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Research Article

Research on Relationships among Different Distress Types of Asphalt Pavements with Semi-Rigid Bases in China Using Association Rule Mining: A Statistical Point of View

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Distress types are significant for asphalt pavement maintenance decision, and relationships among them can greatly influence the decision outcomes. In this study, to analyze the relationships among different distress types from a statistical point of view, 282 asphalt pavements with semirigid base structures in 23 regions of China were surveyed to identify 12 distress types, which were subsequently investigated by association rule mining. Results show that the distress types can be categorized into independent distress types (IDDTs), dependent distress types (DDTs), and rutting secondary distress types (RSDTs) based on the relationships. The relationships among IDDTs are the strongest, and those between IDDTs and DDTs, between rutting and RSDTs, and among depression, pumping, and raveling are also strong, while the others are weak. The weak relationships should be ignored, while the strong ones should be considered to reduce cost and guarantee accuracy of maintenance decision. The IDDTs are the most important distress types, so preventing them from occurring or maintaining them immediately can greatly preserve good performance of asphalt pavements. To help analyze the relationships, a distress-type system was established and verified. In conclusion, this work provides new insights to understand distress types.

1. Introduction

Asphalt pavements play an important role in transportation, and those with good conditions can provide drivers with a safe and comfortable ride. However, asphalt pavements continuously suffer from combined effects of heavy and repeated traffic loadings and the natural environment during service lives [1]. This will bring about different distress types, such as map cracking caused by repeated traffic loadings, moisture damage, transverse cracking at low temperatures, and rutting at high temperatures [2–5]. The distresses can significantly reduce performance and shorten service lives of asphalt pavements [6]. For example, cracks not only contribute to a rough and noisy ride but also allow water to penetrate pavement structures, which accelerates the deterioration of asphalt pavements [1, 7]. Hence, maintaining deteriorated asphalt pavements is an urgent problem for road agencies.

To keep asphalt pavements at a high service level, road agencies should immediately make maintenance decision to select some maintenance activities, which consist of maintenance needs and measures. The most common method for making maintenance decisions is the pavement management system (PMS), a tool that comprises the network and project level, first introduced in 1960s [8, 9]. The network level focuses on maintenance needs for road networks, while the project level aims at maintenance measures for an individual project [9]. The PMS determines maintenance activities by considering management factors (such as maintenance budgets and costs) and engineering factors (such as pavement performance detection and evaluation) [10, 11]. Specially, the pavement performance is evaluated by some indices. For instance, the first pavement index calculated by subtracting deduct values of distress types, namely, the pavement condition index (PCI), introduced by the U.S. Army Corps of Engineers [12].

The PMS determines maintenance activities in the network- and project-level steps sequentially. For the two steps, the work flows are similar, but the latter is more detailed and focused [8]. In the network-level step, road agencies detect pavement condition and evaluate pavement performance mainly using PCI and the riding quality index (RQI). According to the evaluation results, they provide some alternative maintenance strategies, whose pavement performance and cost are subsequently predicted. Afterward, by considering the maintenance budgets, environmental factors, and short- and long-term needs, they allocate limited maintenance resources to road network reasonably and identify the projects need to be funded first [8, 13]. After network-level models have determined pavement sections to be financed, road agencies detect these sections in the project level, more accurate and detailed than the network level [14]. Subsequently, they evaluate pavement performance comprehensively by many indices, such as the pavement structure strength index (PSSI) in addition to PCI and RQI. Based on the evaluation data, some alternative maintenance measures are suggested, then the pavement performance for each alternative is predicted, and the corresponding cost is estimated. Through comparing the cost and effect of every alternative, the most cost-effective maintenance measure is determined for the pavement sections. Through the above process, the PMS performs well at the network level for allocating maintenance funds but inadequately for particular pavement sections at the project level [15, 16]. It is because asphalt pavements with different distress types maybe possess the same value of the pavement performance indices, indicating the same maintenance measure may be selected for the asphalt pavements. However, the same one measure generally cannot produce good effects for different distress types. For example, two asphalt pavements, namely, one with transverse cracking and the other with pothole, can own the same value of PSSI. As a result, slurry seal may be selected for the two asphalt pavements, but it is not specific enough for the above two distress types.

To maintain asphalt pavements accurately and effectively, road agencies should consider not only pavement performance but also particular distress types. Many scholars have explored diverse distress types, especially different cracking, for pavement maintenance. Due to the complexity of cracking, Ouma et al. [1] analyzed the formation and relationships of multiple cracks, which were characterized by longitudinal, transverse, diagonal, block, and alligator, through the wavelet morphology. It shows that the diverse cracks possess some connections and the relationships are important for pavement maintenance, but the detailed relationships are not discussed. The Indiana department of transportation (DOT) found numerous states in the USA cannot manage reflective cracking effectively due to the lack of systematic procedures for selecting appropriate maintenance measures. Hence, they studied the current state of reflective cracking by a survey of all states DOTs and developed a decision-making process to enhance maintenance measures selection [7]. In addition, to investigate thermal cracking of asphalt pavements, based on the data from 46 long-term pavement performance (LTPP) sections, Dong et al. [17] selected six important influence factors. Then, the relationships among the six factors and between the six factors and the thermal cracking development rate were analyzed through association rule mining, and a data miner whose supports and confidences can reflect the strength of relationships. Although this research only focuses on thermal cracking, it shows that the association rules are very suitable for investigating probabilities of mutual induction between different items, namely, relationships between different items. Apart from cracking, potholes and the corresponding maintenance methods were explored through a questionnaire survey of six provincial transportation agencies in Canada by Biswas et al. [18]. Meanwhile, this study also briefly discussed the relationships among potholes, map cracking, longitudinal cracking, bleeding, and raveling. Furthermore, Sollazzo et al. [19] probed the relationships between roughness and the pavement structural condition with an artificial neural network model, which is built and trained based on a huge number of data from the LTPP program. This model can give many clues for road engineers to determine maintenance measures at the project level, in which the pavement structure strength is very important for selecting maintenance measures.

The above studies about diverse distress types can assist road engineers to further understand asphalt pavement conditions and select appropriate maintenance measures. However, the relationships among different distress types were not thoroughly analyzed or deeply discussed. Different distress types possess many relationships with each other, suggesting the existence of one distress type may induce other distress types to occur because of distress causes. It can be further illustrated by an example of three distress types and two distress causes, as presented in Figure 1. For this example, distress type α occurs on an asphalt pavement due to distress cause A; meanwhile, distress cause A can bring about distress type β as well as distress cause B; furthermore, distress cause B can lead to distress type γ. In summary, distress types α, β, and γ occur on the asphalt pavement together. Traditionally, distress types that exist on pavements are considered for pavement maintenance, while other possible distress types are not. For this reason, after some maintenance measures being conducted for the existent failures, other distress types may occur at once. As a result, the serviceability of asphalt pavements is still poor.

The above analysis shows that the relationships among different distress types are significant for pavement maintenance. In addition, the association rule mining, a data miner that was first introduced by Agrawal et al. [20], is a promising tool to analyze relationships between different items [17, 20, 21]. Hence, this study mainly aims to investigate the relationships among different distress types using association rule mining to make pavement maintenance accurate and effective.

2. Objective and Scope

The main purpose of this study is to analyze the relationships among different distress types. Considering the complexity of distress causes and the limited space, this study only

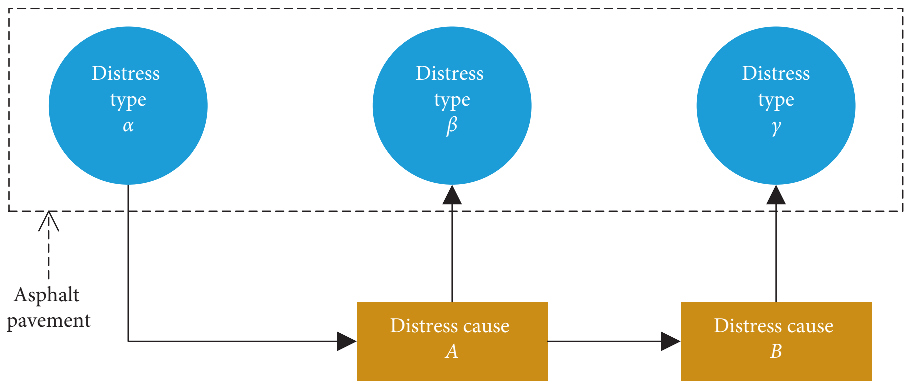

FIGURE 1: Relationships among different distress types.

focuses on the relationships from a statistical point of view. Detailed objectives of this study are as follows:

(1) A total of 282 asphalt pavements with semirigid base structures in 23 regions of China are surveyed, and 12 major distress types are identified

(2) Association rules among the 12 distress types are mined to analyze the relationships

(3) To help analyze the relationships, a distress-type system of asphalt pavements is established and then verified by the occurrence probabilities of the distress types

3. Distress Types Survey

To investigate distress types, a total of 282 asphalt pavements in China that were not maintained were inspected in this study. All the asphalt pavements were freeways with semirigid base structures, the major pavement structures in China [4]. In addition, the surveyed asphalt pavements are located in the 23 regions of China, as shown in Figure 2. This figure displays that the inspected asphalt pavements cover most of China, so they are representative.

Meanwhile, the surveyed 23 regions belong to the six climate zones in China that possess nine climate zones in total. The surveyed climate zones are 1-2, 1-3, 1-4, 2-2, 2-3, and 2-4, while those not inspected are 1-1, 2-1, and 3-2 [22]. For the climate zones, the first number is the high-temperature index and the second is the low-temperature index. Moreover, the smaller the first number, the higher the average maximum temperature of the hottest month, and the smaller the second number the lower the extreme minimum temperature. For the inspected six climate zones, 1-2 includes Beijing City, Hebei Province, Shanxi Province, and Tianjin City; 1-3 contains Anhui Province, Chongqing City, Sichuan Province, Henan Province, Hubei Province, Shandong Province, Hunan Province, Shanghai City, and Jiangsu Province; 1-4 involves Jiangxi Province, Fujian Province, Guangxi Province, Zhejiang Province, and Guangdong Province; 2-2 covers Gansu Province and Liaoning Province; the 2-3 covers Shaanxi Province; and the 2-4 includes Guizhou Province and Yunnan Province. The other three climate zones not surveyed, 1-1, 2-1, and 3-2, are situated in Tibet and Sinkiang Autonomous Regions, which possess few freeways. Given this, the surveyed asphalt pavements are also representative from a climate perspective.

FIGURE 2: Locations of surveyed 23 regions in China.

In addition, the details of the surveyed asphalt pavements, including climate zones, regions, and numbers, are summarized in Table 1 for easy access.

Furthermore, the service lives of all surveyed asphalt pavements ranged from 6 to 10 years because asphalt pavements are easily damaged at this stage. This means the difference in the service lives is small. Hence, the influence of the service lives on different distress types can be ignored when analyzing the relationships among them. Furthermore, the design service life of freeways in China is 15 years following the Chinese standard JTG D50-2017 [23], indicating all investigated distresses occurred within the design service life.

To collect pavement distress data, two main approaches are usually used by road agencies: manual and automated distress data collections [24]. The automated approach is costly because not only advanced equipment is required, but also subsequent photographs need to be processed. Meanwhile, the equipment is so complicated that road engineers should be trained in advance [25]. In

Table 1: Details of surveyed asphalt pavements.

Climate zone	Region	Number
1-2	Beijing City	10
	Hebei Province	6
	Shanxi Province	8
	Tianjin City	6
1-3	Anhui Province	6
	Chongqing City	6
	Henan Province	12
	Hubei Province	12
	Hunan Province	14
	Jiangsu Province	20
	Shandong Province	12
	Shanghai City	16
	Sichuan Province	6
1-4	Fujian Province	10
	Guangdong Province	34
	Guangxi Province	20
	Jiangxi Province	8
	Zhejiang Province	30
2-2	Gansu Province	8
	Liaoning Province	20
2-3	Shaanxi Province	8
2-4	Guizhou Province	6
	Yunnan Province	5

addition, some certain early age distresses could not be detected by the automated approach [14]. Hence, this method cannot be fulfilled by many road agencies. In contrast, the manual approach is cost-effective because it just needs road engineers to inspect failure areas and collect distress data [13]. This task is very familiar for the road engineers in China because they have been working on it for many years according to the Chinese standard JTG H20-2007 [26]. This standard provides detailed descriptions and clear regulations for each distress types, so that the road engineers can evaluate distress condition accurately. Given the above analysis, the manual inspection method was applied to collect distress data and identify distress types in this study.

This study aims at the relationships among different distress types, so the kinds of distresses are the most significant, while the severity levels of distresses are relatively less important. As a result, the severity levels were disregarded here. For example, rutting includes both serious rutting and slight rutting. In terms of this principle, through the manual inspection, this study identified 12 major distress types of asphalt pavements. These distress types are transverse cracking, rutting, map cracking, pothole, longitudinal cracking, raveling, depression, pumping, bleeding, bump, poor skid resistance, and roughness. The acronyms of these distress types are listed in Table 2 for convenience.

4. Preliminary Analysis of Relationships

4.1. Preliminary Classification of Distress Types. To facilitate the analysis of relationships among different distress types, the distress types should be classified at first. Before

Table 2: Acronyms of distress types.

Distress type	Acronym
Transverse cracking	TC
Rutting	RU
Map cracking	MC
Pothole	PO
Longitudinal cracking	LC
Raveling	RA
Depression	DE
Pumping	PU
Bleeding	BL
Bump	BU
Poor skid resistance	PSR
Roughness	RO
Independent distress type	IDDT
Dependent distress type	DDT
Combinations among DDTs	C-DDTs
Rutting secondary distress type	RSDT

classification, the proportions of asphalt pavements with different distress-type numbers were investigated, and the results are presented in Figure 3. The method for calculating the proportions is as follows:

(1) Inspect distress types that existed on each asphalt pavement.

(2) According to the inspection results, count the distress-type number i on each asphalt pavement, where $1 \leq i \leq 12$, since distress types that exist on a pavement are at least one and up to 12.

(3) Count the quantity of pavements with the same distress-type number. The quantity of pavements with distress-type number i is q_i. For instance, q_2 denotes the quantity of pavements with two distress types.

(4) Add the above quantities q_i and obtain the quantity $q_{\text{all}} = \sum_{i=1}^{12} q_i$ of all asphalt pavements, which is 282 in this study.

(5) The proportion of asphalt pavements with distress-type number i in all pavements is given as $\text{proportion}_i = q_i/q_{\text{all}} = q_i/282$.

From Figure 3, 70.21% of asphalt pavements possess two and more distress types, indicating combinations of multiple distress types deserve much attention from road agencies. In addition, although 70.21% of asphalt pavements own multiple distress types, 29.79% of asphalt pavements possess only one distress type. For these pavements, only four distress types, namely, rutting, transverse cracking, map cracking, and pothole, can occur on them independently, as displayed in Figure 3. Hence, these four distress types are called the independent distress types, i.e., IDDTs. Conversely, the other eight distress types cannot occur independently, and they must occur with other distress types, so they are called the dependent distress types, i.e., DDTs. The DDTs include LC, RA, DE, PU, BL, BU, PSR, and RO.

4.2. Preliminary Distress-Type System of Asphalt Pavements. As analyzed previously, a DDT has to occur with other distress types, but it is not clear whether a DDT must occur

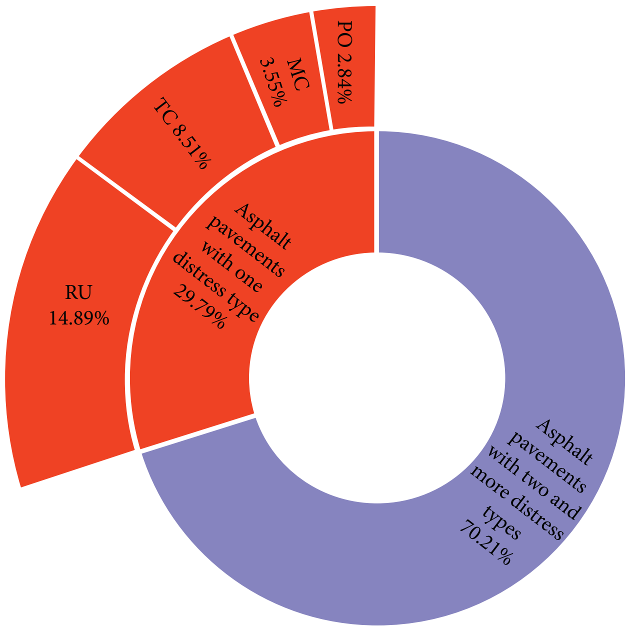

FIGURE 3: Proportions of asphalt pavements with different distress-type numbers.

with other DDTs or/and some IDDTs. This will be discussed in this section.

From Figure 3, approximately 70% of asphalt pavements possess combinations of multiple distress types, so the IDDTs and the DDTs were combined here. To simplify analysis, the combinations among the DDTs are treated as a whole and defined as the C-DDTs. The C-DDTs include some DDTs, maybe only one DDT or maybe all DDTs. In terms of the above definition, the proportions of asphalt pavements with different combinations of the IDDTs and the C-DDTs were calculated, and the results are presented in Figure 4. In addition, the calculation method is as follows:

(1) Inspect distress types emerging on each asphalt pavement.
(2) Based on the inspection results, record the distress types occurring on each asphalt pavement, one or more DDTs are marked as the C-DDTs. For example, regarding two asphalt pavements: one with rutting and bleeding and the other with rutting, bleeding, and roughness, both of the pavements are marked as RU + C-DDTs.
(3) Count the quantity Q of asphalt pavements with the same combinations of distress types. For instance, the quantity of pavements with RU + C-DDTs is $Q_{\mathrm{RU+C-DDTs}}$.
(4) Add the above quantities Q and obtain the quantity Q_{all} of all asphalt pavements, which is 282 in this study.
(5) The proportion of asphalt pavements with different distress types is given as proportion $= Q/Q_{\mathrm{all}} = Q/282$, e.g., $\mathrm{proportion}_{\mathrm{RU+C-DDTs}} = Q_{\mathrm{RU+C-DDTs}}/282$.

From Figure 4, the asphalt pavements with C-DDTs are zero, indicating the combinations among the DDTs cannot occur independently, so a DDT must emerge with some IDDTs. In other words, if one DDT exists on an asphalt pavement, then some IDDTs must exist on the pavement, and otherwise they will occur. When some IDDTs have occurred on asphalt pavements, the C-DDTs own high percentage. As plotted in Figure 4, the asphalt pavements with the C-DDTs and all IDDTs (or except map cracking) are bigger than 10%, and the asphalt pavements with the C-DDTs and transverse cracking/rutting/transverse cracking and rutting are just below 10%.

As analyzed previously, the DDTs have to emerge with some IDDTs, so the DDTs are wholly attached to the IDDTs. For this reason, a preliminary distress-type system of asphalt pavements was established, as shown in Figure 5. In Figure 5, a DDT is attached to the entirety of the IDDTs, and it has to occur with some IDDTs. For instance, longitudinal cracking can occur when transverse cracking exists on an asphalt pavement. If longitudinal cracking exists on an asphalt pavement that possesses no IDDTs, then some IDDTs (maybe transverse cracking) will occur. Furthermore, the relationships which exist between the IDDTs and the DDTs, individuals of the IDDTs, and individuals of the DDTs are not clear. The details on these relationships will be discussed by association rule mining in the later sections.

5. Mining Association Rules

To further investigate relationships among all the distress types, the above statistics were analyzed using the association rule mining because it can identify relevance and dependency of different items [21].

5.1. Fundamental Concepts of Association Rule Mining.

In association rule mining, three fundamental concepts are important, including an item, an item set, and a transaction [27].

(1) An item is the minimum unit in a database. In this work, an item is a distress type, such as transverse cracking, rutting, and pothole. Since a total of 12 major distress types were identified, 12 items were recognized.
(2) An item set is a collection of different items. In this study, it is a combination of different distress types, such as {transverse Cracking, rutting}. The 12 distress types comprise the total item set {TIS = TC, RU, MC, PO, LC, RA, DE, PU, BL, BU, PSR, RO}.
(3) The essence of a transaction is an item set. In this work, a transaction is the distress types occurring on an asphalt pavement, meaning that one pavement corresponds to one transaction. For instance, if transverse cracking and rutting occur on a pavement together, then {transverse cracking, rutting} is the corresponding transaction for this pavement. Since 282 asphalt pavements were surveyed, 282 transactions were identified, making up the transaction database of distress types.

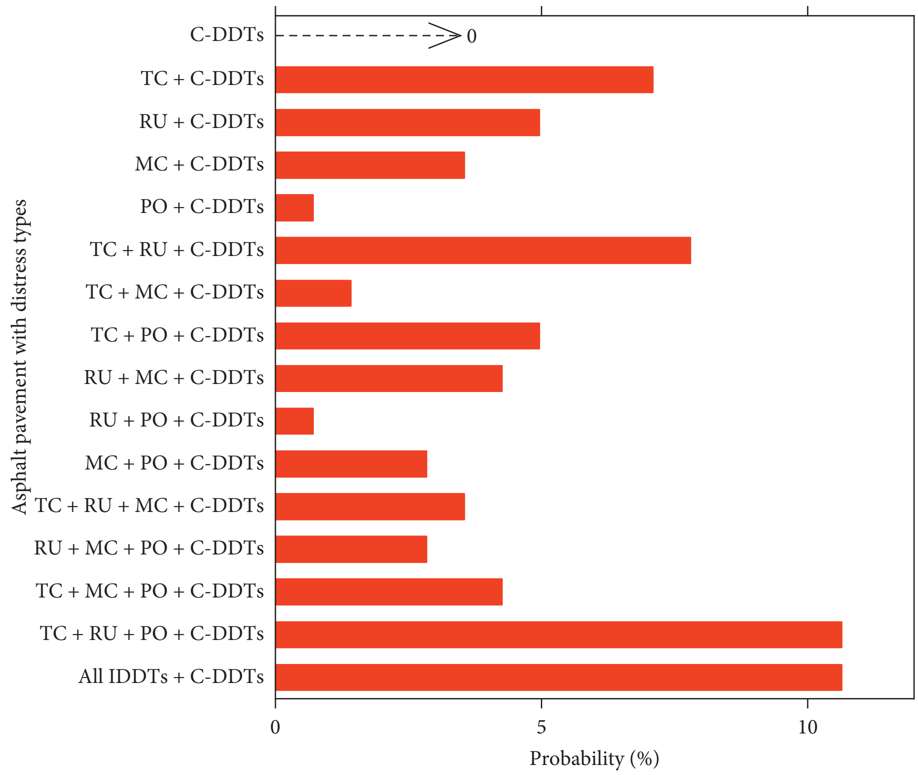

Figure 4: Proportions of asphalt pavements with different combinations of IDDTs and DDTs.

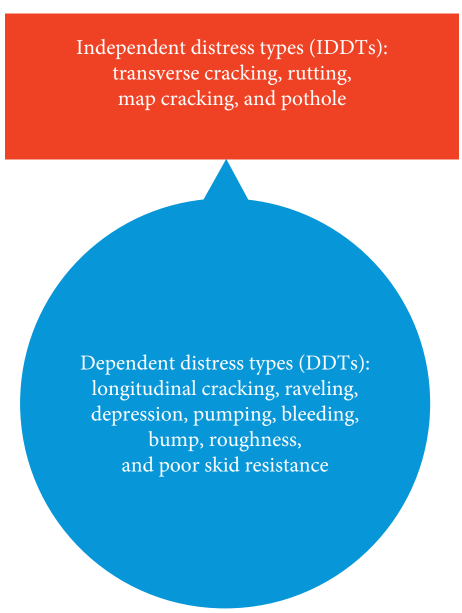

Figure 5: Preliminary distress-type system of asphalt pavements.

By an association rule, it means an implication of the form: $X \longrightarrow Y$, where X and Y are item sets, the proper subsets of the TIS, and $X \cap Y = \varnothing$.

5.2. Evaluating Association Rules. To evaluate association rules, two indicators are necessary: the support and the confidence of association rules.

5.2.1. Support of Association Rules. The support of an association rule is a significant measure that indicates the frequency of occurring patterns and reflects the importance of rules. The support of $X \longrightarrow Y$ is calculated by the following equation:

$$\text{support}\,(X \longrightarrow Y) = \frac{N\,(X \cup Y)}{N\,(\text{ALL})} = P\,(X \cup Y), \qquad (1)$$

where $N\,(X \cup Y)$ is the number of transactions including both X and Y and $N\,(\text{ALL})$ is the number of all transactions in the distress-type database, and it is 282 here. Furthermore, the supports of $X \longrightarrow Y$ and $Y \longrightarrow X$ are equal, and they are the probability of X and Y occurring together, which means the greater the supports, the stronger the relationships among different items.

5.2.2. Confidence of Association Rules. The confidence of $X \longrightarrow Y$ indicates the reliability of the association rule, and it is expressed by the following equation:

$$\text{confidence}\,(X \longrightarrow Y) = \frac{N\,(X \cup Y)}{N\,(X)} = P\,(Y \mid X), \qquad (2)$$

where $N\,(X)$ is the number of transactions containing X. The confidence represents the probability of Y occurring when X exists. The confidence also affects relationships among different items, but it is based on the support.

5.2.3. Example for Support and Confidence. To further illustrate the support and the confidence of association rules, a transaction database is provided in Table 3. As presented in Table 3, three transactions are No. 1, No. 2, and No. 3. Meanwhile, one transaction corresponds to one asphalt pavement with different distress types. The total item set of the transaction database is TIS = {rutting, transverse cracking, pumping}. Many association rules can be generated from this database, and two typical ones of them are selected to illustrate the support and confidence of association rules.

Regarding the association rule *transverse cracking* ⟶ *rutting*, the transaction including both transverse cracking and rutting is only one, i.e., No. 3. Owing to three transactions altogether in the database, the support is calculated by $1/3 = 33.33\%$; the transactions containing transverse cracking are two, namely, No. 1 and No. 3, so the confidence is given by $1/2 = 50\%$. The confidence means rutting owns a 50% occurrence probability when transverse cracking exists on asphalt pavements, and the probability of this situation is 33.33% according to the support. Meanwhile, the support also indicates the probability of transverse cracking, and rutting occurring together is 33.33%.

Concerning the association rule pumping ⟶ transverse cracking, the transaction incorporating pumping and transverse cracking together is only one, i.e., No. 3. Because of this, database possesses a total of three transactions, the support is $1/3 = 33.33\%$; as the transaction, including pumping is also only one, still No. 3, the confidence is calculated by $1/1 = 100\%$. The confidence suggests when pumping emerge on asphalt pavements, transverse cracking must exist on the pavements; if transverse cracking does not exist, it must occur in the future. Meanwhile, the probability of this situation is 33.33% in terms of the support. In addition, the support also means transverse cracking and pumping possess a 33.33% probability of emerging together.

5.2.4. Thresholds of Support and Confidence. The thresholds of support and confidence, namely, the minimum values, should be determined before mining association rules. The minimum support (support threshold), based on project requirements, must be determined to ensure the importance of association rules. Generally, an association rule is important when the support reaches 5% [17, 20]. As mentioned in Section 5.2.1, the greater the supports, the stronger the relationships. Meanwhile, the minimum confidence (confidence threshold) is needed to assure the reliability of association rules since the confidence also has an impact on relationships. Association rule mining is generating strong rules meeting the support and confidence thresholds concurrently.

It is noteworthy that this study aims at investigating relationships among different distress types, meaning all association rules among the 12 distress types are required. For this reason, both the support and confidence thresholds were taken as zero to mine strong association rules.

5.3. Miners of Association Rules. In many association rules miners, the most widely used is the a priori algorithm, first introduced by Agrawal et al. [28]. The a priori algorithm

Table 3: Transaction database of distress types: an example.

Transaction number	Transaction
No. 1	Transverse cracking
No. 2	Rutting
No. 3	Transverse cracking, rutting, pumping

performs in two steps. First, it scans the database and discovers all item sets with an occurrence not less than the support threshold. Second, according to the discovered item sets, a set of strong association rules are mined. The details on the a priori algorithm can be found in Reference [27, 28]. Additionally, the a priori algorithm was executed by Waikato Environment for Knowledge Analysis (WEKA), an open-source tool, universally applied in business, education, and research [29].

6. Analysis of Relationships Based on Association Rules

6.1. Relationships among IDDTs. Regarding the four IDDTs, $C_4^1 \cdot C_3^1 = 12$ association rules exist among the IDDTs. The supports are presented in Figure 6(a), where TC ↔ RU represents the association rules TC ⟶ RU and RU ⟶ TC, so do others. Meanwhile, the confidences are depicted in Figure 6(b).

From Figure 6(a), all supports are bigger than 20% and the average value is 25.06%, meaning the average probability of two IDDTs occurring together is around 25%, indicating powerful relationships among the IDDTs. Because of the powerful relationships among the IDDTs, the IDDTs could not only occur independently but also induce each other to emerge, which can be demonstrated by the confidences in Figure 6(b). This figure shows that the confidences of all association rules change little with an average of 52.47%, meaning the average probability is over 50% that one IDDT induces another to occur.

Of the 12 association rules, TC ↔ RU possess the largest support over 30%, suggesting more than 30% of asphalt pavements own both transverse cracking and rutting. Transverse cracking is widespread because most freeways in China are semirigid base structures, which can easily bring about drying shrinkage and thermal shrinkage and result in transverse cracking [30]. Meanwhile, rutting is prevalent as a consequence of the increase in traffic volume, tire pressure, and axial load [4].

Actually, transverse cracking is not a serious damage for asphalt pavements since it just decreases the pavement smoothness. However, it usually leads to other distress types that are serious for pavements, such as map cracking and potholes. Typically, transverse cracking breaks the integrity of the surface course, so that moisture can penetrate into the surface and accumulate between the lower surface course and the semirigid base course, whose voids are almost zero. When traffic loadings pass through the transverse cracking, the moisture can generate hydrodynamic pressure. The hydrodynamic pressure can also decrease the bonds between the base course and the lower surface course, so that the lower surface course has to bear large tensile stress. When

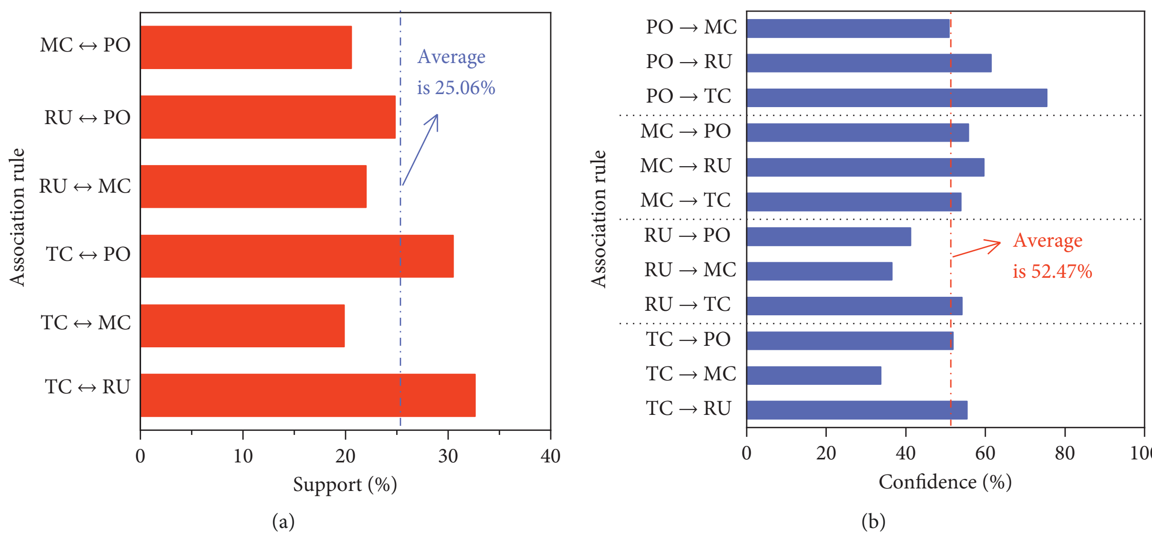

Figure 6: Association rules among IDDTs. (a) Supports in IDDTs. (b) Confidences in IDDTs.

the tensile stress is bigger than the tensile strength, fatigue damage will occur in the lower surface course and spread into the map cracking in the upper surface course with the repeated action of numerous and great traffic loadings. Given this, the support of TC ↔ MC is high, reaching approximately 20%. Meanwhile, the hydrodynamic pressure can diminish the adhesion bonds at the aggregate-mastic interface and peel asphalt films from aggregates [31], contributing to the occurrence of potholes at the transverse cracking. As a result, the support of TC ↔ PO is very large, greater than 30%. In the same way, the moisture, existing in map cracking, will also produce the hydrodynamic pressure with the effect of traffic loadings and give rise to the pothole. Hence, the support of MC ↔ PO is also big, around 20%.

In addition, moisture can usually gather in rutting areas since rutting depth is usually greater than 10 mm [4, 26]. It can bring about hydroplaning when plentiful vehicles passing through the accumulated moisture, which is not safe for road users [4]. Meanwhile, with the repeated effect of the vehicle compressive stress and the vacuum suction generated by high-speeding driving, asphalt films are stripped off aggregates. After that, the aggregates are pulled out by vehicle wheels so that pothole occurs on asphalt pavements. Hence, the support of RU ↔ PO is great, approximately 25%. Furthermore, because the strong relationships between pothole and map cracking, as analyzed earlier, the support of RU ↔ MC is also large, whose value is approximately 20%.

According to the above analysis, the powerful relationships among the IDDTs should be considered to make asphalt pavement maintenance decision accurately. Specifically, for an asphalt pavement with only one IDDT, this existent IDDT as well as other IDDTs that maybe occur should be considered. It can be further illustrated by the example of an asphalt pavement with only transverse cracking. In this example, transverse cracking and pothole should be considered for pavement maintenance because pothole owns an approximately 50% occurrence probability when transverse cracking exists, according to the confidence of TC ⟶ PO in Figure 6(b). Meanwhile, the probability of the above situation is around 30% in terms of the support of TC ↔ PO in Figure 6(a).

6.2. Relationships between IDDTs and DDTs. Because of the four IDDTs and the eight DDTs, there are $2 \times C_4^1 \cdot C_8^1 = 64$ association rules between the IDDTs and the DDTs. All association rules are provided in Figure 7, where TC ⟶ DDTs and DDTs ⟶ TC represent the association rules between transverse cracking and the eight DDTs, so do others.

According to Figure 7(d), it is noteworthy that four confidences are 100%, whose association rules are BL/BU/PSR/RO ⟶ RU. These association rules possess supports of approximately 5% so they cannot be disregarded. Hence, the relationships between the four distress types and rutting are strong. The 100% confidences mean when BL/BU/PSR/RO exists on an asphalt pavement rutting must exist; if rutting does not emerge, then it will occur on the pavement in the future. However, the reverse is not true because the confidences of association rules RU ⟶ BL/BU/PSR/RO are small than 100%, as shown in Figure 7(c). For example, the confidence of association rule RU ⟶ BL is about 10%, so bleeding just owns an about 10% occurrence probability when rutting exists.

The strong relationships between the four distress types and rutting may be because some distress causes can induce them at the same time. Traditionally, the poor construction of asphalt pavements can lead to aggregate gradation segregation, namely, some areas with concentrated coarse aggregates, and some areas with concentrated fine aggregates [32]. For the areas with concentrated fine aggregates, the fine aggregates are so many that they can push the coarse aggregate skeleton of asphalt mixtures open. This will decline the shear strength of asphalt mixtures and bring about rutting and bump [33]. Meanwhile, the overmuch fine aggregates make air voids so small that they may be full of asphalt binder. The asphalt binder will move to the pavement

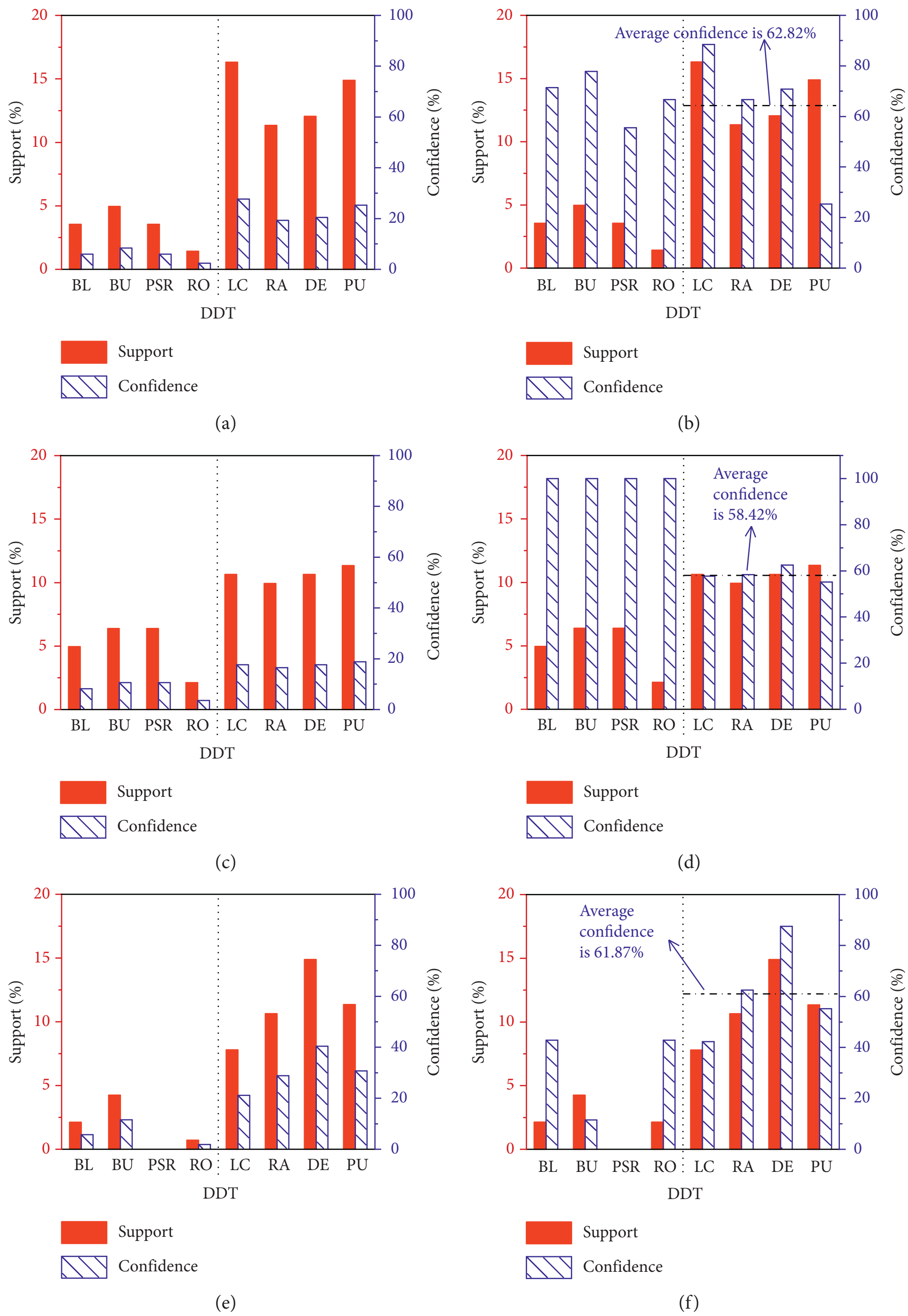

Figure 7: Continued.

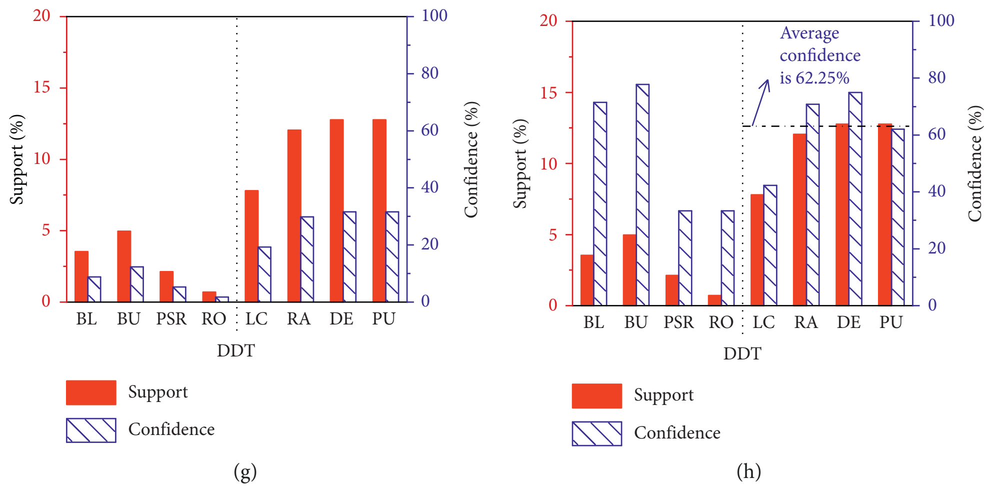

Figure 7: Association rules between IDDTs and DDTs. (a) TC ⟶ DDTs. (b) DDTs ⟶ TC. (c) RU ⟶ DDTs. (d) DDTs ⟶ RU. (e) MC ⟶ DDTs. (f) DDTs ⟶ MC. (g) PO ⟶ DDTs. (h) DDTs ⟶ PO.

upper surface with the effect of traffic loadings in hot weather, contributing to the occurrence of bleeding [34]. Concurrently, the uneven distribution of aggregates leads to the nonuniform distribution of compaction degree, which brings about variable compacted depths on asphalt pavements with compressive stress of various vehicles. Consequently, the pavements will possess roughness. In addition, rutting can emerge on asphalt pavements when the steady state of aggregate skeleton is not good [35], which may be caused by the inadequate strength of aggregates. Furthermore, the insufficient aggregate strength can also result in poor skid resistance of pavement upper surface course.

According to the above analysis, these four distress types must adhere to rutting when occurring, so they are called the rutting secondary distress types, i.e., the RSDTs. Hence, the DDTs are redefined as LC, RA, DE, and PU. So far, the 12 distress types of asphalt pavements are classified into three categories: the IDDTs, the DDTs, and the RSDTs.

From Figures 7(a), 7(c), 7(e), and 7(g), in general, the supports between the IDDTs and the DDTs, which are slightly over 10%, are much bigger than those between the IDDTs (except rutting) and the RSDTs, which are around 2.5%. It is because the RSDTs must adhere to rutting to occur, while the DDTs can emerge with one or more IDDTs. In terms of the analysis, the relationships between the IDDTs and the DDTs are stronger than those between the IDDTs (except rutting) and the RSDTs. The strong relationships can be demonstrated by the confidences in Figures 7(b), 7(d), 7(f), and 7(h). These figures suggest that the average confidences of DDTs ⟶ IDDTs are around 60%, indicating an approximately 60% probability of the IDDTs occurring when the DDTs exist on asphalt pavements.

In brief, the relationships between the IDDTs and the DDTs/RSDTs, those between the IDDTs and the DDTs, and those between rutting and the RSDTs should be considered to take maintenance decision accurately. Conversely, the weak relationships, namely, between the IDDTs (except rutting) and the RSDTs, should be neglected to reduce maintenance decision cost.

6.3. Relationships among DDTs and RSDTs. So far, the relationships among the IDDTs and those between the IDDTs and the DDTs/RSDTs have been analyzed. The remaining relationships, including those among the DDTs, among the RSDTs, and between the DDTs and the RSDTs, are discussed in this section. For these relationships, a total of $C_4^1 \cdot C_3^1 + C_4^1 \cdot C_3^1 + 2 \times C_4^1 \cdot C_4^1 = 56$ association rules exist among the DDTs and the RSDTs, and the association rules are listed in Table 4. In Table 4, DDTs ⟶ DDTs represents the association rules among the DDTs, and RSDTs ⟶ RSDTs owns the same implication. Meanwhile, DDTs ⟶ RSDTs and RSDTs ⟶ DDTs are the association rules between the DDTs and the RSDTs, and LC ⟶ DDTs is the association rules between longitudinal cracking and the other DDTs, so do others. Moreover, in Table 4, S and C denote the support and the confidence of association rules, respectively.

From the bottom-right of Table 4, all supports of RSDTs ⟶ RSDTs are far less than 5%, revealing the probability that two RSDTs occur together is very low, not to mention three or four RSDTs. In other words, the RSDTs can hardly induce each other to occur. Hence, the relationships among the RSDTs are extremely weak. Similarly, from the top-right and bottom-left of Table 4, all supports of DDTs ⟶ RSDTs and RSDTs ⟶ DDTs are below 5%, indicating the relationships between the DDTs and the RSDTs are very weak as well. Concerning an asphalt pavement with only bleeding, in terms of the support of BL ⟶ PSR, PSR should be neglected because the probability of PSR and bleeding occurring together is only 0.71%, as shown in the down-right of Table 4.

Compared with the above weak relationships, the relationships between depression, raveling, and pumping are stronger since the supports of DE ⟶ RA (RA ⟶ DE), DE ⟶ PU (PU ⟶ DE), and PU ⟶ RA (RA ⟶ PU) range from 5% to 10%, as shown in the top-left of Table 4. For convenience, the relationships among the three distress types are plotted in Figure 8. From Figure 8, the average support and confidence among these distress types are 6.82% and 38.15%, respectively. It means the average probability of

Table 4: Association rules among DDTs, among RSDTs, and between DDTs and RSDTs.

	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C
	%															
DDTs	DDTs ⟶ DDTs								RSDTs ⟶ DDTs							
	LC ⟶ DDTs		RA ⟶ DDTs		DE ⟶ DDTs		PU ⟶ DDTs		BL ⟶ DDTs		BU ⟶ DDTs		PSR ⟶ DDTs		RO ⟶ DDTs	
LC			2.84	16.67	4.26	25.00	4.26	20.69	1.42	28.57	2.13	33.33	1.42	22.22	1.42	66.67
RA	2.84	15.38			**7.80**	45.83	**5.67**	27.59	2.84	57.14	3.55	55.56	0.71	11.11	0.71	33.33
DE	4.26	23.08	**7.80**	45.83			**7.09**	34.48	2.84	57.14	3.55	55.56	0.00	0.00	0.71	33.33
PU	4.26	23.08	**5.67**	33.33	**7.09**	41.67			2.84	57.14	2.13	33.33	1.42	22.22	0.71	33.33
RSDTs	DDTs ⟶ RSDTs								RSDTs ⟶ RSDTs							
	LC ⟶ RSDTs		RA ⟶ RSDTs		DE ⟶ RSDTs		PU ⟶ RSDTs		BL ⟶ RSDTs		BU ⟶ RSDTs		PSR ⟶ RSDTs		RO ⟶ RSDTs	
BL	1.42	7.69	2.84	16.67	2.84	16.67	2.84	13.79			2.84	44.44	0.71	11.11	0.71	33.33
BU	2.13	11.54	3.55	20.83	3.55	20.83	2.13	10.34	2.84	57.14			0.71	11.11	0.71	33.33
PSR	1.42	7.69	0.71	4.17	0.00	0.00	1.42	6.90	0.71	14.29	0.71	11.11			1.42	66.67
RO	1.42	7.69	0.71	4.17	0.71	4.17	0.71	3.45	0.71	14.29	0.71	11.11	1.42	22.22		

S and C denote support and confidence of association rules, respectively.

two of them occurring together is 6.82%, and the average probability of one of them inducing another to occur is 38.12%. For example, when depression exists, pumping and raveling have probabilities of 41.67% and 45.83% occurring, respectively.

The relationships between the three distress types are strong maybe because they possess the same distress causes. As analyzed in section 6.1, when transverse or map cracking exists on asphalt pavements, the incomplete pavement structure will be invaded by moisture. The moisture will erode the aggregate-asphalt interface and peel off asphalt binder with the repetitive action of the vacuum suction generated by high-speeding driving. After asphalt binder being stripped off aggregate surface, the asphalt mixtures in the upper surface course will emerge raveling. Meanwhile, the aggregates in the lower surface course will leave the pavement structure with pumping, resulting in large holes in the lower surface course and depression in the pavement structure. Given the above analysis, the strong relationships should also be considered for maintenance.

In summary, for the relationships existing among the DDTs and RSDTs, only those between depression, pumping, and raveling should be considered for asphalt pavement accurate maintenance decision. On the contrary, other relationships, namely, between the DDTs and the RSDTs and among the RSDTs, should be ignored to reduce maintenance decision cost.

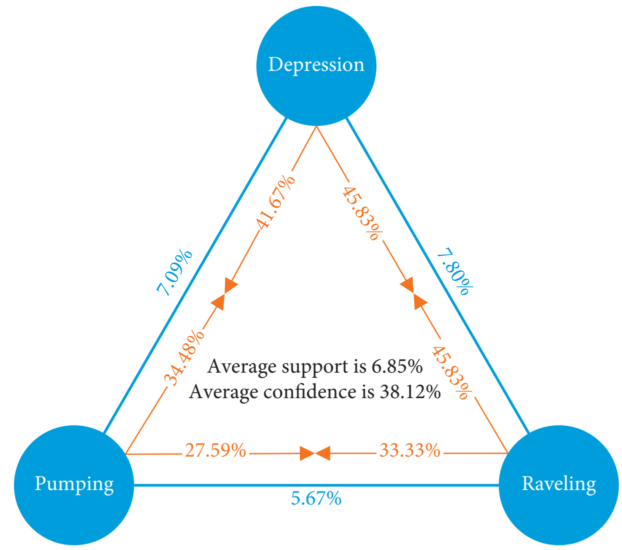

Figure 8: Relationships between depression, pumping, and raveling.

7. Distress-Type System of Asphalt Pavements

7.1. Establishment. In terms of the preliminary distress-type system in Figure 5 (section 4.2), and the relationships between rutting and the RSDTs in Figure 7(d) (section 6.2), the distress-type system of asphalt pavements was established, as depicted in Figure 9. The system can be used to help analyze relationships among different distress types.

From Figure 9, the IDDTs not only occur independently but also induce each other to emerge. Meanwhile, Figure 9 also shows that every DDT is attached to the entirety of the IDDTs, while each RSDT is attached to rutting, indicating a DDT must occur with some IDDTs, while an RSDT has to emerge with rutting. In particular, if a DDT occurs on an asphalt pavement with no IDDT, then some IDDTs will emerge on this pavement. Similarly, if an RSDT appears on an asphalt pavement without rutting, then rutting will occur. In summary, Figure 9 displays that the interrelationships among the IDDTs, between the IDDTs and the DDTs, and between rutting and the RSDTs are strong, but those between the DDTs and the RSDTs are weak. Since the IDDTs occur independently and mutually, and the other distress types have to emerge with them, they are the most important distress types for asphalt pavements.

Furthermore, Figure 9 implies that the four IDDTs correspond to four important properties of asphalt mixtures. Specifically, transverse cracking vs. low-temperature property, rutting vs. high-temperature stability, map cracking vs. fatigue property, and pothole vs. moisture susceptibility. This further confirms the significance of the IDDTs. Given the above analysis, preventing the IDDTs from occurring or maintaining them once they emerge can substantially keep asphalt pavements in good conditions.

7.2. Verification. From Figure 9, the grades of the 12 distress types are so different that it can be speculated the occurrence probabilities of the distress types are also different and the change may be very large. Hence, to verify the distress-type system in Figure 9, this study explored the occurrence probabilities of the 12 distress types. The occurrence probability of a distress types is defined as the occurrence number of this distress type divided by the total occurrence number of the 12 distress types. Concerning the occurrence number, one distress type can occur on many asphalt pavements, so the sum of these pavements is the occurrence number of this distress type. For instance, transverse cracking occurred on 166 asphalt pavements in the database of this study, so it possesses the occurrence number of 166. With this method, the occurrence numbers of all distress types were counted, and they were subsequently added up to determine the total occurrence number, whose value is 814. The processes for determining the occurrence probabilities are as follows:

(1) Inspect distress types occurred on each asphalt pavement

(2) According to the inspection results, count the occurrence number n_j (≥ 1) of every distress type, where j is the distress type and $j = 1, 2, \ldots, 12$

(3) Add up the above occurrence number n_j of the 12 distress types to obtain the total occurrence number $n_{\text{total}} = \sum_{j=1}^{12} n_j$, and the value is 814

(4) The occurrence probability of distress type j is calculated by $\text{Probabilit}_j = n_j / n_{\text{total}}$

It is noteworthy that the total occurrence number n_{total} of all distress types is different from the number of all distress

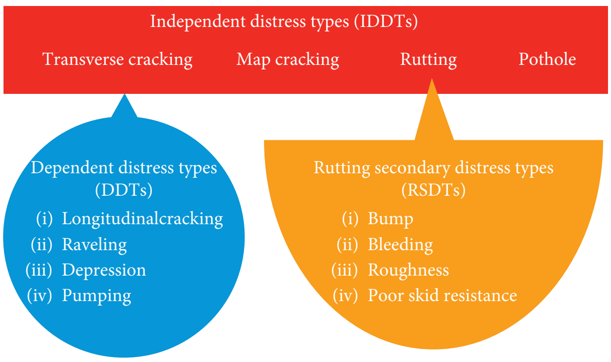

Figure 9: Distress-type system of asphalt pavements.

types. Traditionally, the former is greater than the latter because one distress type can occur many times in a survey sample. In this study, the total occurrence number n_{total} of all distress types is 814, while the number of all distress types is 12, as identified in section 3.

The above method and definitions can be further illustrated by the example in Table 3. This example shows three asphalt pavements: one with transverse cracking, one with rutting, and the other with transverse cracking, rutting, and pumping. In this database, the number of all distress types is three, while the total occurrence number n_{total} are five. Among the n_{total}, transverse cracking and rutting possess two occurrence numbers each and pumping owns one. Hence, the occurrence probabilities of both transverse cracking and rutting are 40% and that of pumping is 20%, as shown in Table 5. Table 5 presents the process for calculating the occurrence probabilities of distress types in the example.

With the above method, the occurrence probabilities of all distress types were calculated, and the results are shown in Figure 10. From Figure 10, overall, the occurrence probabilities of the distress types change largely. Specifically, the occurrence probabilities of the IDDTs are the largest, much bigger than those of the DDTs, which are far greater than those of the RSDTs. The occurrence probabilities are stepped distribution consistent with the distress type system of asphalt pavements in Figure 9. Figure 9 displays that the RSDTs have to emerge with rutting, an IDDT, so they possess the lowest occurrence probabilities. Compared with the RSDTs, the DDTs own greater occurrence probabilities because they can occur with one or more IDDTs. Meanwhile, the RSDTs and the DDTs have to occur with the IDDTs, and the IDDTs can occur independently and mutually, so the IDDTs possess the highest occurrence probabilities.

Regarding the four IDDTs, transverse cracking and rutting own the highest probabilities, and the values are both bigger than 20%, far greater than other distress types. It means transverse cracking and rutting are the most common distress types in China, so they deserve more attention than others from road agencies. This is consistent with the support of association rules TC ↔ RU, which is more than 30%, as shown in Figure 6(a), indicating over 30% of asphalt pavements possess both transverse cracking and rutting.

Table 5: Calculation process of occurrence probabilities for the example in Table 3.

Distress type	Occurrence number n_j	Total occurrence number n_{total}	Occurrence probability
Transverse cracking	2	5	2/5 = 40%
Rutting	2		2/5 = 40%
Pumping	1		1/5 = 20%

8. Conclusions

To investigate the relationships among different distress types, this study surveyed 282 asphalt pavements with semirigid bases in 23 regions of China and identified 12 major distress types. Through the above analysis, the main conclusions are as follows:

(1) The 12 distress types were categorized into the IDDTs, DDTs, and RSDTs based on statistical analysis and association rules. Specifically, the IDDTs not only occur independently but also induce each other to emerge; every DDT must occur with some IDDTs; each RSDT must emerge with rutting, an IDDT.

(2) The relationships among the IDDTs are the most powerful, followed by those between the IDDTs and the DDTs, between rutting and the RSDTs, and among depression, pumping, and raveling. However, the relationships between the IDDTs (except rutting)/DDTs and the RSDTs, and those among the RSDTs are very weak. The weak relationships should be ignored to reduce maintenance decision cost, while the strong relationships should be considered to make asphalt pavement maintenance decision accurately.

(3) The IDDTs are the most significant distress types, so avoiding them occurring or maintaining them instantly when they emerge can largely keep asphalt pavements in good conditions.

(4) A distress-type system of asphalt pavements, which can reflect the relationships between the IDDTs, DDTs, and RSDTs, was established to help analyze the relationships among different distress types. Furthermore, the system is verified by the occurrence probabilities of different distress types, which change greatly and are stepped distribution.

(5) Transverse cracking and rutting deserve more concern than other distress types from road agencies since they are the most widespread distress types in China. Precisely, they both have over 20% occurrence probabilities and more than 30% of asphalt pavements possess them together.

Because the surveyed asphalt pavements were all semirigid base structures, the relationships may be different from other pavement structures, such as cement concrete pavement structures and full-depth asphalt pavement structures. Therefore, this study has limitations

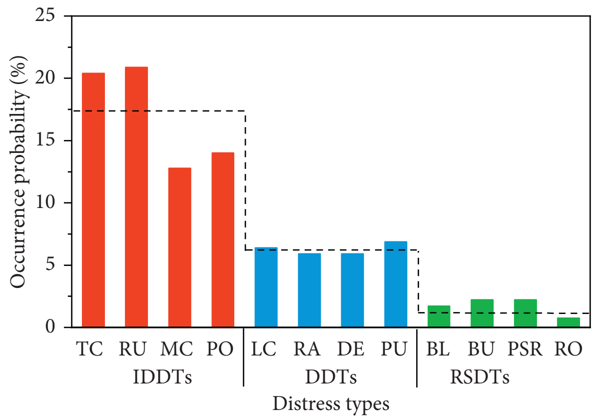

FIGURE 10: Distribution of occurrence probabilities of different distress types.

and cannot be expanded to other pavement structures. However, this study aims to provide a new perspective to investigate relationships among different distress types, so the results and conclusions can be used as references. Moreover, this study only quantitatively analyzed the relationships among different distress types from a statistical point of view. Although the reasons for these relationships are described, and we will investigate distress causes in future research to further illustrate the relationships among the distress types.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

No conflicts of interest exist in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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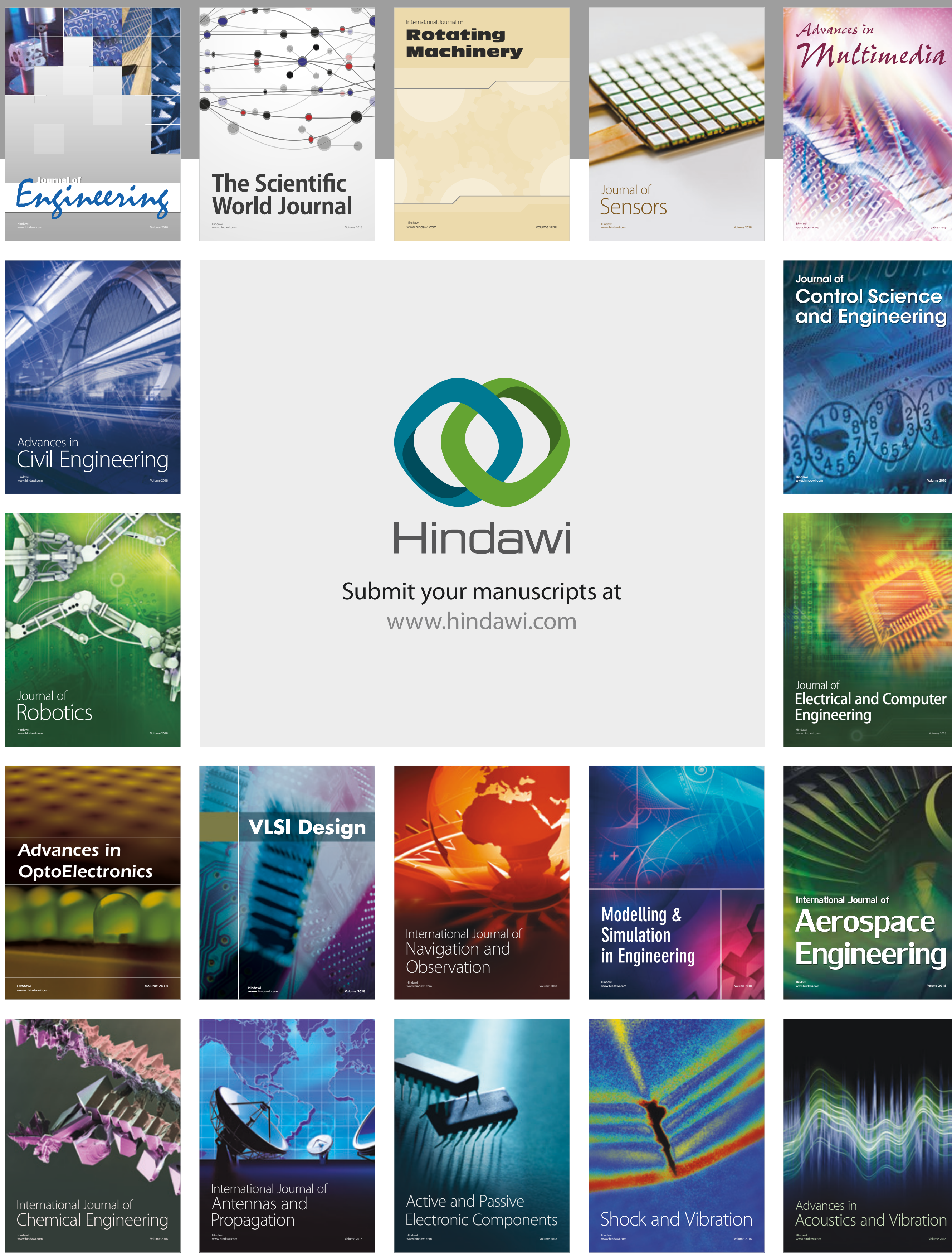
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