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Hybrid belief rule base for regional railway safety assessment with data and knowledge under uncertainty☆

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ABSTRACT

Keeping regional railway transportation safe is of great importance for railway system engineers and decision makers. However, there are still great challenges in modeling the complicated conditions in regional railway transportation: (1) Multiple types of data and knowledge in complicated correlations need to be analyzed, and (2) The approach must be open and accessible to decision makers so that a balanced decision can be made. To address the above challenges, a safety assessment approach using the hybrid Belief Rule Base (BRB) is proposed. In the new approach, multiple types of information are modeled under the hybrid assumption, and thus, hybrid rules are constructed to form the hybrid BRB. With this, both data and knowledge in complicated correlations can be used for the safety assessment on regional railway transportation, rather than only a single railway station or equipment component. Moreover, the assessment process remains open and accessible which provides good interpretability to stakeholders. An empirical regional railway safety assessment case is studied on the existing line and high speed line in the Cheng-Yu region located in the southwestern China. Five aspects, namely, the environment, equipment, management, passengers, and accident, are analyzed and then disintegrated into sub-factors. With the aspects and sub-factors, a comprehensive model is constructed. Case study results show that (1) the overall safety levels of the high speed line are better than the existing line, (2) the safety assessment results are consistent with the historical reports of accidents and system failures, (3) among all aspects, the environment and equipment have a more direct effect on the overall safety levels, and (4) consistency has also been found with railway accident statistics collected from Japan and Canada.

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1. Introduction

Railway transportation is paramount to economic growth and social interactions since it is cheaper than flight and highway as well as faster than shipping. As railways are normally used to connect cities and regions far away, the safety of the regional railway transportation is vital for ensuring the delivering of passengers and cargos from departure to destination. Thus, it is important to conduct railway safety assessment from a regional perspective rather than just focusing on one single train component or a station.

However, it is quite a challenging task. The primary reason is that it is difficult to gain a clear understanding of the complicated factors that affect regional railway transportation in the first place [3,10,11]. First of all, railway lines are often operating under the influence of complicated environmental conditions. For example, there are normally heavy wind and rain in the summer and strong frost and fog in the winter in certain regions of China. There are also other disastrous environmental conditions, such as earthquakes and landslides, especially in mountainous regions with thick forests. Those events pose a severe threat to regional railway transportation [1,8,12]. Secondly, accidents and equipment failures are another safety concern that can directly cause accidents [7,12]. Thirdly, the managerial ability is also connected to railway safety. For example, the cross-sector communication ability plays a critical role in how an accident or system failure is prevented, handled or worsened [25]. Finally, the conditions of passengers/freight and how to prevent/reduce/rescue accidents also need to be considered [14]. Only by fully analyzing these aspects and factors can a comprehensive safety assessment model be constructed.

To fully investigate the regional railway safety assessment problem, its characteristics must be analyzed.

First, there are multiple factors from multiple aspects in varied forms and types. As discussed above, multiple factors in different types and forms must be taken into consideration, e.g., environment, equipment, management, passengers, and accident. Most environmental factors are numerical and quantitative, e.g., raindrop volume, visibility caused by fog, etc., and more are linguistic and qualitative, e.g., staff quality, accident rescue ability, etc.

Moreover, the correlations among factors need to be analyzed. There are different correlations among factors, either in a conjunctive, disjunctive or a hybrid fashion, which should be properly represented, transformed, and integrated. As a result, it calls for a new approach to address such complicated conditions.

Finally, the transparency is highly valued because experts and decision makers are involved in the process. On one hand, human knowledge is needed as inputs in the assessment process. On the other hand, safety assessment results need to be understood so that they can be trusted, plans for safety improvement can be designed, and the balanced decision can be made.

So far, multiple studies have been conducted in safety assessment for a single railway station or components of locomotives, cars, or signal systems [1,4,7,8,12,13,19,21,26]. Those studies have provided support and guidance in daily decision-making under practical exercises. However, we have not found studies on regional railway transportation. Nevertheless, it is still worthy of reviewing present literatures on safety assessment researches and even not limited within railway transportation, as presented in Section 2.

Based on the characteristic of the regional railway safety assessment and the present literature review, a hybrid Belief Rule Base (BRB) approach is proposed in this study. A hybrid rule is constructed under a hybrid assumption that allows both the conjunctive and disjunctive correlations among attributes to coexist in one rule. Moreover, the hybrid BRB inferencing procedure is also been proposed. It consists of four steps, including (i) calculation of matching degrees for a single attribute, (ii) calculation of matching degrees for a rule, (iii) weight calculation, and (iv) rule combination using the evidential reasoning algorithm. The inferencing process of hybrid BRB is still open and accessible to experts and decision makers as it is essentially a white box model [31,32]. In other words, the new hybrid BRB approach can meet the requirements of safety assessment for regional railway transportation.

An empirical case is studied for validation to assess the safety levels of a railway transportation system in the Cheng-Yu region, with ***Cheng*** standing for the city of ***Chengdu*** which is the capital city of the ***Sichuan*** province and ***Yu*** for the alternate name for the city of ***Chongqing***. At present, there are an existing line and a parallel high speed line connecting *Chengdu* and *Chongqing*. Correspondingly, two hybrid BRB models are constructed. The safety assessments are conducted using data gathered from 2017/1/1 to 2018/8/31. The case study results are then validated through comparison with historical reports of accidents and system failures, as well as railway accident statistics from Japan and Canada.

The remainder of this study is organized as follows. Section 2 reviews the present literature. Section 3 gives preliminaries on BRB and its challenges. Section 4 proposes the hybrid BRB approach. Section 5 gives an empirical case study of the Cheng-Yu regional railway safety assessment. Conclusions are presented in Section 6.

2. Literature review

As an important public transportation means, railways are key for ensuring social and economic development. Many endeavors have been proposed to ensure its safety. It has been identified that the railway level crossing, or enclosure of railway lines from a generic sense, has been a serious threat to railway transportation safety [4,21]. This finding has also been corroborated with many reports from different counties (see Section 5.7) and would guide the modeling process in this study (see Section 5.2). More studies have been only focusing on component levels of trains, signal systems, etc [1,7,8,12,13,19,26]. However, these studies are not conducted from a regional perspective which is the main topic of this study. Nevertheless, previous studies are still quite helpful as they can provide useful technical guidance for this study. Next, we would present the literature review on safety assessment in a generic sense.

(1) Qualitative approaches [8,26], e.g., brainstorming, questionnaires, the Analytical Hierarchy Process (AHP), Delphi and so on. Qualitative approaches are mostly used when qualitative information is gathered from humans such as experts, technicians, decision makers, etc. The qualitative approaches can be easily implemented and well understood. However, such approaches can also be biased due to human knowledge limits and prejudice.

(2) Quantitative approaches are normally perceived to be objective because they are based on data and analytical processes without human intervention [20]. One characteristic that such approaches share in common is the high requirement of data. However, it is quite a high requirement since data are often imperfect and even incomplete under many practical conditions such as the safety assessment of large scale systems like regional railway networks.

In addition to the above qualitative and quantitative approaches, other approaches have also been proposed as follows.

(3) Simulation-based approaches [29]. Simulation models can be built to analyze a railway transportation system as a dynamic process. The advantage of using a simulation-based approach is that it generates visual images that are suitable for demonstrating the dynamic features of a railway transportation system. However, simulation modeling requires detailed information, e.g., analytical constraints, which can be rather difficult to derive in practice. Moreover, it is also difficult to interpret different simulation results as they vary in each run.

(4) Network-based approaches [23,24,30]. As a railway operates in a transportation network, network-based approaches can be applied by modeling cities (stations) as nodes and routes between two cities (connections) as lines. A network-based approach is more suitable for problems with a complex structure and more nodes, e.g., problems with a national or global background where there are many nodes and lines. Nevertheless, for the Cheng-Yu region in this study, there are only two lines and over a dozen of nodes, which is insufficient for constructing a network model.

(5) Failure-oriented approaches [9,22]. System failures and accidents can be used to assess the safety levels of railway transportation systems. Typical failure-oriented approaches include timed fault trees [22] and failure mode effects and criticality analysis (FMECA) [9], among others. In the failure-oriented approaches, whether a railway is “unsafe” is determined by whether an accident or a system failure occurs, which is essentially an “exterior” perspective. However, in railway transportation practices, such accidents or system failures do not occur very frequently, resulting in data insufficiency.

(6) Expert systems-based approaches [1,2,4,22,27,33]. Expert systems approaches have been applied in safety/risk assessment and have shown the advantages of integrating heterogeneous information and representing the knowledge inference process of humans, e.g., machine learning, fuzzy sets, Bayesian network, and neural networks. Their applicability should be discussed and certain revisions should be made to meet the requirement of a specific problem.

(7) Hybrid approaches [34,36]. For a very complex problem, multiple aspects need to be considered. Thus, multiple approaches can be applied for each aspect, and a hybrid approach is thus formed. The disadvantage of hybrid approaches lies in the low transferability because they are normally designed specifically for a complex problem and is only applicable to that problem.

In other words, current approaches have shown advantages in solving one type of safety assessment problems, but cannot be universally transferred to solve other types of problems. With this, a hybrid BRB modeling and inference approach for regional railway safety assessment is proposed in Section 4 by extending from conventional BRB methodology (see in Section 3).

3. BRB basics and its challenges

BRB is comprised of multiple belief rules that are used to represent human inference knowledge [31]. As a white box approach, its modeling and inference process is transparent for experts and decision makers, which makes its assessment results easily understandable. BRB can represent, transform, and integrate different types of information under uncertainty [16,32]. BRB has been applied to modeling and analyzing complex problems in many fields [5,15,18].

Normally, BRB is constructed under the conjunctive assumption (**conjunctive BRB**) [17,30,32,35]. A conjunctive rule is given in (1):

$$\begin{aligned} R_k: \ & \text{if } \left(x_1 \text{ is } A_1^k\right) \wedge \left(x_2 \text{ is } A_2^k\right) \wedge \cdots \wedge \left(x_M \text{ is } A_M^k\right), \\ & \text{then}\{(D_1, \beta_{1,k}), \cdots, (D_N, \beta_{N,k}) \text{ with rule weight } \theta_k \text{ and attribute weight } \delta_m \end{aligned} \tag{1}$$

where $x_m (m = 1, \cdots M)$ stands for the mth attribute, $A_m^k (m = 1, \cdots M; k = 1, \cdots K)$ for the kth reference value of the mth attribute, M for the number of attributes, $\beta_{n,k} (n = 1, \cdots N)$ for the belief degree for the nth assessment grade D_n, N for the number of assessment grades, and "$\wedge$" for the conjunctive operator.

Note that the rule weight θ and attribute weight δ are not necessarily indispensable for all rules, especially in the initialization part where no prior knowledge is available. Normally, θ and δ can be assumed as “1” in the initialization part and later be optimized based on collected data.

Example 1. In the safety assessment of railway transportation systems regarding the environmental aspect, rain and wind are two key factors. Suppose that the rain and wind can be classified into three categories (heavy/medium/mild for rain and strong/medium/mild for wind). The following conjunctive rules can be constructed:

$$\begin{array}{l} R_1: \text{if } (\textit{rain} \text{ is mild}) \wedge (\textit{wind} \text{ is strong}) \text{ then } \{(\textit{caution}, 30\%), (\textit{severe}, 70\%)\} \text{ with } \theta_1 = 1 \\ R_2: \text{if } (\textit{rain} \text{ is medium}) \wedge (\textit{wind} \text{ is strong}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_2 = 1 \\ R_3: \text{if } (\textit{rain} \text{ is heavy}) \wedge (\textit{wind} \text{ is strong}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_3 = 1 \\ R_4: \text{if } (\textit{rain} \text{ is heavy}) \wedge (\textit{wind} \text{ is mild}) \text{ then } \{(\textit{caution}, 20\%), (\textit{severe}, 80\%)\} \text{ with } \theta_4 = 1 \\ R_5: \text{if } (\textit{rain} \text{ is heavy}) \wedge (\textit{wind} \text{ is medium}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_5 = 1 \end{array} \tag{2}$$

There are other situations where a conclusion is drawn when antecedent attributes are disjunctively correlated with each other, denoting that such a conclusion can be drawn if any of the attributes is activated. Such a BRB is called a **disjunctive BRB** [5,6]. A disjunctive belief rule is given in (3):

$$\begin{array}{l} R_k: \text{if } \left(x_1 \text{ is } A_1^k\right) \vee \left(x_2 \text{ is } A_2^k\right) \vee \cdots \vee \left(x_M \text{ is } A_M^k\right), \\ \quad \text{then } \{(D_1, \beta_{1,k}), \cdots, (D_N, \beta_{N,k})\} \text{ with rule weight } \theta_k, \text{ attribute weight } \delta_m \end{array} \tag{3}$$

where "$\vee$" denotes that the rule in (3) follows the disjunctive assumption.

Example 2. For assessment of the environmental aspect of railway transportation safety, certain indirect factors can be taken into accounts, such as earthquake and landslide, and a train would normally stop when such conditions occur. In other words, the environmental aspect would be rated as "*severe*" when any of the above conditions occur, regardless of what the rain/wind condition is:

$$R_6: \text{if } (\textit{earthquake} \text{ is true}) \vee (\textit{landslide} \text{ is true}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_6 = 1 \tag{4}$$

Remark 1. The conjunctive and disjunctive rules are not completely contradicted with each other. There are two perspectives to understand this statement. First, conjunctive and disjunctive rules are correlated with each other under certain circumstances. For example, Rules 3 and 5 from (2) are correlated with Rule 3' in (5), and Rule 6 from (4) is correlated with Rules 6' and 6" in (6).

$$\begin{array}{l} R_{3'}: \text{if } (\textit{rain} \text{ is heavy}) \wedge ((\textit{wind} \text{ is strong}) \vee (\textit{wind} \text{ is medium})) \\ \quad \text{then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_{3'} = 1 \end{array} \tag{5}$$

$$\begin{array}{l} R_{6'}: \text{if } (\textit{earthquake} \text{ is true}) \wedge (\textit{landslide} \text{ is true}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_{6'} = 1 \\ R_{6''}: \text{if } (\textit{earthquake} \text{ is true}) \wedge (\textit{landslide} \text{ is false}) \text{ then } \{(\textit{severe}, 100\%)\} \text{ with } \theta_{6''} = 1 \end{array} \tag{6}$$

Second, they are not "equivalent" in that it cannot be drawn that all conjunctive rules can be transformed into disjunctive rules and vice versa. The equivalency between conjunctive and disjunctive rules is a much more complex subject that will not be further addressed in this paper.

4. Hybrid BRB modeling and inference approach for railway safety assessment

4.1. Hybrid BRB

A more common and practical condition is that attributes can be conjunctively or disjunctively correlated with each other, not just with conjunctive rules and disjunctive rules coexisting in one BRB.

Definition 1. Attribute group

An attribute group is a collection of multiple attributes that have strong ties to each other and are correlated under the same assumption.

For example, in the Cheng-Yu region, rain and wind often arrive together in summer (as in Example 1), whereas frost and fog often arrive together in winter. Under this condition, they form different attribute groups and both of which belong to the environmental aspect.

The attributes group is the fundamental unit in a hybrid rule for two reasons: (1) the attributes within one attribute group are logically closer and follow the same assumption, and (2) it is the most basic cell for constructing a hybrid rule.

Definition 2. Hybrid rule

A hybrid rule is comprised of multiple attribute groups in which different attribute groups could be correlated under different assumptions (attributes within one group are still correlated under the same assumption). A hybrid rule is given as in (7),

$$\begin{array}{l} R_k: \text{if } \left(\left(x_1 \text{ is } A_1^k\right) \vee \left(x_2 \text{ is } A_2^k\right)\right) \wedge \cdots \wedge \left(\left(x_{M-1} \text{ is } A_{M-1}^k\right) \vee \left(x_M \text{ is } A_M^k\right)\right), \\ \quad \text{then } \{(D_1, \beta_{1,k}), \cdots, (D_N, \beta_{N,k})\} \text{ with rule weight } \theta_k, \text{ attribute weight } \delta_m \end{array} \tag{7}$$

Example 3. Taking the environmental aspect into account, earthquakes and rain/wind are considered. Rules 7-9 are given as in (8):

$$\begin{array}{l} R_7: \text{if } (earthquake \text{ is false}) \wedge ((\text{rain is medium}) \vee (wind \text{ is mild})) \\ \quad \text{then } \{(severe, 10\%), (caution, 50\%), (safe, 40\%)\} \text{ with } \theta_7 = 0.7 \\ R_8: \text{if } (earthquake \text{ is true}) \wedge ((\text{rain is medium}) \vee (wind \text{ is mild})) \\ \quad \text{then } \{(severe, 100\%)\} \text{ with } \theta_8 = 1 \\ R_9: \text{if } (earthquake \text{ is true}) \vee ((\text{rain is heavy}) \wedge (wind \text{ is medium})) \\ \quad \text{then } \{(severe, 90\%), (caution, 10\%)\} \text{ with } \theta_9 = 0.8 \end{array} \tag{8}$$

Definition 3. Hybrid BRB

Based on Definitions 1 and 2, a hybrid BRB is the combination of multiple hybrid rules with or without conjunctive/disjunctive rules or the combination of both conjunctive and disjunctive rules.

More specifically, the makeup of a hybrid BRB could be in five conditions: (1) only hybrid rules, (2) hybrid rules with conjunctive rules, (3) hybrid rules with disjunctive rules, (4) hybrid rules with both conjunctive and disjunctive rules, and (5) both conjunctive and disjunctive rules. In addition, if there are only conjunctive or disjunctive rules, then such a BRB would be a conjunctive or disjunctive BRB.

For example, Rules 7-9 (all of which are hybrid rules), or even Rules 1-9 (Rules 1-6 are either conjunctive or disjunctive rules) can form a hybrid BRB.

Remark 2. A hybrid rule could be related to multiple conjunctive and disjunctive rules, but they are far from being equivalent because the motives and knowledge for deriving different types of rules are different, which is why we have different rules for describing and modeling different conditions in the first place.

Remark 3. There is always a prevailing assumption in a hybrid rule. By considering an attribute group as an "integrated attribute", there would be no attribute group left in a hybrid rule. In other words, a hybrid rule follows only one prevailing assumption while the attribute groups within a hybrid rule could follow different assumptions.

Remark 4. To continue with Remark 3, a hybrid rule is essentially a multi-layer BRB. By considering an attribute group as an "integrated attribute", it becomes a smaller BRB, and a hybrid rule becomes a multi-layer BRB. By doing so, it becomes apparent that each attribute group or a smaller BRB follows only one assumption, whereas different attribute groups can follow different assumptions.

However, a hybrid rule would not be equivalent to a multi-layer BRB as a hybrid rule would not be equivalent to multiple conjunctive and disjunctive rules (see Remark 2). Moreover, it would be neither wise or necessary to transform a hybrid rule into a multi-layer BRB because that would require more rules and make the modeling process quite complicated since multiple hybrid rules would then mean multiple multi-layer BRBs.

4.2. Applicability of a hybrid BRB for the safety assessment

This subsection discusses the applicability of a hybrid BRB for railway safety assessment. Suppose that there are five aspects (used as attributes in the hybrid BRB) in safety assessment, namely, A_1, A_2, A_3, A_4, and A_5, and assessment results are given in three safety assessment grades (used to define the scale of the hybrid BRB), namely, *safe, caution,* and *severe*.

Then, a conjunctive rule can be constructed as follows:

$$\begin{array}{l} R_{10}: \text{if } (A_1 \text{ is safe}) \wedge (A_2 \text{ is safe}) \wedge (A_3 \text{ is safe}) \wedge (A_4 \text{ is safe}) \wedge (A_5 \text{ is safe}), \\ \text{then } \{(safe, 100\%))\} \text{ with } \theta_{10} = 1 \end{array} \tag{9}$$

which states that if all aspects are considered to be in their "*safe*" status, then the railway transportation system should be assessed to be "*safe*" with a high belief.

A disjunctive rule can be constructed as follows:

$$\begin{array}{l} R_{11}: \text{if } (A_1 \text{ is severe}) \vee (A_2 \text{ is severe}) \vee (A_3 \text{ is severe}) \vee (A_4 \text{ is severe}) \vee (A_5 \text{ is severe}), \\ \text{then } \{(severe, 100\%))\} \text{ with } \theta_{11} = 1 \end{array} \tag{10}$$

which states that if any aspect is considered "*severe*", then the railway transportation system should be assessed as "*severe*" with a high belief.

More complicated conditions can be introduced in the form of a hybrid rule as follows:

$$\begin{array}{l} R_{12}: \text{if } ((A_1 \text{ is safe}) \wedge (A_2 \text{ is safe}) \wedge (A_3 \text{ is safe})) \wedge ((A_4 \text{ is caution}) \vee (A_5 \text{ is caution})) \\ \text{then } \{(safe, 20\%), (caution, 70\%), (severe, 10\%)\} \text{ with } \theta_{12} = 1 \end{array} \tag{11}$$

which states that if A_1, A_2, and A_3 are *safe* and either A_4 or A_5 is *caution*, then it would lead to a high belief (70%) of being *caution*. Rule 11 also shows that A_1-A_3 and A_4-A_5 are considered within different attribute groups.

Furthermore, if assessment grades are quantified, then a probabilistic assessment result can also be quantified using its expectation. For example, by assigning *safe, caution* and *severe* with the utilities of 100, 80, and 0, respectively, the unified grades of Rules 10-12 can be derived as in (12),

$$\begin{aligned} &U(R_{10}) = 100 * 100\% = 100 \\ &U(R_{11}) = 0 * 100\% = 0 \\ &U(R_{12}) = 100 * 20\% + 80 * 70\% + 0 * 10\% = 76 \end{aligned} \tag{12}$$

In conclusion, a hybrid BRB comprised of multiple types of belief rules, such as Rules 10-12, can be used to perform the safety assessment for regional railway transportation systems. With the construction of a hybrid BRB and the values of different aspects/factors gathered as the input, certain rules can be activated and further integrated. The assessment result could be represented either in a belief distribution or a single value with consideration of utilities of different scales.

4.3. Hybrid BRB inference approach

The hybrid BRB inference approach for regional railway safety assessment is comprised of four steps as follows.

Step 1: Matching degree calculation for a single attribute

Suppose that there are M attributes within the hybrid rule, and initially $m = 1$.

Step 1.1: For the mth attribute, go to Step 1.2 if it is of a discrete value, or go to Step 1.3 if it is of a linguistic term.

Step 1.2: When the mth attribute is of discrete values (suppose the mth attribute has a total of $|A_m|$ reference values), the similarity between the input and the mth attribute $\varphi(x_m, A_m^j)$ is calculated using Eq. (13):

$$\varphi(x_m, A_m^j) = \begin{cases} \dfrac{A_m^{k+1} - x_m}{A_m^{k+1} - A_m^k} & j = k(A_m^k \le x_m < A_m^{k+1}) \\ \dfrac{x_m - A_m^k}{A_m^{k+1} - A_m^k} & j = k+1 \\ 0 & j = 1, 2, \ldots|A_m|, j \neq k, k+1 \end{cases} \tag{13}$$

where x_m denotes the value of the input concerning the mth attribute, A_m^j denotes the jth reference value of the mth attribute with $j \in (1, 2, \ldots|A_m|)$ and $|A_m|$ denotes the number of nonrepeated discrete reference values for the mth attribute with $A_m^1 < \cdots < A_m^k < A_m^{k+1} < \cdots < A_m^{|A_m|}$.

Step 1.3: When the reference values for an attribute are linguistic terms, for any given input, the similarity can be directly calculated.

For example, there are three reference values for *rain*, heavy, medium and mild. For any input, it has to be one of the three. Thus, the reference values are directly used. For special conditions, such as {(heavy, 20%), (medium, 80%)}, there is $\varphi(rain, \text{heavy}) = 0.2$, and $\varphi(rain, \text{medium}) = 0.8$.

Step 1.4: Matching degrees calculation for a single attribute

If the reliability of the input concerning the mth attribute is ε_i, then the matching degree for the mth attribute by the input is,

$$\alpha_m^k = \varphi_m \varepsilon_m \Big/ \sum_{m=1}^{M} \varphi_m \tag{14}$$

Step 2: Matching degree calculation for a hybrid rule

Suppose that there are G attribute groups within the hybrid rule, and initially g=1.

Step 2.1: For the gth attribute group, go to Step 2.2 if it is under the conjunctive assumption; otherwise go to Step 2.3.

Step 2.2: Conjunctive attributes group matching degree calculation

When the conjunctive assumption is applied, their matching degree is calculated using Eq. (15) [31,35],

$$\alpha_{k,g} = \prod_{m=1}^{M} (\alpha_m^k)^{\overline{\delta}_{km}}, \overline{\delta}_{km} = \frac{\delta_{km}}{\max\{\delta_{km}\}} \tag{15}$$

where the relative weight of an attribute is normally assumed to be 1 ($\delta_{km} = 1$), and therefore $\overline{\delta}_{km} = 1$.

Step 2.3: Disjunctive attributes group matching degree calculation

When the disjunctive assumption is applied, their matching degree is calculated using Eq. (16) [5,6],

$$\alpha_{k,g} = \sum_{m=1}^{M} (\alpha_m^k)^{\overline{\delta}_{km}}, \overline{\delta}_{km} = \frac{\delta_{km}}{\max\{\delta_{km}\}} \tag{16}$$

where there is also $\delta_{km} = 1$ and therefore $\overline{\delta}_{km} = 1$.

Step 2.4: If $g = G$, then go to Step 2.5; otherwise, let $g = g + 1$ and go to Step 2.1.

Step 2.5: Matching degrees calculation for a hybrid rule

With the matching degrees for the gth attribute group, the integrated matching degree for the kth rule α_k is calculated by Eq. (17) if it is the conjunctive assumption or Eq. (18) if it is disjunctive.

$$\alpha_k = \prod_{g=1}^{G} (\alpha_{k,g}) \tag{17}$$

$$\alpha_k = \sum_{g=1}^{G} (\alpha_{k,g}) \tag{18}$$

Step 3: Weight calculation

For K activated rules, the weight for the kth rule is calculated as in Eq. (19),

$$\omega_k = \theta_k \alpha_k \Big/ \sum_{k=1}^{K} \theta_k \alpha_k \tag{19}$$

where θ_k denotes the initial weight for the kth rule.

Step 4: Integration using ER

After the activation of certain rules, the activated K rules are integrated using ER as in Eqs. (20)–(21) [28],

$$\beta_n = \frac{\mu\left[\prod_{k=1}^{L}\left(w_k\beta_{n,k} + 1 - w_k\sum_{n=1}^{N}\beta_{n,k}\right) - \prod_{k=1}^{L}\left(1 - w_k\sum_{n=1}^{N}\beta_{n,k}\right)\right]}{1 - \mu\left[\prod_{k=1}^{L}(1 - w_k)\right]} \tag{20}$$

$$\mu = \left[\sum_{n=1}^{N}\prod_{k=1}^{L}\left(w_k\beta_{n,k} + 1 - w_k\sum_{n=1}^{N}\beta_{n,k}\right) - (N-1)\prod_{k=1}^{L}\left(1 - w_k\sum_{n=1}^{N}\beta_{n,k}\right)\right]^{-1} \tag{21}$$

where β_n represents the belief for the nth scale, D_n.

Moreover, an integrated grade U can be calculated using Eq. (22) by assigning the nth scale with a utility $U(D_n)$,

$$U = \sum_{n=1}^{N} U(D_n)\beta_n \tag{22}$$

Remark 5. To correctly use Eqs. (15) and (17) which are under the conjunctive assumption, it is required that the observation of assessment values on any attribute be not affected by whether the observations of other attributes are known or not. To correctly use Eqs. (16) and (18) which are under the disjunctive assumption, it is required that the observations of assessment values on all attributes can be mutually disjoint from each other with no overlap at all.

Remark 6. The belief structure of a hybrid rule is determined by grouping certain attributes in a conjunctive or disjunctive fashion. However, the matching degree of the inner attribute group should be calculated before deriving the matching degree for the rule. After the matching degrees for the attribute groups are calculated, the rule should be either conjunctive or disjunctive, which is consistent with Remarks 3–4: A hybrid rule still follows a single assumption in which one or more attribute groups could follow a different assumption.

Remark 7. Although motivated by the regional railway safety assessment problem, the hybrid BRB construction and inferencing procedures are still in a generic sense. It is not only applicable for this specific problem but for multi-attribute decision analysis (MADA) problems with similar characteristics.

Remark 8. Note that the optimization for the hybrid BRB is not discussed in this study mainly because there is no label for the collected data. However, it would be quite an interesting topic for future work. Moreover, many previous BRB training and learning researches can also be used for references and provide insights for hybrid BRB optimization.

4.4. Railway transportation safety assessment using hybrid BRB

The railway safety assessment approach using hybrid BRB is given as follows:

Step 1: Problem analysis. Determine relevant aspects and factors as well as their correlation as the belief structure for hybrid BRB model construction.
Step 2: Construct a hybrid BRB model. Invite experts and decision makers to construct a hybrid BRB model with the belief structure determined in Step 1.
Step 3: Hybrid BRB inference including multiple steps as provided in Section 3.4.
Step 4: Result derivation. The results can be derived either in a belief distribution or expectation.
Step 5: Discussion and validation. Conduct further analysis in comparison with historical reports of accidents and system failures for validation.

5. Case study

5.1. Basics of the Cheng-Yu region and its railway lines

Located in the southwestern China, the **Cheng-Yu** region is comprised of one major province (the *Sichuan* province, whose capital city is ***Cheng****du*) and one province-level metropolis (the city of *Chongqing*, whose alternate name is ***Yu***), as shown in Fig. 1(a/b).

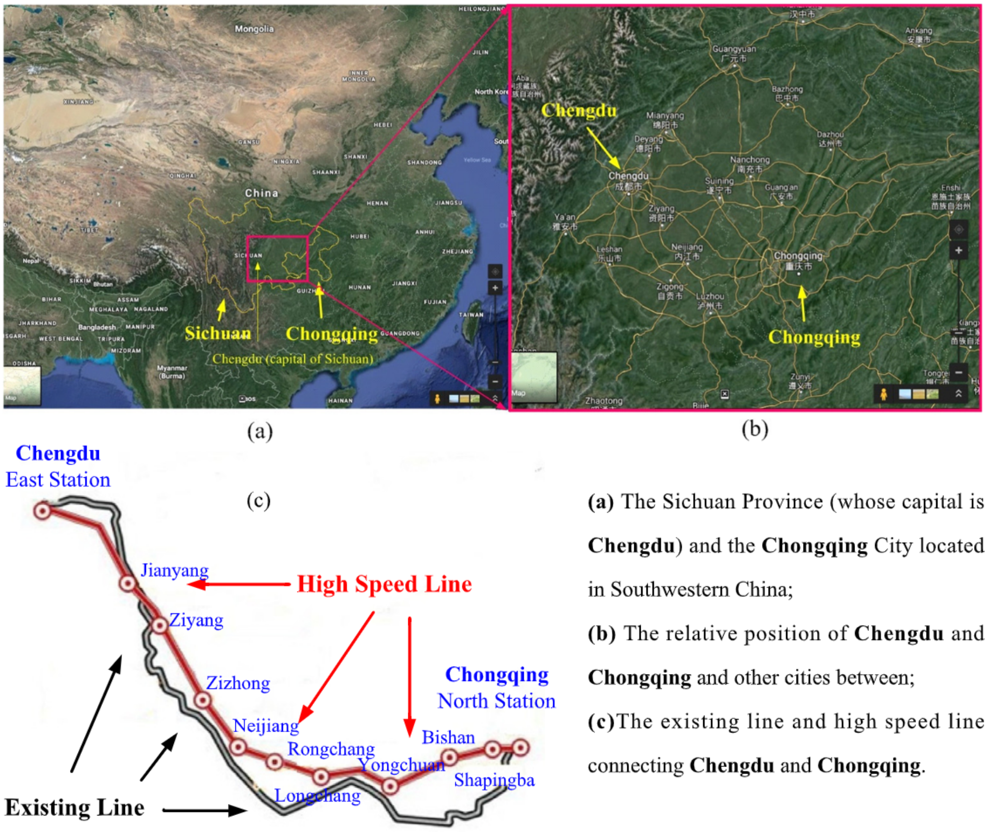
Despite the unprivileged mountainous terrain, a thriving economy has been developed in the Cheng-Yu region. In 2018, *Chongqing* and *Chengdu* ranked 5th and 8th in GDP in China, respectively. For this, many thanks should be granted to the transportation network that has been constructed in recent years. At the same time, the thriving and continually growing economy also provides a strong backup for future transportation development, especially railway transportation. Presently, there are primarily two railway lines connecting *Chengdu* and *Chongqing*, namely, the Cheng-Yu railway line (which transports passengers and freight, referred to as the existing line) and the Cheng-Yu High Speed railway line (which only transports passengers by *Hexie* trains, referred to as the high speed line), as shown in Fig. 1(c).

Comparatively, the high speed line in the Cheng-Yu region transports many more passengers (43680 passengers vs. 15104 passengers) via more shifts (78 shifts vs. 8 shifts). Moreover, the commuting time has been significantly reduced (76 min vs. 270 min). However, it does not necessarily mean that the high speed line is safer. For example, "high speed" would lead to a much more severe consequence if accidents happen. In fact, the occurrence of railway accidents has not stopped in railway transportations, not only in the Cheng-Yu region but all around the world.

Thus, the questions remain: has the safety level been improved? What are the main influential aspects/factors of regional railway transportation safety? What can be done to further improve the safety levels? These are the main motivation and contribution of this study.

5.2. Safety assessment for Cheng-Yu regional railway transportation

For the existing line and high speed line in the Cheng-Yu region, five aspects are considered, namely, environment, equipment, management, passengers, and accidents. The environmental aspect primarily refers to weather conditions, such as



(a) (b) (c)

(a) The Sichuan Province (whose capital is **Chengdu**) and the **Chongqing** City located in Southwestern China;

(b) The relative position of **Chengdu** and **Chongqing** and other cities between;

(c) The existing line and high speed line connecting **Chengdu** and **Chongqing**.

Fig. 1. The Cheng-Yu region in southwestern China and the existing and high speed lines.

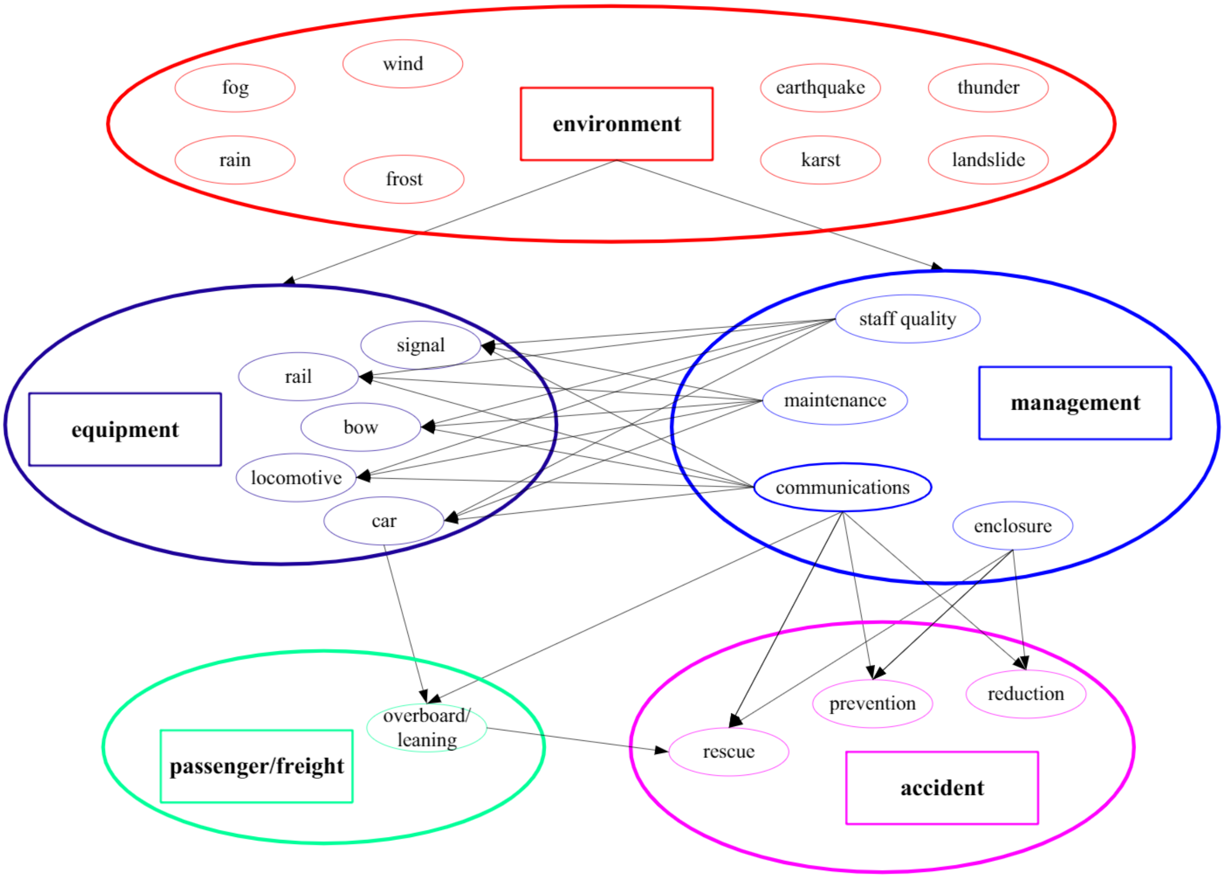


Fig. 2. Safety assessment model for railway transportation in the Cheng-Yu region.

rain/wind in summer and fog/frost in winter, and to disastrous environmental conditions, such as earthquakes and landslides. The equipment aspect primarily refers to the mechanical and electrical malfunction in locomotives, cars, rails, signal systems, and bow, among others. The managerial aspect primarily refers to staff quality, maintenance abilities, cross-section communications and railway enclosure [7,25]. The passenger factor primarily refers to the conditions of passenger overboarding and freight overloading. The accident factor primarily refers to the prevention, reduction, and rescue abilities.

Apparently, the five aspects and further factors are correlated with each other. On one hand, if the rail or the signal system is broken, the safety level would be lowered. If disturbed by bad weather conditions, the rail or signal system would be worsened and the safety level could be even lower. On the other hand, with proper maintenance, the situation could be resolved and the safety level could return to normal.

The five aspects can be further disintegrated into detailed factors, as shown in Table 1 and Fig. 2. For the aspects and factors, they are classified into three categories for convenience in practical data gathering, namely, safe, medium, and severe (the name could be different depending on different aspects/factors). For the overall safety level, it is classified into five categories to provide better discrimination for managerial decision-making purposes, namely, safe, caution, extreme caution, severe, and extreme severe.

5.3. Hybrid BRB for the existing line

For each of the five aspects, certain rules are given to construct a hybrid BRB model (Table A.1 in Appendix A) for the existing line.

5.3.1. Environment

If disastrous environmental conditions occur, then the status of the assessment result is *severe*. Normally, the train would be stopped until further notice. If no such incidents occur, then it is *safe*.

$$\begin{aligned} &R_1: \text{if } (earthquake \text{ is true}) \vee (landslide \text{ is true}) \vee (karst \text{ is true}) \vee (fire \text{ is true}), \text{ then } \{(severe, 100\%)\} \text{ with } \theta_1 = 1 \\ &R_2: \text{if } (earthquake \text{ is false}) \wedge (landslide \text{ is false}) \wedge (karst \text{ is false}) \wedge (fire \text{ is false}), \text{then } \{(safe, 100\%)\} \text{ with } \theta_2 = 1 \end{aligned} \tag{23}$$

Table 1
Indices for the railway transportation safety assessment in the Cheng-Yu region*.

Aspects	Indices	Referenced values	Informatics
Environment	Rain	Mild, medium, heavy	The Cheng-Yu region can receive very heavy rain in summer from Jul. to Sep. The speed of the existing line (high speed line) needs to be decreased to 120 km/h if the rainfall is 35 mm/h (50 mm/h), to 45 km/h for 70 mm/h (100 mm/h) and to 0 for 100 mm/h (120 mm/h).
	Wind	Mild, medium, strong	Strong wind often arrives with heavy rain in the Cheng-Yu region in summer. If the wind speed reaches 20/25/30 m/s, the speed for the high speed trains is 300/200/120 km/h and for the existing line it is 100/60/stop.
	Fog	Mild, medium, severe	The Cheng-Yu region frequently experiences heavy fog due to its special environment (surrounded by mountains and with high humidity). Heavy fog normally occurs in winter (mostly in Dec. or Jan.). For the existing line (high speed line), a lookout is expected if visibility is less than 500 m (200 m), the speed must be reduced if it is decreased to 300 m (100 m), and a stop is expected if it is decreased to 100 m (50 m).
	Frost	Mild, medium, severe	Frost in winter prevents rails from having the proper operation. Normally, this would cause a speed reduction or even a stop before defrosting. Frost normally occurs in Dec. or Jan.
	Disastrous environmental conditions	True, false	Earthquakes and other catastrophes pose a very serious threat in this region because it is one of China's most active earthquake regions (10 over Bound 4 (51 over Bound 3) in the last 20 months). However, the effect of an earthquake remains indirect. If an earthquake smaller than 4 bound occurs, a train needs to stop for 2-6 h for a security check. For an earthquake above Bound 4, it needs to stop until further notice.
	Snow	*It is not a common factor in the Cheng-Yu region because this region is in southern China*	
	Thunder Lightning	*Thunder and lightning accompany storms in the Cheng-Yu region, primarily in summer. However, they are harmless unless certain equipment is harmed or caused to malfunction.*	
Equipment	Locomotive	Safe, medium, severe	The locomotives are the command center of the trains. For the existing line, it is mostly mechanical failure. For high speed trains, it is mostly the ATP system, which is a computer system failure. This could cause serious safety threats for both lines.
	Car	Safe, medium, severe	The cars are the main transportation component of a train. For the existing line, many components can malfunction, including the doors, hoods, and windows. For high speed trains, it is primarily the air-conditioning system. Comparatively, failures in cars are not very common.
	Rail	Safe, medium, severe	The rails are one of the most consuming parts. The trains are running on the rails all day long, which could result in serious damage, e.g., rail wear, sinking, and so on. These damages could in turn damage the wheels of the locomotives and cars or even the suspension system. Although this equipment can be repaired with proper maintenance, this type of damage remains a serious threat.
	Signal	Safe, medium, severe	The signal system is directly connected to conveying the commands to the trains and transmitting the status back to the operation command center. Therefore, it is very important for railway safety. The signal system could be harmed by a mechanical flaw, a harsh environment (thunder and lightning, etc.) or improper maintenance. Failures in the signal system are among the main threats to the high speed line.
	Connecting bow	Safe, medium, severe	The bow and the connecting net are the power source for modern trains (existing lines and high speed line). The bow could be disrupted by many intruding objects, for example, plastic bags blown by strong winds, fallen trees caused by a landslide, or a collision with a truck. These situations are also serious threats to railway transportation safety.
Management	Staff quality	Safe, medium, severe	• Operating staff quality. The first factor is the technical level, which can be evaluated by tests after training. The second factor is the emergency handling ability, which can be assessed by plans and training. The third factor is the safety awareness among the staff, which has been specifically examined in the Chengdu railway station using the A/B/C/D ratings (directly connected to salary). • Management staff quality. There are primarily two factors: the ability to accomplish the daily designated managing tasks, and the responsibility in management at high levels during a long term operation period (as the trains run 24/7 continuously), especially in making plans and ensuring that the staff has good morale and the equipment is in good condition. • Commanding ability of drivers: this is very important for the existing line, which is less dependent on automation systems than the high speed train (with drivers mainly observing and correcting if necessary).

(*continued on next page*)

Table 1 (*continued*)

Aspects	Indices	Referenced values	Informatics
	Maintenance	Intact, broken	Many possible safety concerns regarding rails and signals can be corrected by careful daily maintenance. • Education. A good education for the workers can elevate their responsibility towards performing the daily maintenance and care; • Human factors, procedure standardization, regulation. All work should be conducted under standardized regulations and inspections. If so, many possible accidents and system failures can be avoided; • Equipment maintenance and quality (the maintenance window is 4 hrs for the high speed line and 90 min-2 hrs for the existing line). All planned maintenance should be conducted without a delay or omission.
	Communication	Safe, medium, severe	An equipment failure always involves multiple sections. Thus, cross-sectional communication ability becomes very important, especially when cross-sectional guidance is required to fulfill a maintenance task. For example, if an accident occurs on the railway, then not only should the railway section (the *Gongwu* section) be involved but possibly also the *signal* section. If an accident occurs on the connecting bow, then not only is the *Dianwu* section concerned but probably also the *Gongwu* section and the *signal* section. With more equipment being deployed, this issue has become more urgent for ensuring the safety and immediate recovery of railway transportation.
	Enclosure	Safe, medium, severe	The enclosure for the railway transportation denotes that the railway should be not trespassed by intruders. As many accidents are caused by the breach of a passage that should be closed due to occupation or maintenance activity, an enclosure is very important for railway safety. • To avoid an enclosure breach in the first place, the first precaution is the design. For example, railroads should not cross motorways. Special signs and blocks/barriers should be put in place. Alert systems should also be installed to warn trespassing objects/humans. • Another hazard point is where trains enter and depart to avoid an enclosure breach; • Special attention should be paid to "**windows**" when a temporary enclosure is established for sections under maintenance. The enclosure for windows is very important for where workers are sent. Accidents in windows could lead to higher casualties.
Passengers/freight	Passengers	Safe, medium, severe	For the existing line and the high speed line, a limited number of "over-numbered" passengers are allowed to board the train during holidays, which should be regulated and monitored by ticket selling. However, many more passengers would buy a ticket to a nearer station but disembark at their real farther destinations, which is quite common during the Spring Festival. • Mechanical effects: this could cause the air suspension to fail, which could further cause the train to stop and even derail. • Crowded passengers could result in fast consumption of limited supplies, which could cause unnecessary tension or even riots; • If an accident occurs, overboarded passengers could worsen the safety level by causing more deaths.
	Freight	Safe, medium, severe	Overloaded freights could cause the cars to lean. Overloaded freights are mostly caused by improper bounding. Leaning normally occurs in the transportation process (en route) rather than in the loading time (within the station).
Accident	Prevention	Safe, medium, severe	To prevent an accident from occurring, the best solution is to use a better design, which can ensure the enclosure of the railway. Warnings of bad weather conditions and the preparation of contingency plans could also help.
	Reduction	Safe, medium, severe	The most efficient means to reducing the accident levels is through education, training and a good implementing of regulations as well as responsible leadership among the sections to ensure that the equipment is in good condition to avoid accidents and system failures.
	Rescue	Safe, medium, severe	Plan: Emergency plans as a response should be well-conceived (not only for accidents but also for emergencies, such as terrorist attacks, etc.). If at a station, firefighters and their rescue trucks and equipment should have access to the fire/wounded passengers/broken equipment. If en route, the train/passengers should be able to be transferred fast and rescue responders should also have access to provide help (it is more severe for the high speed line because they are mostly closed).

[*] Environmental inputs are derived from the websites of the Chengdu/Chongqing meteorological bureau and earthquake information is derived from the China Earthquake Administration. Other information concerning the two lines is gathered using historical reports as well as technicians and experts from the respective stations.

Fog and frost normally occur in winter. If they are mild, then it is *safe*. If one is deemed medium and the other is mild, it should be deemed *caution*. If both are deemed medium or if either is deemed severe, it should be deemed *severe*.

$$\begin{aligned}
&R_3 : \text{if } (fog \text{ is mild}) \wedge (frost \text{ is mild}), \text{then } \{(safe, 100\%)\} \text{ with } \theta_3 = 1\\
&R_4 : \text{if } (fog \text{ is medium}) \wedge (frost \text{ is mild}), \text{then } \{(caution, 100\%)\} \text{ with } \theta_4 = 1\\
&R_5 : \text{if } (fog \text{ is mild}) \wedge (frost \text{ is medium}), \text{then } \{(caution, 100\%)\} \text{ with } \theta_5 = 1\\
&R_6 : \text{if } (fog \text{ is medium}) \wedge (frost \text{ is medium}), \text{then } \{(severe, 100\%)\} \text{ with } \theta_6 = 1\\
&R_7 : \text{if } (fog \text{ is severe}) \vee (frost \text{ is severe}), \text{then } \{(severe, 100\%)\} \text{ with } \theta_7 = 1
\end{aligned} \tag{24}$$

Rain and wind normally occur in summer. If both are mild, then it is *safe*. If one is deemed medium and the other is mild, it should be deemed *caution*. If both are deemed medium or either is deemed severe, it should be deemed *severe* (see Rules 8-12 in Table A.1 in Appendix A).

As there is not much available prior information, the rule weights θ and attribute weights δ are assumed to be "1" for all rules in this study.

Another key question for hybrid BRB modeling is completeness. To ensure its completeness, all possible conditions should be analyzed first and then rules can be constructed with no condition left.

For example, in constructing the corresponding rules concerning the fog and frost factors, a total of nine possible conditions should be analyzed since the two factors are both with three referenced values. Rules 3-6 would cover four conditions and Rule 7 would cover the rest five. Therefore, all conditions concerning the fog and frost factors have been constructed.

Note that the modeling process only requires covering all possible combinations but not constructing the complete conjunctive rules first. If the complete conjunctive rules are constructed first, then it would be unnecessary to adopt the hybrid BRB at all. In fact, the size of a hybrid BRB would be far smaller than a complete conjunctive BRB since a hybrid rule would be able to represent multiple combinations.

5.3.2. Equipment

If all equipment is normal, it is *safe*. If locomotive or car is deemed medium while rail/signal/bow are deemed normal, then it is *safe*. If locomotive and car are deemed medium while rail/signal/bow are deemed normal, then it is *caution*. If any of locomotive, car, rail, signal or bow is deemed flawed, then it is *severe*.

$$\begin{aligned}
&R_{13} : \text{if } (loco \text{ is normal}) \wedge (car \text{ is normal}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{13} = 1\\
&R_{14} : \text{if } (loco \text{ is medium}) \wedge (car \text{ is normal}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{14} = 1\\
&R_{15} : \text{if } (loco \text{ is normal}) \wedge (car \text{ is medium}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{15} = 1\\
&R_{16} : \text{if } (loco \text{ is medium}) \wedge (car \text{ is medium}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(caution, 100\%)\} \text{ with } \theta_{16} = 1\\
&R_{17} : \text{if } (loco \text{ is fault}) \vee (car \text{ is fault}) \vee (rail \text{ is fault}) \vee (signal \text{ is fault}) \vee (bow \text{ is fault}),\\
&\quad \text{then } \{(severe, 100\%)\} \text{ with } \theta_{17} = 1
\end{aligned} \tag{25}$$

If any of rail, signal or bow is medium and none is severe, then it is *caution* (see Rules 18-20 in Table A.1 in Appendix A).

5.3.3. Management

If staff/maintenance/communication/enclosure is good/intact, then it is *safe*. If staff quality is low, or maintenance is poor, or communication is poor, or enclosure is broken, then it is *severe*. If maintenance is medium while staff/communication is good or medium and enclosure is intact, then it is *caution* (see Rules 21-23 in Table A.1 in Appendix A).

If either staff or communication is good and others are medium while enclosure is intact and maintenance is good, then it is *safe*. If staff and communication are medium while enclosure is intact and maintenance is good, then it is *caution* (see Rules 24-26 in Table A.1 in Appendix A).

5.3.4. Passengers

If passenger is normal/medium and freight is normal, then it is *safe*; If passenger is normal/medium and freight is medium, then it is *caution*; If either passenger or freight is severe, then it is *severe* (see Rules 27-29 in Table A.1).

5.3.5. Accidents

If all factors are good, then it is safe. If either prevention, reduction or rescue is severe, then it is *severe*. If the rescue is good/medium and prevention or reduction is medium, then it is *caution*. If the rescue is medium and prevention and reduction are medium, then it is *safe* (see Rules 30-34 in Table A.1).

5.3.6. Composite

If all factors are safe, then it is *safe*. If the environment, equipment, and management are safe, and passenger is caution and accident is safe or passenger is safe and accident is caution, then it is *safe*;

$$\begin{aligned}
&R_{35}: \text{if } (envir \text{ is safe}) \wedge (equip \text{ is safe}) \wedge (mang \text{ is safe}) \wedge (pass \text{ is safe}) \wedge (acc \text{ is safe}),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{35} = 1\\
&R_{36}: \text{if}((envir \text{ is safe}) \wedge (equip \text{ is safe}) \wedge (mang \text{ is safe})) \wedge ((pass \text{ is caution}) \wedge (acc \text{ is safe})),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{36} = 1\\
&R_{37}: \text{if}((envir \text{ is safe}) \wedge (equip \text{ is safe}) \wedge (mang \text{ is safe})) \wedge ((pass \text{ is safe}) \wedge (acc \text{ is caution})),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{37} = 1
\end{aligned} \tag{26}$$

If environment, equipment, and management are safe, and passenger and accident are caution/severe, then it is *caution*; (see Rules 38-39 in Table A.1);

If either environment, equipment or management is caution and the other two are safe, (regardless of whatever passenger and accident is), then it is *caution* (see Rules 40-42 in Table A.1 in Appendix A);

If any two of environment, equipment, and management are caution and the other one is safe, (regardless of whatever passenger and accident is), then it is *extreme caution* (see Rules 43-45 in Table A.1 in Appendix A);

If any of environment, equipment, or management is severe and the other two are safe, (regardless of whatever passenger and accident is), then it is *extreme caution* (see Rules 46-48 in Table A.1 in Appendix A);

If environment, equipment, and management are severe, caution and safe, (regardless of which one is which and whatever passenger and accident are), then it is *severe*; if any two of environment, equipment, management are severe, (regardless of whatever passenger and accident are), then it is *extreme severe* (see Rules 49-57 in Table A.1 in Appendix A);

5.4. Hybrid BRB for the high speed line

For each of the five aspects, certain rules are provided to construct a hybrid BRB model (Table B.1 in Appendix B) for the high speed line.

5.4.1. Environment

If all factors are false, then it is *safe*. If any of the following occurs, it would be deemed *severe* and the train would be stopped until further notice.

$$\begin{aligned}
&R_1: \text{if } (earthquake \text{ is true}) \vee (landslide \text{ is true}) \vee (karst \text{ is true}) \vee (fire \text{ is true}), \text{then } \{(severe, 100\%)\} \text{ with } \theta_1 = 1\\
&R_2: \text{if } (earthquake \text{ is false}) \wedge (landslide \text{ is false}) \wedge (karst \text{ is false}) \wedge (fire \text{ is false}), \text{then } \{(safe, 100\%)\} \text{ with } \theta_2 = 1
\end{aligned} \tag{27}$$

Fog and frost normally occur in winter. If both are mild, then it is *safe*. If one is medium and the other is mild, it is *caution*. If any is deemed severe, the condition is more complex, as shown by the following rules.

$$\begin{aligned}
&R_3: \text{if } (fog \text{ is mild}) \wedge (frost \text{ is mild}), \text{then } \{(safe, 100\%)\} \text{ with } \theta_3 = 1\\
&R_4: \text{if } (fog \text{ is medium}) \wedge (frost \text{ is mild}), \text{then } \{(caution, 100\%)\} \text{ with } \theta_4 = 1\\
&R_5: \text{if } (fog \text{ is mild}) \wedge (frost \text{ is medium}), \text{then } \{(caution, 100\%)\} \text{ with } \theta_5 = 1\\
&R_6: \text{if } (fog \text{ is severe}) \wedge (frost \text{ is mild}), \text{then } \{(caution, 20\%), (severe, 80\%)\} \text{ with } \theta_6 = 1\\
&R_7: \text{if } (fog \text{ is mild}) \wedge (frost \text{ is severe}), \text{then } \{(caution, 40\%), (severe, 60\%)\} \text{ with } \theta_7 = 1\\
&R_8: \text{if } (fog \text{ is medium/severe}) \wedge (frost \text{ is medium/severe}), \text{then } \{(severe, 100\%)\} \text{ with } \theta_8 = 1
\end{aligned} \tag{28}$$

Rain and wind normally occur in summer. If both are mild, then it is *safe*. Other conditions are more complex, as Rules 9-15 in Table B.1 in Appendix B;

5.4.2. Equipment

If all factors are normal, it is *safe*. If locomotive or car is medium while rail/signal/bow are normal, then it is *caution*. All of the other conditions are deemed to be *severe*.

$$\begin{aligned}
&R_{16}: \text{if } (loco \text{ is normal}) \wedge (car \text{ is normal}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(safe, 100\%)\} \text{ with } \theta_{16} = 1\\
&R_{17}: \text{if } (loco \text{ is medium}) \wedge (car \text{ is normal}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(caution, 100\%)\} \text{ with } \theta_{17} = 1\\
&R_{18}: \text{if } (loco \text{ is normal}) \wedge (car \text{ is medium}) \wedge (rail \text{ is normal}) \wedge (signal \text{ is normal}) \wedge (bow \text{ is normal}),\\
&\quad \text{then } \{(caution, 100\%)\} \text{ with } \theta_{18} = 1\\
&R_{19}: \text{if } (loco \text{ is medium}) \wedge (car \text{ is medium}), \text{then}\{(severe, 100\%)\} \text{ with } \theta_{19} = 1\\
&R_{20}: \text{if } (rail \text{ is medium}) \vee (signal \text{ is medium}) \vee (bow \text{ is medium}), \text{then } \{(severe, 100\%)\} \text{ with } \theta_{20} = 1\\
&R_{21}: \text{if } (loco \text{ is fault}) \vee (car \text{ is fault}) \vee (rail \text{ is fault}) \vee (signal \text{ is fault}) \vee (bow \text{ is fault}),\\
&\quad \text{then } \{(severe, 100\%)\} \text{ with } \theta_{21} = 1
\end{aligned} \tag{29}$$

5.4.3. Management

If staff/maintenance/communication/enclosure is good/intact, then it is *safe*. If staff is medium, and maintenance/communication/enclosure is good/intact, then it is *caution*. All of the other conditions are deemed to be *severe* (see Rules 22-24 in Table B.1 in Appendix B);

5.4.4. Passengers

Because there is no freight on the high speed line, only passengers are concerned. If passenger is normal/medium/severe, then it is *safe*/*caution*/(*safe*/*caution*) (see Rules 25-27 in Table B.1 in Appendix B);

5.4.5. Accidents

If prevention and reduction are safe and rescue is good/medium, then it is *safe*. If any of prevention, reduction or rescue is severe, then it is *severe*. If the rescue is good/medium, and either prevention or reduction is medium, then it is *caution* (see Rules 28-32 in Table B.1 in Appendix B);

5.4.6. Composite

When the environment, equipment, and management are safe/medium, if passenger and accident are safe/medium, then it is *safe*; if either or both passenger and accident is/are severe, then it is *caution* (see Rules 33-34 in Table B.1 in Appendix B);

If any of environment, equipment or management is severe and the others are safe or medium, and passenger and accident are safe or caution, then it is *extreme caution*. If any of environment, equipment, or management is severe and the others are safe or medium, and passenger and accident are severe, then it is *severe* (see Rules 35-40 in Table B.1 in Appendix B);

If more than two of environment, equipment, management are severe, regardless of what the other is and what passenger and accident are, then it is *extreme severe* (see Rules 41-43 in Table B.1 in Appendix B);

There are fewer rules in the safety assessment of the high speed line, primarily because the principle is far stricter for the high speed line and more conditions are assessed at a stricter safety level.

5.5. Comparative assessment results

To conduct a comparative analysis of the existing line and the high speed line, the environmental inputs (rain/wind/frost/fog) and certain disastrous environmental conditions (landslide, fire, etc.) are derived from the Chengdu Meteorological Bureau (http://www.cdmb.gov.cn/service/slist/typeid/70) and the Chongqing Meteorological Bureau (http://www.cqmb.gov.cn/qxfw/qhxx), and specifically the earthquake information is derived from the China Earthquake Administration (http://www.cea.gov.cn/publish/dizhenj/464/479/index.html). Other information concerning the two lines is gathered from historical reports and aided by technicians and experts from the connecting stations of the Chengdu Railway Bureau.

Although the historical records date back to 2016/1/1, the environmental records from the Chengdu Meteorological Bureau only date back to August of 2017 and those from the Chongqing Meteorological Bureau only date back to January of 2017. Thus, the inputs without missing data are gathered from 2017/1/1 to 2018/8/30.

The safety levels provided in Fig. 3 and Table 2 are assessed with the gathered inputs and the hybrid BRBs for the existing line (see Section 5.2) and the high speed line (see Sections 5.3).

From the empirical case study results in Fig. 3 and Table 2, the following observations can be made.

(1) As shown in Fig. 3(a/d) and Table 2, the high speed line is safer than the existing line. More specifically, out of 608 days in 20 months, 441 days (72.53%) and 552 days (90.79%) are assessed as safe for the existing line and the high speed line, respectively. Two days (0.33%) are assessed to be extreme severe for the existing line, whereas no days are assessed to be extreme severe for the high speed line.
(2) There are also monthly and seasonal differences. As shown in Fig. 3(b/c), both lines are relatively safe in spring and autumn (April/June/August/October), whereas the safety levels are worsen in winter (mostly January). The high speed line performs better in winter than the existing line in terms of safety levels.
(3) The only times when the existing line outperformed the high speed line were in the spring (April/May) of 2017 and 2018 when the weather conditions were excellent and the high speed line suffered from equipment failure while the existing line did not.

Table 2
Summarized statistical results.

Item	Relatively safe (bound/utility)			Relatively severe (bound/utility)	
	Safe (100)	Caution (90)	Extreme caution (80)	Severe (60)	Extreme severe (40)
existing line	441(72.53%)	118(19.41%)	33(5.43%)	14(2.30%)	2(0.33%)
	592 (97.37%)			16 (2.63%)	
time (month)	2017/4, 2017/6, 2017/10, 2018/3-4, 2018/8			2017/1, 2018/1	
time (season)	spring, autumn			winter	
high speed line	552(90.79%)	28(4.62%)	26(4.28%)	2(0.33%)	0
	606 (99.67%)			2(0.33%)	
time (month)	2017/4, 2017/6, 2017/10, 2018/3-4, 2018/8			2017/1, 2017/12, 2018/1	
time (season)	spring, autumn			winter	

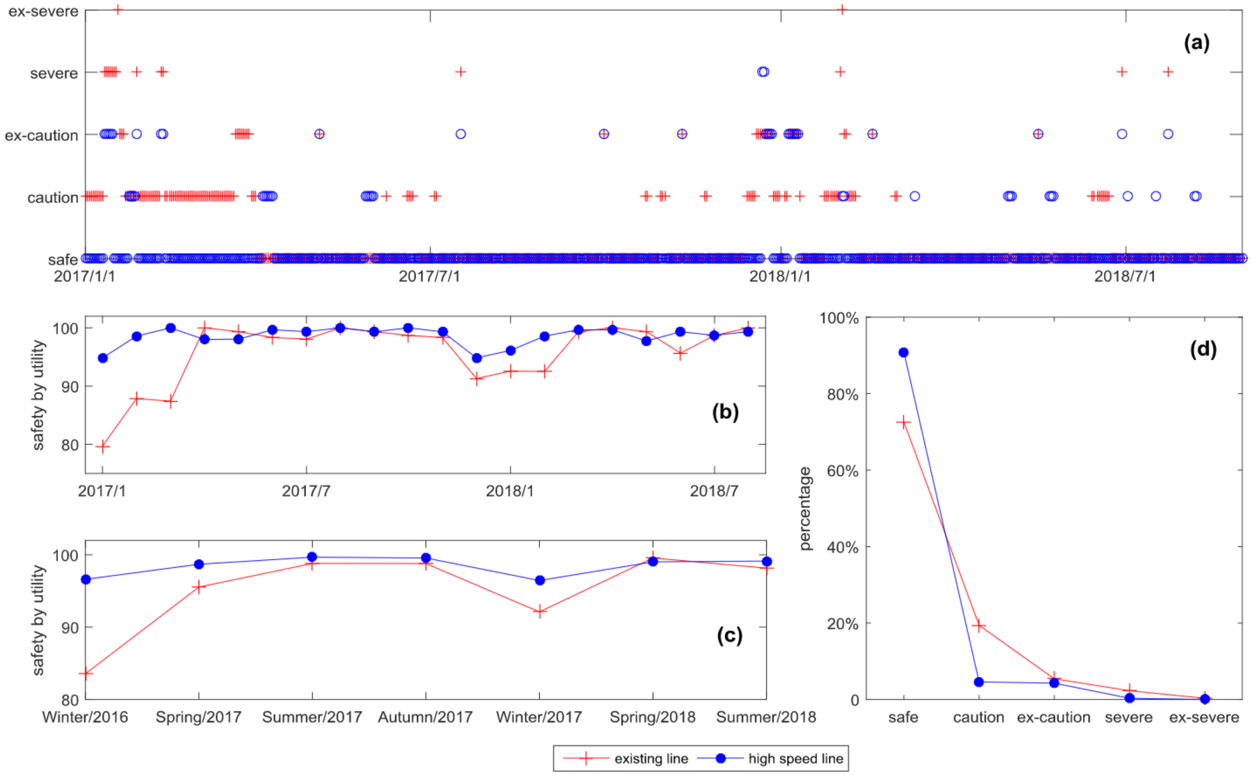


Fig. 3. Assessment results for the existing line and high speed line.
(a: comparison per day; b: comparison per month; c: comparison per season; d: composite comparison, utilities for five bounds are 100/90/80/60/40).

5.6. Validation with accident and system failure reports

Unfortunately, no safety assessment has been conducted by the railway stations within the Cheng-Yu region, mostly because they are not affiliated with one bureau. Nevertheless, accident reports and system failure records have been kept which can be served as a validation means. Accidents and system failures that result in a train stopping for over 6 hours in the day and/or 8 hours in the night are considered, as presented in Table D.1 in Appendix D. Other minor system faults are considered “relatively safe” if the train stopping is less than 6 hours.

Fig. 4 shows the safety assessment results in comparison with the accidents/failures for the existing line and high speed line (more detailed results are in Table C.1 in Appendix C).

Based on the comparative results and Fig. 4, it is found that:

(1) All *severe* and *extreme severe* assessment results are consistent with certain accidents and/or system failures except that three accidents for the existing line and one for the high speed line failed to be correctly identified, which preliminarily validate the efficiency of the proposed safety assessment approach.
(2) The correctly identified safety assessment results show that the elevated safety levels in summer usually do not last long (primarily because heavy rains and strong winds would not last for days), whereas winter tends to have lasting worsened safety levels (primarily because severe fog and frost tend to persist). Note that disastrous environmental conditions do not seem to have the most serious influence as expected. For example, an earthquake does not directly cause any severe accidents unless combined with harmful environmental or equipment failures. This is mainly because such disastrous environmental conditions automatically result in a train being stopped, which can prevent a more serious accident from occurring.
(3) All of the unidentified safety assessment results (3 out of 19 for the existing line and 1 out of 14 for the high speed line) are caused by single most extreme factors, namely, environmental or critical system failures. This is because a single factor would not likely result in an extreme result by a hybrid model whereas it is possible under practical conditions if such a single factor is severe enough, e.g., if an equipment failure is so severe and cannot be fixed in time, or if a fog in winter is so thick that visibility is extremely low. From this perspective, it calls for further modification of the hybrid BRB model.

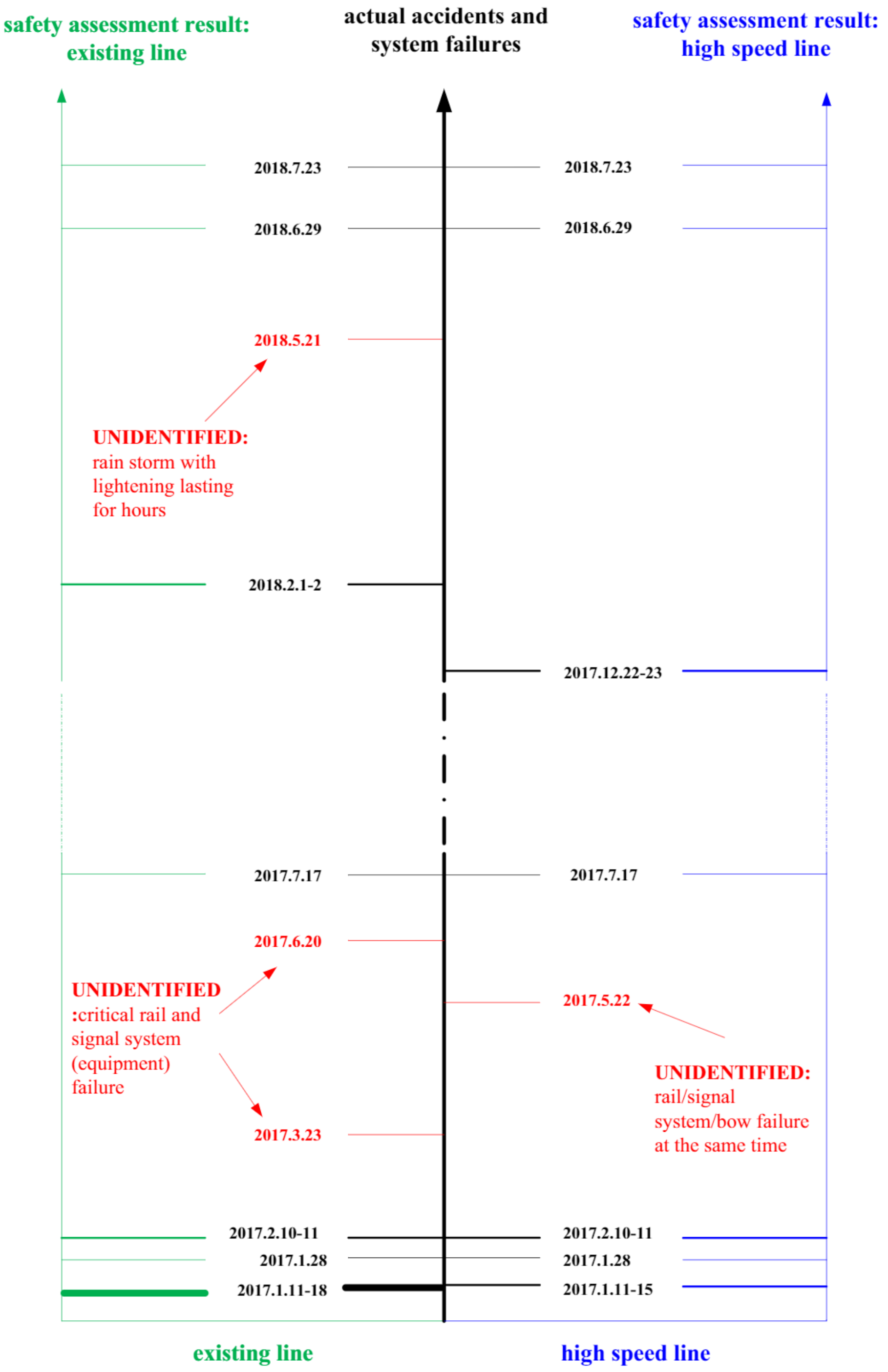
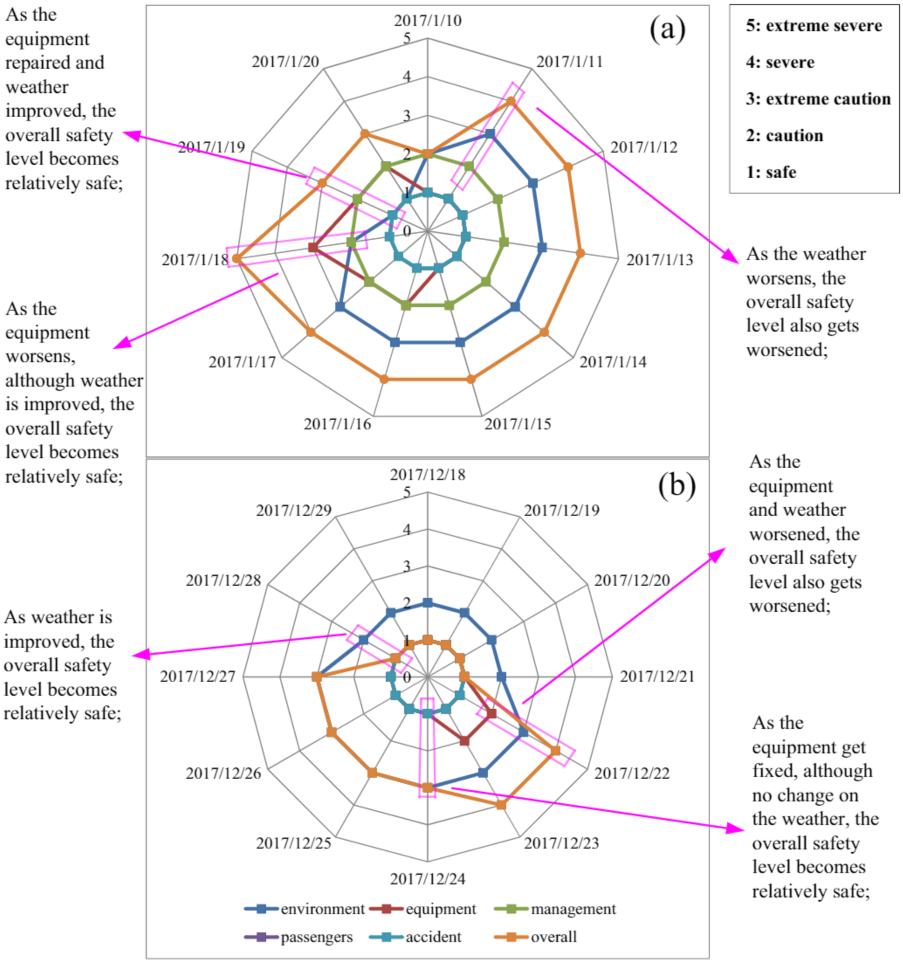


Fig. 4. Safety assessment results in comparison with accidents/failures.

To further explore the causes of such a safety assessment result, two periods with prolonged elevated safety levels are analyzed. Fig. 5(a/b) provide the overall safety levels of the five aspects for the existing line (2017/1/10-20) and the high speed line (2017/12/18-29), respectively.

Fig. 5(a) shows the overall safety level as well as five aspects for the existing line. In 2017/1/10-11, the overall safety level was worsened from *caution* to *severe* because a severe fog occurred. In 2017/1/11-17, the overall safety level and the safety level in the five aspects were unchanged as the weather was not lifted. Yet on 2017/1/18, the overall safety level was worsened from *severe* to *extreme severe* (the highest level) because of a rail accident while the fog level was unchanged. The



As the equipment repaired and weather improved, the overall safety level becomes relatively safe;

As the weather worsens, the overall safety level also gets worsened;

As the equipment worsens, although weather is improved, the overall safety level becomes relatively safe;

As the equipment and weather worsened, the overall safety level also gets worsened;

As weather is improved, the overall safety level becomes relatively safe;

As the equipment get fixed, although no change on the weather, the overall safety level becomes relatively safe;

Fig. 5. The overall safety level and that of five aspects for (a) the existing line from 2017/1/10 to 2017/1/20 and (b) the high speed line from 2017/12/18 to 2017/12/29.

overall safety levels returned to *extreme caution* only when the equipment failure received maintenance and the fog cleared off on 2017/11/19 and became *safe* when the equipment failure was completely fixed.

Comparatively, Fig. 5(b) studies the high speed line. In 2017/12/12, both an equipment failure and a severe fog occurred, and the overall safety level got worsened from *safe* to *severe*. As the equipment failure got fixed on 2017/12/24, the overall safety level returned to *extreme caution* although there were no changes in weather conditions. As weather conditions got improved on 2017/12/28, the overall safety level returned *safe*.

From Fig. 5(a/b), the following additional observations can be made.

(1) Both examples show that the safety levels worsened in winter, which is partly because the fog/frost can last for days, whereas rain/wind normally lasts for only one or two days. In this sense, the assessment has painted a **dynamic** picture of how the safety level changes, which can help to identify how to improve the safety levels.
(2) The **environment** and **equipment** play relatively more important roles in determining the overall safety levels. The environment is sometimes a constant factor that affects the overall safety level (up to *severe*), whereas the equipment is a determining factor that sets the safety level to *extreme severe*.
(3) Passengers and accident aspects do not play a direct role in affecting the safety levels, which does not mean that they are not important but only that they are not determinant. In this case study, overboarded passengers (overloaded freight) and severe accidents did not occur often, which means that there is little data for these events. In addition, good management has already reduced the possibility of such accidents to the minimum.

As explored by the case study results, it is found that the high speed line is safer than the existing line for the following reasons.

(1) The high speed line is less affected by environmental factors. For example, the high speed line can endure more severe environmental conditions (e.g., heavy rain, strong wind, and severe frost, etc.) than the existing line.

(2) As the high speed line is relatively new and has received more attention, its overall management level is better than the existing line, which results in well maintained equipment (which has already been in relatively better condition than the existing line) and fewer overboarded passengers (whereas the existing line has to additionally transport freight), among others.

This case study shows that the following factors play a critical role in safety assessment.

(1) The environmental and equipment aspects tend to be more influential than other aspects. The environmental aspect has a lasting impact in winter, whereas the equipment factor plays a more determinant role in elevating the safety level. Furthermore, disastrous environmental conditions, such as earthquakes, do not have as much influence as expected, mainly because the trains are automatically stopped in response to disastrous environmental conditions such as earthquakes.
(2) Good management levels can improve the ability of equipment maintenance, which can indirectly help resolve the worsened conditions. Moreover, good cross-sector communication can also be helpful in improving the safety level by avoiding casualties or severe financial losses.
(3) The passenger and accident aspects tend to have a less severe effect, probably because they did not occur so often and people have already made countermeasures for possible conditions.

5.7. Comparison with railway accident statistics from Japan and Canada and further discussion

We also analyzed the railway accident statistics from Japan (railway statistics collected from the Japan Transportation Safety Board, http://www.mlit.go.jp/jtsb/statistics_rail.html) and Canada (railway statistics collected from the Transportation Safety Board of Canada, http://www.tsb.gc.ca/eng/stats/rail/). The following conclusions can be drawn:

(1) Derailment/collision caused by improper equipment maintenance or failure and train accidents involving vehicle/pedestrian caused by enclosure breach are among the most frequent causes for railway accidents.
In Japan from January 2001 to July 2019, derailment and level crossing accidents make up 193/56 out of a total of 287 accidents. Especially in only 7 months from January to July 2019, 13 accidents (of which 6 were in June 2019) have occurred which are more than that in 2018 (12 accidents).
With main-track collisions and derailment being the leading causes of accidents in Canada (31% for main-track collision and 37% for derailment), over 30% of assigned factors are equipment-related from 2007 to 2017. However, in 2018, 1172 accidents and 57 rail-related fatalities have been reported, of which 34 deaths are trespassers. Nevertheless, there has been no declination in crossing-accident fatalities in comparison with both 2017 and 5-year average.
(2) Poor environment conditions, over-boarded passengers, and dangerous goods could further aggravate the severity of an accident.

In Japan, its high speed train Shinkansen has resulted in multiple train accidents with passenger/pedestrian casualties, and the most recent accident was on June 14, 2018, with one passenger dead. The only good news is that there had been none heavy leakage of dangerous objects in Japan since 2001.

However, accidents involving dangerous goods are a serious threat in Canada. In 2017, dangerous goods were involved in 10% of non-main-track derailment accidents and one resulted in severe petroleum crude oil release. In 2018, there were 125 dangerous-goods-involved accidents and 6 resulted in quite detriment situations.

The above conclusions are consistent with that derived from the case study results: equipment is a decisive factor for railway transportation safety while the passenger/freight factor is relatively indirect but could aggravate the conditions if improperly handled.

Based on the above analysis, the following measures can be adopted to improve railway transportation safety levels.

(1) For the environment, special attention should be paid to severe and lasting weather conditions, especially for abnormally heavy rain and extremely strong wind in summer and thick fog conditions that last for days in winter.
(2) For equipment, attention should be paid to the rails, signals, and bows, which cause most safety concerns. Most of the equipment problems are caused by improper maintenance plus poor communication under the influence of bad weather.
(3) For management, ensuring the enclosure is of the greatest importance. Moreover, maintenance and communication are more influential than the other two factors. They are directly affected by the staff quality, indicating that these two factors can be avoided by improving staff quality. In a word, workers should be more diligent and managers should be more responsible.
(4) Over-boarded passengers and over-loaded freight occur mostly in seasonal festivals. However, if an accident involves fatalities, then it could severely upgrade the accident levels. Thus, attention should also be paid to these aspects.
(5) Accidents are directly connected with the management and equipment aspects. Therefore, their influence could be significantly reduced if the staff is properly managed and the equipment is kept in good conditions.

6. Conclusion

A novel hybrid BRB modeling and inference approach is proposed for the first time for regional railway safety assessment. With the new hybrid BRB approach, varied types of aspects/factors can be modeled as attributes. Furthermore, more complicated conditions among the influential aspects/factors under conjunctive, disjunctive or hybrid assumptions can be analyzed and correlated with the safety assessment results in one hybrid BRB. Last but not least, building on conventional BRB, hybrid BRB is still open to experts and decision makers as it is still essentially a white-box approach.

An empirical Cheng-Yu regional railway safety assessment is studied using the proposed hybrid BRB. The case study results show that the high speed line can significantly improve the safety levels in comparison with the existing line. Further exploration shows that the environment and equipment play a more important role than the other factors in determining the safety levels. Moreover, it is found that harsh environment incidents, such as earthquakes and landslides, do not cause as severe consequences as expected. The comparison with railway accident statistics from historic records as well as that from Japan and Canada is also conducted, which shows a high consistency with the case study results by the hybrid BRB approach. Moreover, the suggestions on how to improve railway transportation safety are proposed for each aspect.

There are also limitations of the proposed approach. If conjunctive rules make most of the hybrid BRB, the hybrid BRB still has to face the combinatorial explosion problem that needs to be addressed. Moreover, the assessment structure of hybrid BRB is more complicated than conjunctive/disjunctive BRB, which may be a challenge for practical problem modeling.

For future studies, the hybrid BRB approach could be further improved with special consideration of very severe harsh environmental conditions. Moreover, with the accumulation of more data, optimization, training and learning approaches can also be used to improve the modeling accuracy by the initial hybrid model. If the proposed approach is used for other transportation means or in other regions, the model should be revised accordingly.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ins.2019.12.035.

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