Examining the Impact of Adverse Weather on Urban Rail Transit Facilities on the Basis of Fault Tree Analysis and Fuzzy Synthetic Evaluation

Jiaqi Ma[1]; Yan Bai[2]; Jianfeng Shen[3]; and Fang Zhou[4]

Abstract: The increasingly frequent extreme weather disasters caused by global climate change have attracted more attention to adverse weather's effect on infrastructure systems. This paper aims to establish an integrated approach to assessing adverse weather's effect on urban rail transit facilities and to provide decision makers with a powerful tool to analyze potential risks and allocate limited sources for risk management. First, fault tree analysis is used to understand where the risks are, how the risks will occur, and what factors have the most significant effects by analyzing all possible basic events. All wind-, rain-, and snow-related adverse weather, along with human-related factors (construction leftover problems and design drawbacks), are found to potentially cause great risks. Adverse impact scenarios are summarized based on the fault tree analysis. Next, an analytic hierarchical process (AHP)–based fuzzy synthetic evaluation model is established to assess the risk level based on an evaluation index system. AHP is used to calculate the weights between the indices for each adverse weather factor. A fuzzy synthetic evaluation process is then carried out to identify the risk level of an evaluation target, an urban rail transit station, or line section. A case study on the Beijing URT Line 8 Olympic Center Station is conducted to illustrate the process of evaluation. The results show that the risk level is high and it becomes acceptable only after countermeasures are taken. Potential countermeasures regarding facility capacity, protection area management, and monitoring/inspection are then briefly discussed. **DOI: 10.1061/(ASCE)TE.1943-5436.0000630.**

Author keywords: Adverse weather; URT facilities; Fault tree analysis (FTA); Analytic hierarchical analysis (AHP); Fuzzy synthetic evaluation (FSE); Risk analysis.

Introduction

With the fast development of urban rail transit (URT) systems in the world, safety issues have attracted more and more attention, especially against the backdrop of global warming and frequent weather disasters. Extreme weather has been occurring more and more frequently and the effect on URT systems is one of the greatest problems facing today's urban transportation. Therefore, systematically evaluating the potential risks of the systems under adverse weather is of critical importance for URT operational safety.

Compared with urban rail systems, conventional heavy rail freight and passenger systems have been studied for many years and are the focus of more literature. They typically cover large geographic areas, and are exposed to a variety of weather conditions. According to the Federal Railway Administration (2012), at least 861 railway incidents were related to weather disasters from 2001 and 2011. Major weather factors include violent storms, heavy snow and rain, and high temperatures. Many researchers have focused on facility structural response to adverse weather conditions and improvements in design and maintenance to make them less vulnerable to adverse weather. For example, Nummelin (2002) described special turnout constructions and maintenance practices during Finland's extreme weather conditions. Meanwhile, another issue of similar importance is to identify the locations of potential risks and hazards and then deploy countermeasures. This is very meaningful, especially considering limited resources available for risk management. Ko Ko (2005) introduced an approach for assessing the hazards and risks of rainfall-induced landslides along a 30-km section of railway track. Rainfall data for previous storms, which led to widespread landslides, were analyzed to calculate the annual probability of widespread landslide occurrence. This value, combined with information on the frequency of train operations, enabled the estimation of the annual risk of human casualty, which was then compared with proposed tolerable or acceptable levels. Xia (2013) made use of a national infrastructure dataset of the Netherlands to estimate the effects of weather conditions such as wind, temperature, and precipitation on railway operator performance of passenger train services. Rossetti (2002) studied the potential effect of climate change on railways, and described the effect of weather at different levels and different times. He suggested the use of a future scenario database to model the relationship between climate change and railway systems. All of these analyses use or demonstrate the importance of using available datasets to identify and assess the potential risks. No literature, however, mentions risk analysis when data are not available.

URT systems are different from conventional freight and passenger rail systems in many aspects. URT systems are located in

[1]Graduate Research Assistant, Center for Transportation Studies, Univ. of Virginia, P.O. Box 400742, Charlottesville, VA 22904-4742 (corresponding author). E-mail: jm7md@virginia.edu

[2]Associate Professor, School of Civil and Environmental Engineering, Beijing Jiaotong Univ., No. 3 Shang Yuan Cun, Hai Dian, Beijing 100044, China. E-mail: ybai@bjtu.edu.cn

[3]Graduate Research Assistant, School of Transportation Engineering, Tongji Univ., 239 Siping Rd., Shanghai 200092, China. E-mail: jianfengshen1@hotmail.com

[4]Research Assistant, School of Economics and Management, Beijing Jiaotong Univ., No. 3 Shang Yuan Cun, Hai Dian, Beijing 100044, China. E-mail: fangzhou1227@gmail.com

Note. This manuscript was submitted on November 10, 2012; approved on September 4, 2013; published online on September 6, 2013. Discussion period open until April 29, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering***, © ASCE, ISSN 0733-947X/04013011(10)/$25.00.

urban areas with dense populations and are closely linked to people's daily lives. They are potentially more susceptible to extreme weather, such as underground URT tracks and stations during heavy rain, and more types of extreme weather factors. The failure of a small portion of URT systems may cause heavy casualty and economic losses (LUL 2002; BRE 2004). The good news is that URT systems usually cover only limited urban areas and it is possible and reasonable to make such a small- or medium-scale network weatherproof if limited resources can be assigned to strengthen the weak links identified through certain analyses.

Although most of the research results from conventional rail systems, such as design and maintenance improvements, could be adopted for the case of URT, many questions are yet to be answered for URT: What are the major risky weather factors? How will hazards occur? And where are the potential risks and hazards in existing systems? Unfortunately, URT system risks under adverse weather have only been addressed in a few policy analyses so far (Arkell and Darch 2005; Ault 2006). No literature is found to have conducted a special analysis on the effect of adverse weather on URT infrastructure systems, or to have directly answered these questions.

This paper aims to establish an integrated approach for assessing the effect of adverse weather on URT facilities and to provide decision makers with a powerful tool to analyze potential risks and allocate limited resources to risk management. First, by analyzing all possible events, the fault tree analysis (FTA) assesses the system risks and sheds some light on these risks and what factors have the largest effects. Next, an AHP-fuzzy synthetic evaluation model is established for the risk evaluation of a given target. A case study of a Beijing URT Station is used to illustrate the process of evaluation. The methodology structure is represented by the flowchart in Fig. 1, which details each step, section by section, in this paper.

Fault Tree Analysis

Fault Trees Construction

Fault tree analysis (FTA) is a top–down, deductive reasoning failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. It is used to understand the logic leading to the top event/undesired state, to prioritize the contributors leading to the top event, to minimize and optimize resources in designing or maintaining a system, and to function as a diagnostic tool in identifying and correcting causes of the top event. Fault tree analysis is adopted in this paper to answer two questions: (1) What are the major risky weather factors?, and (2) how will hazards occur? The reader could refer to the literature [e.g., Haimes (1998), DeLong (1970)] for further details on the concepts and symbols used in fault tree analysis.

The authors first specify the undesired state of the system, *URT system failure*, as the top event of the fault tree. Then, a list is compiled of all possible ways in which this event can occur. Based on the discussion within the research team, on-site surveys, and consultation with experts of Beijing URT operational authorities, four events—subgrade damage, poor maintenance, tree invasion, and track damage—are summarized as the major intermediate events to URT system failure during adverse weather. Each of the intermediate events is then examined independently to find out how it can occur until it is no longer feasible or cost-effective to carry out the analysis any further. The lowest-level events are called basic events, such as various design or weather factors. All of the events are laid out in a *tree* form connected by gates that can show the relationship among successive levels of the tree, as shown in Figs. 2–6. Rare extreme events for most URT systems, such as terrorist attacks and earthquakes, are not included in the analysis.

Minimal Cut Set

The next step is to obtain minimal cut sets, referring to the sets of basic events that if none of them will occur, the top event will in turn not occur. By analyzing all of the minimal cut sets of all combinations of basic events, the importance of basic events will be obtained (DeLong 1970; Ericson 1999).

The algebra of sets is usually used to calculate minimal cut sets. However, simple analysis can help to find minimal cut sets directly in this study. Because an OR gate is used in the total fault tree as shown in Fig. 2, any set of basic events that leads to the occurrence of an intermediate event will lead to the occurrence of the top event. Hence, it is only necessary to find the minimal cut sets for each of the fault trees of intermediate events. For each one of them, the AND gate is used only in the upmost level and then the minimal cut sets are the combination of any basic event on each side of the AND gate. After a thorough analysis, the minimal cut sets are $\{X_1, X_2\}$, $\{X_1, X_3\}$, $\{X_1, X_4\}$, $\{X_1, X_5\}$, $\{X_1, X_6\}$, $\{X_1, X_8, X_9\}$, $\{X_1, X_8, X_{10}\}$, $\{X_1, X_8, X_2\}$, $\{X_7, X_8, X_9\}$, $\{X_7, X_8, X_{10}\}$,

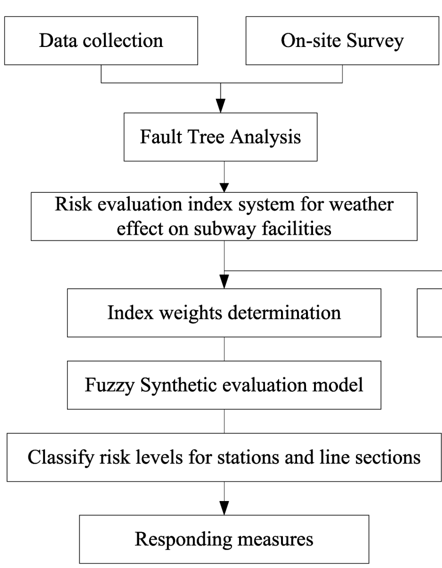

Fig. 1. Flowchart of proposed integrated evaluation approach

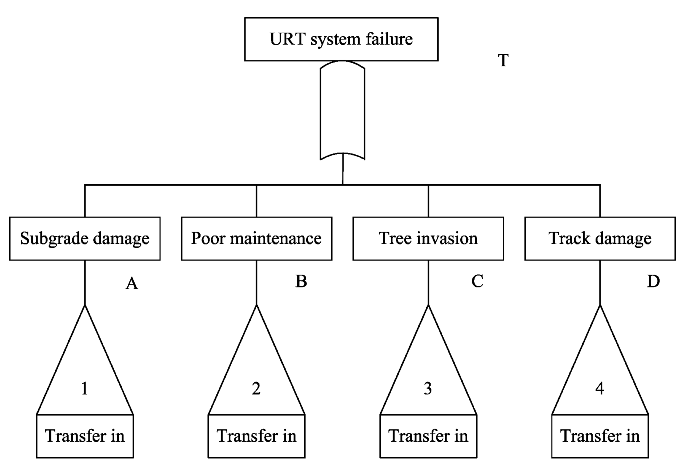

Fig. 2. Total fault tree

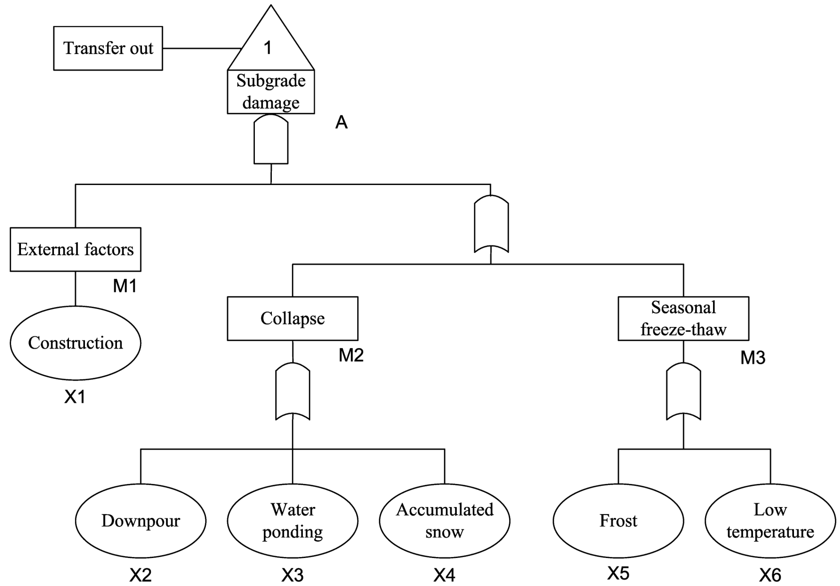

Fig. 3. Fault tree of subgrade damage

$\{X_7, X_8, X_2\}$, $\{X_1, X_{12}\}$, $\{X_1, X_{10}\}$, $\{X_1, X_4\}$, $\{X_1, X_{13}\}$, $\{X_1, X_{11}\}$, $\{X_1, X_2\}$, $\{X_1, X_8\}$, $\{X_1, X_9\}$, $\{X_7, X_5\}$, $\{X_7, X_{10}\}$, $\{X_7, X_{13}\}$, $\{X_7, X_{14}\}$, $\{X_7, X_6\}$, $\{X_7, X_4\}$, $\{X_7, X_{11}\}$, and $\{X_7, X_9\}$

The 27 minimal cut sets indicate that there are possibly 27 ways leading to URT system failure during adverse weather, and that extreme weather factors can easily affect URT system operations. The most frequent two are X_1 (construction) and X_7 (design drawbacks), with 17 and 12 times, respectively. In addition, X_8, occurring 7 times, becomes the third most frequent one, indicating that typhoon will be one of the greatest threats. The next two are X_9 and X_{10}, appearing four times in all of the minimal cut sets, representing drifting snow and hail.

Fault Tree Importance Analysis

The next step of FTA is to decode the degree of importance of all bottom events. In general, data need to be collected to obtain the occurrence probability for each bottom event of a fault tree. However, because it is very difficult to know the probability of the occurrence of certain weather factors, especially extreme weather, they are assumed to be equally likely to occur with probability p based on experience with the weather system in Beijing and most other major metro areas in China with URT systems. In this study, any value between 0 and 1 can be used for p with the equal probability assumption because the degree of importance of basic events will depend only on the structure of fault trees. With the minimal cut sets obtained in the last section, as calculated by Eq. (1), where the p is assumed to be $1/2$, the importance degree for each bottom event could be calculated as follows:

$$\mathrm{I}_{\varphi}(x_i) = 1 - \prod_{x_i \in k_j} \left(1 - \frac{1}{2^{N_j - 1}}\right) \tag{1}$$

where k_j = jth minimal cut set and N_j = number of basic events in the minimal cut set j in which the basic event is located.

For a bottom event such as X_5, all of the minimal cut sets are included: X_5, $\{X_1, X_5\}$ and $\{X_7, X_5\}$. The N_1 and N_2 are

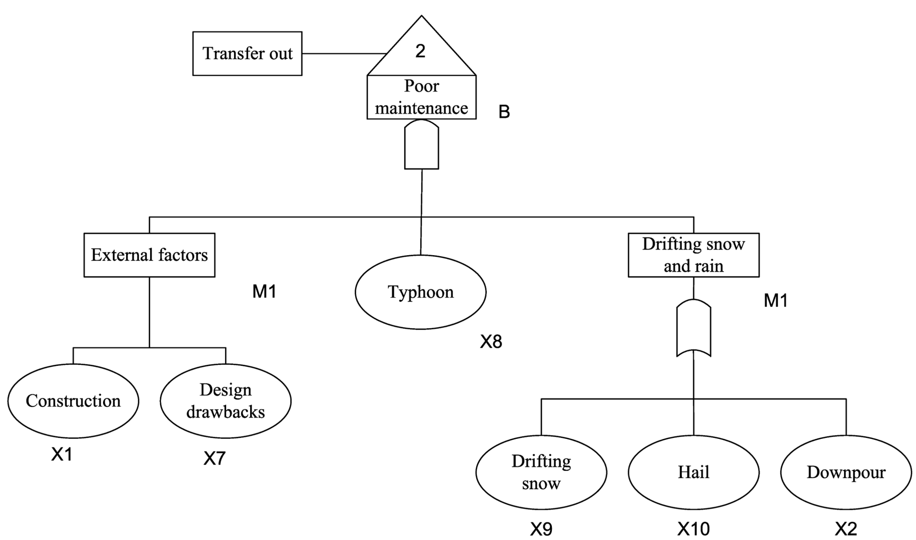

Fig. 4. Fault tree of poor maintenance

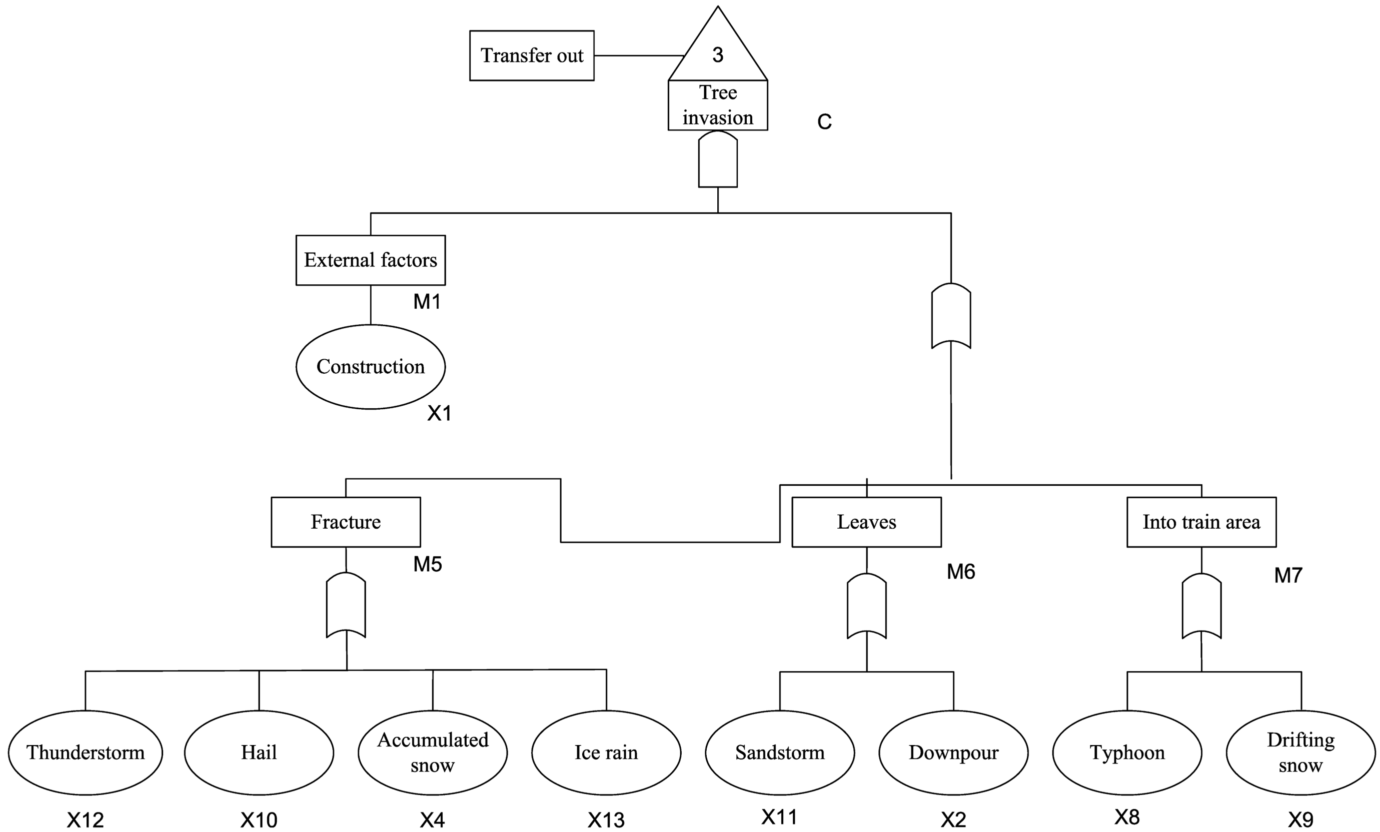

Fig. 5. Fault tree of tree invasion

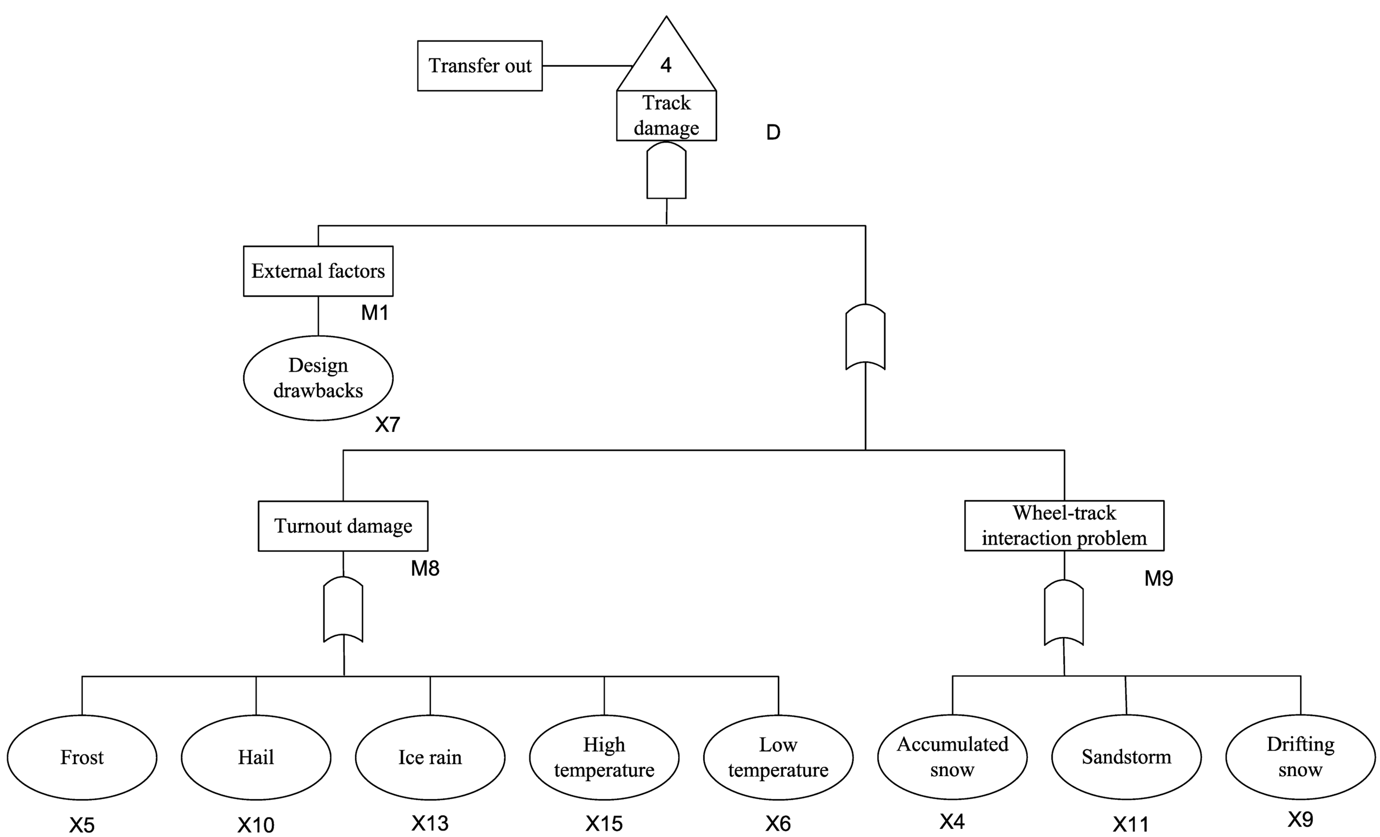

Fig. 6. Fault tree of track damage

both 2. Then, $I_\varphi(x_5) = 1 - (1 - 1/2^{2-1})(1 - 1/2^{2-1}) = 0.75$. The calculation results are as follows: $X_1 = X_7 = 0.999 \approx 1$, $X_8 = 0.911$, $X_4 = 0.875$, $X_2 = X_9 = X_{10} = 0.859$, $X_5 = X_6 = X_{11} = X_{13} = 0.75$, $X_{12} = X_{14} = 0.5$, $X_3 = 0.25$.

The order of basic events in terms of degree of importance is $X_1 = X_7 > X_8 > X_4 > X_2 = X_9 = X_{10} > X_5 = X_6 = X_{11} = X_{13} > X_{12} = X_{14} = X_{15} > X_3$.

The most important two factors, when considering risks caused by weather, originated from humans: construction leftover problems and design drawbacks. This indicates that the construction leftover problems and design drawbacks, combined with weather factors, play a big role in the damage to facilities, though they are indirect factors. Accumulated snow and typhoon are the two most important weather factors. Downpour, drifting snow, hail, frost, low temperature, sandstorm, and ice rain are all critical factors and have significant effects. Therefore, when the potential risks are examined and the responding measures are carried out, the attention should be focused on the most critical weather factors related to construction and design problems.

Adverse Effect Scenarios

All extreme wind, rain, and snow events could have serious effects on URT facilities, as concluded from the FTA. In this paper, the analysis embedded in FTA is listed in addition to the scenarios in which URT facilities are adversely affected. The process of identifying adverse effect scenarios always goes hand in hand with the process of building fault trees. Building fault trees usually helps analyzers to find every possible risk in the target system.

URT ground lines and elevated lines are most vulnerable to extreme wind weather. Extreme wind may blow away URT operational equipment and facilities, tear off branches of surrounding trees and leave them on or near the URT rail, damage surrounding temporary buildings and billboards and leave the debris on or near the URT rail, overturn the roof of elevated URT stations, impose extreme cross-wind effects on trains of ground and elevated URT lines, significantly increase the wind strength through *funneling* effects when there are many high-rise buildings near the URT line, and impose huge wind pressure on the wind/noise barriers installed at both sides of ground and elevated lines in city centers, thus reducing the overall structural stability of elevated bridges.

The underground URT lines and the cutting sections of the ground lines are most vulnerable to extreme rain weather. Many stations and URT tunnel sections are below ground level and may be adversely affected by the backflow of storm water–logging and surface/ground water seepage. These may cause mildew in construction materials and communication and signal equipment malfunction, causing safety problems. Subgrade soil may be *softened* by water-logging, and this may lead to large vertical settlement deformation, causing URT line subgrade damage or collapse. Also, subgrade protection elements, such as retaining walls, may be damaged by rainstorm, which then reduces the stability of the entire structure. Additionally, rainstorms may tear off branches of surrounding trees and leave them on or near the URT rail of ground lines. Furthermore, underground spaces are more vulnerable to flooding by rainstorm than aboveground spaces. If no countermeasures are taken to prevent water from flowing into the underground spaces, the flood may spread very quickly in the underground spaces and cause large damage.

Elevated URT lines, cutting sections of the ground lines, and open-air sections of the ground lines are most vulnerable to extreme snow weather. Snow effects include (1) friction loss between a wheel and a rail resulting from lubrication by snow and water, making the train more difficult to restart after a stop in stations and to travel along continuous upgrade sections; (2) dense snow near the track switch, causing poor switch fitting and leading to safety problems; (3) heavy snow that can tear off branches of surrounding trees and leave them on or near URT rails; (4) heavy snow that can damage temporary buildings and billboards, causing debris to fall onto the rail areas; (5) snow water that may make electrical equipment short-circuit; and (6) snow that can block signals, leading to train speed reduction or a stop.

AHP–Fuzzy Synthetic Evaluation

To evaluate the potential operational risks for a given target in terms of the most important weather factor related to construction and design problems identified through the FTA, the analytic hierarchical analysis (AHP)–based fuzzy synthetic evaluation (FSE) method is used. A fuzzy method is used because the factors are hard to quantify and detailed historical data are not available. Fuzzy methods are often adopted in this case to achieve a balance between objectivity and subjectivity. Fuzzy synthetic evaluation (FSE) is used in this paper for risk evaluation (Klir and Yuan 1995; Lu and Lo 1999).

Before FSE is carried out, an evaluation index system is established based on the results of FTA. The indices included in the evaluation index system should be picked carefully so that various risks discussed in the FTA can be evaluated, as shown in Fig. 7. For wind, trees in the protection area (usually defined as 20–30 m from URT structures, facilities, and equipment for URT operation safety) (A1 in Fig. 7) and debris from damaged surrounding buildings (A2) are highly likely to fall on the rail and may be a great threat to train operation safety. Therefore, it is necessary to look at how fast these trees will grow and the distance between the trees and URT rail. A3 is the *funneling* effect. A4 and A5 consider the wind pressure on the noise barrier. A6 considers different types of wind barriers. For rain, B3 considers how much the entrance/exit is higher than ground level. B5 addresses whether the facilities can meet nationally required standards and whether it is necessary to raise the capacity level in areas where there are frequent severe rain events. B6 considers the facility service life and required maintenance work to see whether, e.g., ceilings, side walls, and drainage pipes are functioning well. For snow, C1 considers whether the roof can sustain a large snow load. C2 considers real-time monitoring of snow accumulation depth. C3 prevents snow from falling on track switches and electrical equipment. Other indices are likely easy for readers to understand.

The FSE procedure is as follows:

1. Determine evaluation factors. Set $U = \{u_1, u_2, u_3\}$ as the three weather factors of rain, wind, and snow. The evaluation factors of a subsystem can also be expressed as $u_i = \{u_{i1}, u_{i2}, \ldots, u_{il}\}$, where $u_{ij} = j$th index of the ith weather subsystem.
2. Determine the evaluation set. The evaluation set is the set of all possible judgments that an expert might give, expressed as $V = \{v_1, v_2, \ldots, v_m\}$. This paper defines eight levels for risks: extremely high, very high, fairly high, high, medium, low, fairly low, and extremely low, expressed as $V = \{V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8\} = \{8, 7, 6, 5, 4, 3, 2, 1\}$, respectively. *Extremely high* and *very high* refers to levels that are not allowed at any time and the risk should be eliminated immediately; *fairly high, high*, and *medium* refer to undesired levels and are only acceptable after countermeasures are taken to reduce the risks. *Low, fairly low*, and *extremely low* refer to ignorable risks. The evaluation set is unbalanced and has more

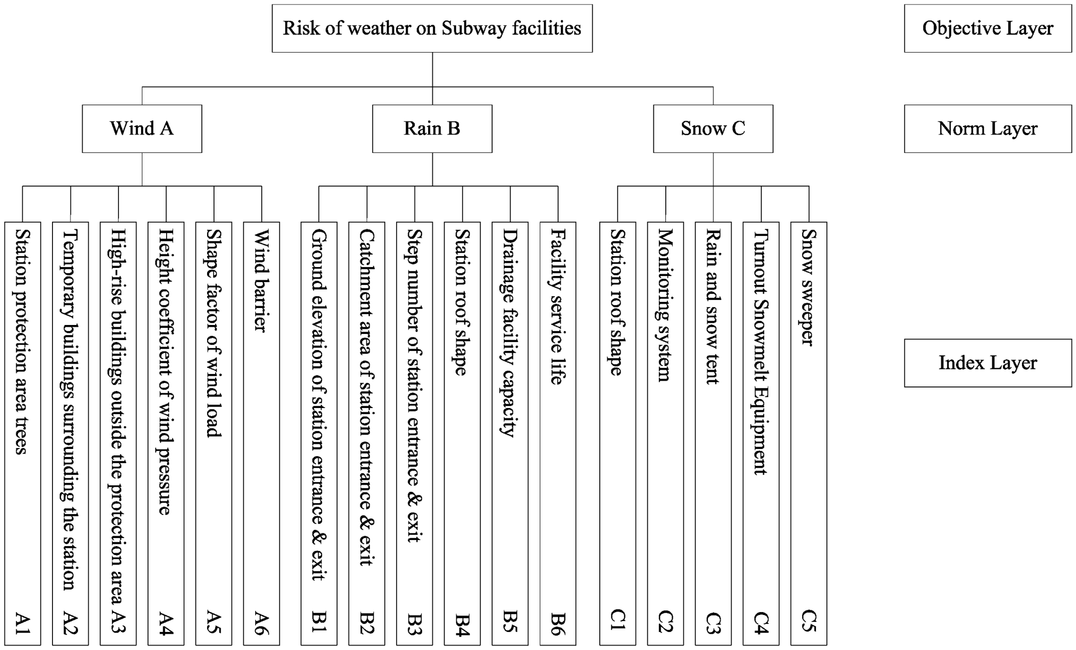

Fig. 7. Three-layer weather effect risk evaluation index system

elements for higher risks because the authors are interested in finding out the stations or line sections of high risks, so distinguishing among stations of lower risks makes less sense.

3. Determine weight vectors. Analytic hierarchical process (AHP) is used to calculate the weights among different weather factors and among the indices of each weather factor subsystem (Drake 1998). First, experts are invited to give their judgments pairwise by assigning the value 1 if the elements are of equal importance, value 3 to a weakly more important element, value 5 to a strongly more important element, value 7 to a very strongly important element, and value 9 to an absolutely more important element. The values 2, 4, 6, and 8 are not used because more scale levels might be more confusing to experts. The outcome of each set of pairwise comparisons can be expressed in a form as in Table 1, called a *judgment matrix*, after which the eigenvector method is often used to derive the final weight vectors for each of the factors and indices. The calculation process is expressed as follows in Eqs. (2)–(7).
   a. Normalization for every column

$$\bar{b}_{ij} = \frac{b_{ij}}{\sum_{k=1}^{n} b_{kj}}, \qquad (i, j = 1, 2, \ldots, n) \tag{2}$$

   where b_{ij} = element of judgment matrix B; $\bar{b}_{ij}$ = element of normalized judgment matrix $\bar{B}$.
   b. Add all of the elements in the rows of normalized judgment matrix $\bar{b}$ to obtain vector $\bar{w}$

$$\bar{w}_i = \sum_{j=1}^{n} \bar{b}_{ij}, \qquad (i = 1, 2, \ldots, n) \tag{3}$$

   c. Normalize $\bar{w}_i$ to obtain $w = (w_1, w_2, w_3, \ldots w_n)$ as the eigenvector

$$w_i = \frac{\bar{w}_i}{\sum_{j=1}^{n} \bar{w}_j}, \qquad (i = 1, 2, \ldots, n) \tag{4}$$

   d. Calculate the largest eigenvalue $\lambda_{\max}$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(B \cdot w)_i}{n \cdot w_i} \tag{5}$$

   where $(B \cdot w)_i$ = ith element of vector obtained by multiplying judgment matrix B by weight vector w.
   e. Check for consistency. To check for consistency in the judgments of decision makers, Saaty (2010) defined the consistency ratio (CR), which is a comparison of the consistency index (CI) with the random consistency index (RI), as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{6}$$

   where CI is given by

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{7}$$

   where n is the size of the matrix. RI is usually given in a table and readers can refer to the literature (Saaty 2010). A matrix is considered consistent only if $\mathrm{CR} \leq 0.1$.

4. Determine membership matrix. A membership matrix R from U to V is determined by the opinions of experts on the potential risks of the evaluation target in terms of each index (Table 2).

Table 1. Outcome of Expert Opinions for a Index System

A	A1	A2	A3	A4	A5	A6
A1	1.000	1.400	4.600	3.400	3.400	8.200
A2	0.714	1.000	3.800	3.800	3.400	7.800
A3	0.217	0.263	1.000	0.333	0.286	3.800
A4	0.294	0.263	3.000	1.000	2.200	3.800
A5	0.294	0.294	3.500	0.455	1.000	4.600
A6	0.122	0.128	0.263	0.263	0.217	1.000

Table 2. Questionnaire for the Effect of Weather Factors on URT Facilities

Index	Level							
	Extremely high	Very high	Fairly high	High	Medium	Low	Fairly low	Extremely low
Wind								
Station protection area trees	—	—	9	8	3	—	—	—
Temporary buildings surrounding the station	—	—	8	6	6	—	—	—
High-rise buildings outside the protection area	—	—	8	6	5	1	—	—
Height coefficient of wind pressure	—	—	—	6	8	6	—	—
Shape factor of wind load	—	—	5	8	7	—	—	—
Wind barrier	—	—	—	—	11	8	1	—
Rain								
Ground elevation of station entrance and exit	—	9	11	—	—	—	—	—
Catchment area of station entrance and exit	—	9	2	9	—	—	—	—
Step number of station entrance and exit	—	—	8	6	6	—	—	—
Station roof shape	—	—	—	6	11	3	—	—
Drainage facility capacity	—	6	9	5	—	—	—	—
Facility service life	—	—	—	11	8	—	1	—
Snow								
Station roof shape	—	—	—	9	5	6	—	—
Monitoring system	—	—	—	5	6	5	4	—
Rain and snow tent	—	—	3	5	6	6	—	—
Turnout Snow melt Equipment	—	—	—	3	3	10	4	—
Snow sweeper	—	—	—	3	6	11	—	—

$$R = (r_{ij})_{m\times n} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix},$$
$$(i = 1, 2, \dots, m; j = 1, 2, \dots, n) \tag{8}$$

where r_{ij} of matrix R = element to the frequency of u_i in v_j. In general it will be normalized so that $\sum_{j=1}^{n} r_{ij} = 1$.

5. Calculate the fuzzy synthetic evaluation set. The effect of different factors u_{ij} in one weather factor subsystem on the evaluation target can be calculated as

$$Q = w \times R = (w_1, w_2, \dots w_n) \times \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \tag{9}$$

where q_i = membership degree corresponding to the ith element of the evaluation set v_i. The value indicates which risk level the evaluation target belongs to under certain evaluation weather factors.

6. Conclusion. Two methods can be adopted to reach the evaluation conclusion from the membership degree matrix Q: (1) maximum membership degree method, taking the v_i corresponding to the biggest q_i as the result; and (2) weighted average method, taking the weighted average of q_i for every v_i as the weights as shown in Eq. (10)

$$V = \frac{\sum_{j=1}^{n} q_j v_j}{\sum_{j=1}^{n} q_j} \tag{10}$$

7. Determine the overall risk level. Although it is necessary to use eight levels of risk in the FSE because a more detailed evaluation can be carried out, the Beijing URT operational staff involved in this research expressed the hope that simpler classification results can be produced for government use for the convenience of recording, visualization (Fig. 8), and standardization of formulating responding measures. In addition, knowing the overall risk level is critical and will help decision makers in allocating limited resources and formulating responding measures because, for example, the difference between *extremely high risk* and *very high risk* might not be clear and make little sense to policymakers when allocating risk management resources. Therefore, a conversion is made to make the classification simpler. Risk Level 1 covers *extremely high* and *very high*. Risk Level 2 covers *fairly high, high*, and *medium*. Risk Level 3 covers *low, very low*, and *extremely low*. Level 3 indicates that the risks are acceptable and no immediate measures are required. Level 1 and Level 2 indicate that great risks might exist and they will be acceptable only after corresponding countermeasures are taken to reduce the risks and Level 3 risk is attained.

Case Study

This paper uses the Beijing URT Line 8 Olympic Center Station as an example and makes use of the fuzzy synthetic evaluation method to assess the effect of adverse weather factors—rain, wind, and snow—on URT facilities. The Beijing URT Line 8 Olympic Center Station is located in Beijing's Chaoyang district and around the city's fourth ring. It is an underground, two-story station with four entrances and exits B1, B2, C, and D, with B1 and B2 around the southern gate of Olympic Park, and C and D leading to Olympic Center and the Chinese National Park, respectively. B1 and B2 are below the surrounding building ground elevation, and there are many fast-growing trees in the protection area. Therefore, large adverse weather-related risks may exist, such as tree branches falling onto the rail. Because of the space constraints of this paper, only the evaluation of the effect of wind is evaluated here; the effects of rain and snow can be evaluated using similar steps.

Data Collection

A total of 20 experts were invited to fill in the form designed by the research team. The results are shown in Table 2. The number in a cell of the table corresponds to the number of experts who check

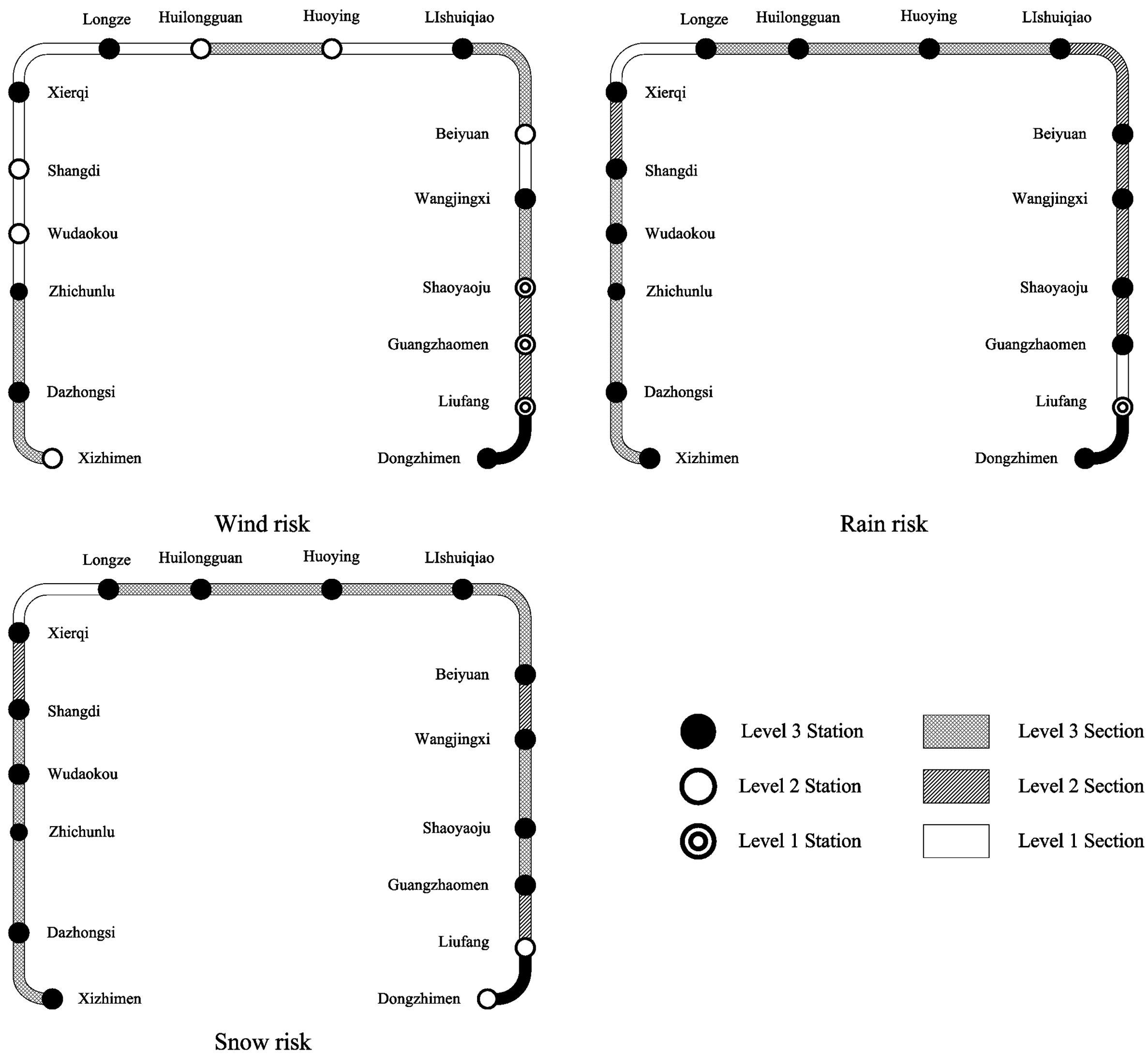

Fig. 8. Evaluation results for a Beijing URT line

this cell when they are invited to give the evaluation. Accompanying tables are also provided to experts to maintain the same standards when different experts are conducting the evaluation. One example of an accompanying form on the protection area trees is shown in Table 3.

The 20 experts also gave scores independent of their preference on the relative importance among indices, and their judgments are averaged to obtain the final score. The final score of pairwise comparisons for the indices in the wind subsystem is expressed in Table 1.

Risk Calculation

In this section, the evaluation steps for the wind subsystem A are detailed. The evaluation factors are the same as in the AHP analysis, including six factors: U = {station protection area trees, temporary buildings surrounding the station, high-rise buildings outside the protection area, height coefficient of wind pressure, shape factor of wind load, wind barrier}. The choice set is defined as previously discussed: V = {extreme high, very high, fairly high, high, medium, low, fairly low, extremely low}. Weights of the

Table 3. Evaluation Standards for Station Protection Area Trees

Risk level	Description	Score
Extremely high	Trees rich in branches and leaves, 5 m within protection area, tree crown higher than rail line area	8
Very high	Trees rich in branches and leaves, 5 m within protection area, tree crown with same height as rail line area	7
Fairly high	Trees rich in branches and leaves, 5 ~ 10 m within protection area, tree crown higher than rail line area	6
High	Trees rich in branches and leaves, 5 ~ 10 m within protection area, tree crown with same height as rail line area	5
Medium	Trees sparse in branches and leaves, 5 ~ 10 m within protection area, tree crown higher than rail line area	4
Low	Trees sparse in branches and leaves, 10 m within protection area, tree crown with same height as rail line area	3
Fairly low	Trees sparse in branches and leaves, outside10-meter-radius area of protection area, tree crown higher than rail line area	2
Extremely low	Trees sparse in branches and leaves, outside10-meter-radius area of protection area, tree crown with same height as rail line area	1

factors are decided by the AHP method. The calculation for the weights of index layer A, based on Table 1, is shown below.

$$b = \begin{bmatrix} 1 & 1.4 & 4.6 & 3.4 & 3.4 & 8.2 \\ 0.714 & 1 & 3.8 & 3.8 & 3.4 & 7.8 \\ 0.217 & 0.263 & 1 & 0.333 & 0.286 & 3.8 \\ 0.294 & 0.263 & 3 & 1 & 2.2 & 3.8 \\ 0.294 & 0.294 & 3.5 & 0.455 & 1 & 4.6 \\ 0.122 & 0.128 & 0.263 & 0.263 & 0.217 & 1 \end{bmatrix} \to \bar{b}$$

$$= \begin{bmatrix} 0.379 & 0.418 & 0.285 & 0.368 & 0.324 & 0.281 \\ 0.270 & 0.299 & 0.235 & 0.411 & 0.324 & 0.267 \\ 0.082 & 0.079 & 0.062 & 0.036 & 0.130 & 0.130 \\ 0.111 & 0.079 & 0.186 & 0.108 & 0.209 & 0.130 \\ 0.111 & 0.088 & 0.217 & 0.049 & 0.095 & 0.158 \\ 0.046 & 0.038 & 0.016 & 0.028 & 0.021 & 0.034 \end{bmatrix} \to \bar{w}$$

$$= \begin{bmatrix} 2.053472 \\ 1.80575 \\ 0.415953 \\ 0.823182 \\ 0.717608 \\ 0.184035 \end{bmatrix} \to w = \begin{bmatrix} 0.342 \\ 0.301 \\ 0.069 \\ 0.137 \\ 0.120 \\ 0.031 \end{bmatrix}$$

The largest eigenvalue is calculated next: $\lambda_{\max} = 6.610$.

Then, referring to the RI value reference table (Saaty 2010), $\mathrm{RI} = 1.24$ when $n = 6$.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{\frac{\lambda_{\max}-n}{n-1}}{\mathrm{RI}} = \frac{\frac{6.610-6}{6-1}}{1.24} = 0.098 < 0.10$$

Therefore, the consistency requirement is met. The weight vector for subsystem A is

$$w_A = (0.342, 0.301, 0.069, 0.137, 0.120, 0.031)$$

The norm layer weights and index layer weights are calculated in the same way and the results are shown in Table 4. Based on the scores given by the experts from Table 2, the membership degree matrix of wind effect area is obtained.

$$R = \begin{bmatrix} 0 & 0 & 0.438 & 0.375 & 0.188 & 0 & 0 & 0 \\ 0 & 0 & 0.375 & 0.313 & 0.313 & 0 & 0 & 0 \\ 0 & 0 & 0.375 & 0.313 & 0.250 & 0.063 & 0 & 0 \\ 0 & 0 & 0 & 0.313 & 0.375 & 0.313 & 0 & 0 \\ 0 & 0 & 0.250 & 0.375 & 0.375 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.563 & 0.370 & 0.063 & 0 \end{bmatrix}$$

The weight vector of wind effect factors is multiplied by the membership degree matrix to obtain the synthetic evaluation

Table 4. Weight Results for Norm Layer, Index Layer A, Index Layer B, and Index Layer C

Norm layer	A[a]	B	C			
w	0.230	0.667	0.103			
Index layer A	A_1	A_2	A_3	A_4	A_5	A_6
w_A	0.342	0.301	0.069	0.137	0.120	0.031
Index layer B	B_1	B_2	B_3	B_4	B_5	B_6
w_B	0.432	0.151	0.095	0.047	0.244	0.031
Index layer C	C_1	C_2	C_3	C_4	C_5	
w_C	0.231	0.414	0.220	0.083	0.052	

[a]Please refer to Figure 8 for the definitions of the indices, A, B, C, A_i's, B_i's and C_i's.

$$Q = w \times R = (0, 0, 0.319, 0.332, 0.290, 0.059, 0.002, 0)$$

The largest membership degree method (pick value 0.332) is used, and indicates the risk level as *high*. Therefore, the overall risk state of this station for wind is Level 2. Similar analyses are also carried out for the rain and snow subsystems. The analyses show that the overall risk level is Level 2 for rain and Level 3 for snow. The result shows that when extreme windy and rainy weather events occur, great risk might exist for this station and measures need to be taken to reduce the wind- and rain-related risks.

Discussion

Network Screening

The methodology proposed in this paper is ready and easy to implement when examining the risks of adverse weather for every station and line section in a URT network. Evaluation should be conducted for each of the stations and line sections. One evaluation result for one of the Beijing URT lines is shown in Fig. 8. This type of results is very convenient for visualization and could help decision makers to locate potential risks and allocate the limited resources for risk management.

Responding Measures

After the potential risks are determined and understood, responding countermeasures need to be taken against the URT station or line sections exhibiting Risk Level 1 or Level 2, whereas Risk Level 3 is ignorable considering the limited resources. Based on the FTA analysis, three areas of great importance were identified for improvement, if necessary: (1) existing facility capacity, (2) protection area management, and (3) monitoring and inspection. This is different from an evaluation process because the evaluation could focus on all factors of design and construction, whereas countermeasures can only complement rather than redesign or reconstruct. Each of the three areas is examined carefully against the identified risky weather factors. A brief discussion is made for the reader's reference. In addition, countermeasures for Risk Level 1 stations should be of higher standards than Risk Level 2 stations. The formulation of responding measures should be based on the results of FTA analysis and the experience and judgments of experts.

Existing facility capacities

The earlier design problems may cause facility capacity inefficiencies. Existing facility upgrades are necessary to guard against potential extreme weather risks as identified though the analysis. For wind, windbreak measures should be taken, such as installing porous wind barrier or planting slowly growing trees around the ground or elevated lines. For rain, the related facility could be upgraded by, e.g., enlarging the volume of water collection tanks, increasing drainage ditches, installing water barriers (to let water flow into corresponding drains when on slopes), erecting water shields for open-air entrances/exits and constructing slope protection. For snow, more snow barriers or snow sheds could be installed to prevent snow from falling on the key facilities, and station/line sections should be equipped with more snow removers.

Protection area management

The protection area is identified as key risk sources for ground and elevated lines. For stations that have ongoing construction outside their protection areas, protection such as grid guards should be installed. It is better that the trees in the protection area be slow-growing. Warning signs need to be installed to make the protection areas well organized. For Risk Level 1 stations, dangerous trees, billboards, and temporary buildings should be removed.

Monitoring and inspection
The monitoring of wind, rain, and snow needs to be strengthened. Monitoring mechanisms need to be established for wind, snow, and rain, respectively, including data collection, monitoring standards, and monitoring locations. Key facilities, such as drainage facilities within the protection areas and access passages, should be inspected every week or month to guard against the occurrence of extreme weather. For stations/sections with higher risks, the monitoring standard should be higher than normal to ensure smooth operation.

Transferability

The analysis methodology and results of the integrated approach are ready to be transferred to other case and geographical areas with limited variations. The fault trees were based on knowledge of the URT systems in Beijing. Because URT systems have much in common throughout the world, the fault trees could be borrowed directly or with small changes, such as adding local factors. For example, Japanese researchers could add *earthquake* to the factors and consider its potential damage to facilities. For FSE analysis, the index system could be borrowed with small changes to reflect local conditions and also to reflect the analysis results of FTA. Experts are invited next to evaluate the potential risks of analysis targets for the accompanying fuzzy analysis. One of the necessary processes and also greatest advantages of this approach is the best use of the subjectivity in the objective analysis so that the analysis could be carried out even if no historical data are available.

Conclusions

Operational safety is undoubtedly one of the priorities of URT systems. This paper proposes an integrated approach to understanding and assessing the risks caused by adverse weather on URT facilities.

First, fault tree analysis is used to understand the weather-related risks in the URT system and to identify the basic events that will most likely cause URT system failure. Analysis of this step is critical because better understanding of how system risks occur could help decision makers to identify the system risk structure and most critical factors in URT operation. The FTA also serves as a foundation for the fuzzy synthetic evaluation.

Second, the AHP-based fuzzy synthetic evaluation method is used to carry out the risk evaluation procedure for a target. A risk evaluation index system with 17 indices is established mostly on design and construction issues related to the FTA results. This approach combines subjective and objective analysis and is especially useful when only limited data are available.

Third, the integrated approach is applied to the evaluation of the Beijing URT Line 8 Olympic Center Station. Twenty experts were invited to give their judgment on relative importance and potential risk levels for each of the indices. The evaluation shows that the station is at *high* risk, Risk Level 2 among three levels. Knowing the overall risk level is critical and will help decision makers to allocate limited resources in risk management.

Finally, the integrated approach is ready to be transferred to other cases or geographical regions. The paper also recommends responding countermeasures from the perspective of facility capacity, protection area management, and monitoring and inspection.

The research in this paper proves to be effective and valuable, providing direction for future research in risk evaluation. Specifically, more accurate weights, based on the probability of weather factors, could be obtained through historical data. Furthermore, the methodology can be used for risk evaluation of other transportation systems. The ongoing work to evaluate the track system risks for the daily operations of URT makes use of the integrated approach proposed in this paper.

References

Arkell, B., and Darch, G. (2005). “Moving ahead: Managing climate change risks to London’s transport systems.” *Technical Rep.*, Greater London Authority and London Climate Change Partnership, London.

Auld, H., MacIver, D., and Klassen, J. (2006). “Adaptation options for infrastructure under changing climate conditions.” *Paper presented at IEEE EIC Climate Change Technology Conf.*, IEEE, Washington, DC.

Boddington, E. W. (2002). *Station and tunnel environment: A position paper*, London Underground Limited, London.

Building Research Establishment (BRE). (2004). “Understanding thermal comfort on trains and stations.” *Rep. No. 216996*, Building Research Establishment for London Underground Limited, London.

DeLong, T. (1970). “A fault tree manual.” M.S. thesis, Texas A&M University, College Station, TX.

Drake, P. R. (1998). “Using the analytic hierarchy process in engineering education.” *Int. J. Eng. Educ.*, 14(3), 191–196.

Ericson, C. (1999). “Fault tree analysis—A history.” *Proc., 17th Int. Systems Safety Conf.*, International System Safety Society, Unionville, VA, 419–441.

Federal Railroad Administration. (2012). “Federal railroad administration office of safety analysis.” ⟨http://safetydata.fra.dot.gov/oceofsafety⟩ (Aug. 05, 2012).

Haimes, Y. Y. (1998). *Risk modeling, assessment and management*, Wiley, New York.

Klir, G. J., and Yuan, B. (1995). *Fuzzy sets and fuzzy logic—theory and applications*, Prentice-Hall, Englewood Cliffs, NJ.

Ko Ko, C., Chowdhury, R., and Flentje, P. (2005). “Hazard and risk assessment of rainfall-induced landsliding along a railway line.” *Q. J. Eng. Geol. Hydrogeol.*, 38(2), 197–213.

Lu, R-S., Lo, S-L., and Hu, J-Y. (1999). “Analysis of reservoir water quality using fuzzy synthetic evaluation.” *Stochastic Environ. Res. Risk Assess.*, 13(5), 327–336.

Nummelin, M. (2002). “Modern turnouts for extreme weather conditions.” *Proc., Int. Conf. of Railway Engineering*, Engineering Technics Press, Edinburgh.

Rossetti, M. A. (2002). “Potential impacts of climate change on railroads.” *The Potential Impacts of Climate Change on Transportation Workshop*, USDOT Center for Climate Change and Environmental Forecasting, ⟨http://climate.dot.gov/documents/workshop1002/workshop.pdf⟩ (Aug. 05, 2012).

Saaty, T. L. (2010). *Mathematical principles of decision making (Principia mathematica decernendi)*, RWS, Pittsburgh.

Xia, Y., Van Ommeren, J. N., Rietveld, P., and Verhagen, W. (2013). “Railway infrastructure disturbances and train operator performance: The role of weather.” *Transp. Res. D Transport Environ.*, 18, 97–102.