help firefighters predict the impacts of fire, effectively comb the pipeline for any loophole, and instruct people living in the affected area, especially an area where fire may spread across quickly, to be cautious against the occurrence of any fire accident. It may even help planners derive secondary plans for the city's natural gas pipeline network or residential quarters so that we can nip any fire accident in the bud.

5. Conclusions

Any accident related to an urban natural gas pipeline is accompanied by serious disasters such as fires and explosions that may result in injury or death of personnel or collateral damage to property or the environment. We introduce GIS analysis to manage the urban natural gas pipeline network. After analyzing the impacts of an urban natural gas pipeline fire and studying related models simulating fire spread within the urban area, in this study, we propose a new framework that combines analysis of the impacts of an urban natural gas pipeline accident with dynamic simulation of fire spread. We use a semi-quantitative risk analysis method to analyze the impacts of fire accidents. After studying the special background of a natural gas leak based on theoretical models, we develop an applicable urban fire spread model, that is, a natural gas pipeline leak pre-warning system developed using C# programming and the ArcGIS Engine platform. We use the pre-warning system to dynamically simulate and analyze the impacts of a natural gas pipeline accident. The pre-warning system can export figures outlining the affected areas as well as the areas across which the fire is likely to spread according to various parameters under different conditions including time.

According to the characteristics of a natural gas pipeline accident, this proposed pre-warning system can simulate the occurrence, development, and destructiveness of the fire accident. The results play an important role in preventing any potential spread accident in hazard-prone areas through which pipelines pass. Furthermore, the results also prove useful in urban planning, because the found hazard-prone areas can be paid more attention by urban planning department or natural gas management to consider the secondary planning. In addition, it helps related decision-makers to devise emergency plans, and firefighters also deploy their forces effectively, when the fire spread accident starts initially.

Ours is the first study to combine the analysis of an urban natural gas pipeline accident with the spread of an urban fire. However, the works may be limited due to considering the single fire model, and we also expect to implement more fire models, for example, flash fire model, which may increase or change the chance of original ignition source. Moreover, the GIS analysis raises another question, the two-dimensional map can hardly produce a life-like fire spread simulation; in other words, we analyze fire spread on a macroscopic scale because our research is at a preliminary stage. In the future, we plan to realize a virtual life-like fire spread simulation after constructing a three-dimensional scene including above-ground buildings and underground pipeline networks. More importantly, we plan to orientate our research to the interaction between accident pre-warning and emergency response.

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