Determination of Critical Track Conditions and their Impact on the Performance of Concrete Crossties and Fastening Systems

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ABSTRACT

In North America, the use of concrete crossties has increased steadily over the past decade as concrete crossties have emerged as an economic alternative to timber crossties to accommodate heavy axle freight train loads. As the number of concrete crossties has grown, the importance of understanding the performance of these components has also increased. This is especially true when considering the criticality of ensuring safe operation of the track infrastructure, as there have been derailments that were linked to the health of concrete crossties. The behavior of poorly supported or degraded concrete crossties and fastening systems (and their components) is not fully understood, but it is widely accepted that these conditions may have a significant influence on the demands placed on the track components including the concrete crosstie and fastening system. In order to better understand which conditions influence the risk of accidents on concrete crosstie track, researchers at the University of Illinois at Urbana-Champaign (UIUC) are gathering pertinent information to guide laboratory experimentation aimed at investigating this questions. Sources include the Federal Railroad Administration (FRA) accident database, published literature, the results of a railway industry survey, and extensive input from concrete crosstie experts in the U.S. rail industry. This paper provides a summary of these inputs and their influence on laboratory experimentation priorities.

INTRODUCTION

The Federal Railroad Administration (FRA) divides accidents into five groups based on their cause: Infrastructure, Equipment, Signal and Communication, Human Factors, and Miscellaneous (*1*). Based on data from the FRA Office of Safety (*2*), the two most common causes of accidents are Miscellaneous and Infrastructure (Table 1). As the name suggests, the Miscellaneous category is very broad, including environmental conditions, highway-rail grade crossing accidents, unusual operational situations, etc. Therefore, when the Miscellaneous group is removed from the list of categories, infrastructure causes are the most prevalent.

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TABLE 1 Train Accidents on Class I Mainlines Grouped by Accident Causes (*1*)

Accident Cause Category	Number of Accidents	Percentage
Infrastructure	3,104	26%
Equipment	2,510	21%
Human Factor	2,383	20%
Signal and Communication	45	0%
Miscellaneous	3,992	33%
Total	12,034	100%

Data obtained from FRA's Office of Safety Analysis Web Site from 2004 to 2013

Having identified the primary causes of accidents, there is still need to narrow down the type of track for a more precise analysis that is relevant to concrete crossties and fastening systems. While timber crossties are the most common type of crosstie used in North America, concrete crossties have emerged as an economic alternative to accommodate heavy axle freight and high and higher speed passenger train loads (*3*). As the number of concrete crossties increases, understanding the performance of these components takes on increasing importance. Therefore, this paper focuses on identifying the most relevant infrastructure problems associated with concrete crosstie track in North America and provides a literature review summary, analysis of the relevant portions of the FRA accident database, and a survey of rail infrastructure experts.

BACKGROUND

Most of the published literature that identifies critical railroad track conditions in North America does not distinguish between the crosstie material (e.g. concrete, timber, etc.) that was present at the location of the accident. Dick showed that broken rail and track geometry deviations are the most frequent derailment causes in the United States, and both conditions lead to higher than average number of cars derailed per accident, a proxy for accident severity (*4*). While this information is more representative of railway lines with timber crossties due to their greater use in North America, these trends may also be applicable for concrete crosstie track. Understanding that the primary differences between these two types of track are the crosstie material and the fastening systems typically used with each material, our literature review focuses on identifying the most critical problems associated with concrete crossties.

Rail Seat Deterioration (RSD)

In 2011, researchers at the University of Illinois at Urbana-Champaign (UIUC) conducted an international concrete crosstie and fastening system survey (*5*). They presented a rank of typical failure modes of concrete crossties and fastening system both internationally and domestically. Table 2 summarizes this study, with common crosstie and fastening system problems ranked from 1 to 8, with 8 being most critical. UIUC found that rail seat deterioration (RSD) was considered the most critical failure associated with concrete crossties in the U.S. Zeman identified five mechanisms that can cause RSD: abrasion, crushing, freeze-thaw cracking, hydraulic-pressure cracking, and hydro-abrasive erosion (*6*). Kernes investigated the mechanics of abrasion on concrete crosstie rail seats (*7*) and Greve examined the effect of RSD on rail seat load distribution (*8*).

TABLE 2 Ranked List of Critical Concrete Crosstie and Fastening System Problems in the U.S. (higher numbers indicate increased criticality) (*5*)

Failure	Rank
Deterioriation of concrete material beneath the rail	6.43
Shoulder/fastening system wear or fatigue	6.38
Cracking from dynamic loads	4.83
Derailment damage	4.57
Cracking from center binding	4.50
Tamping damage	4.14
Other (e.g., manufactured defect)	3.57
Cracking from environmental or chemical degradation	3.50

Two Amtrak derailments caused by RSD in 2005 and 2006 corroborate the importance of the topic, and the potential for RSD to lead to a derailment. After these accidents, the FRA formed a task force to evaluate the problem, which resulted in changes to the Code of Federal Regulations (CFR) 213, the FRA Track Safety Standards (TSS), introducing new regulations relating to this topic (*9*-*10*). Currently, the FRA TSS states that concrete crossties should not be deteriorated or abraded at any point under the rail seat to a depth of ½ inch (12.7 mm) or more (*11*). Additional research relating RSD to rail rollover and gage widening was published by researchers from the John A. Volpe National Transportation Systems Center (Volpe) (*12*-*13*).

Crosstie Cracking

A different point of view is presented by Taherinezhad, who suggests that cracking could be the most important failure of prestressed concrete crossties (*14*). Taherinezhad discusses the fact that the use of high strength concrete increases the crosstie brittleness when compared to normal concrete strength, making it more prone to cracking (*14*). However, categorizing the types of cracks is helpful since there are variations of how they manifest themselves and the potential risk (or lack thereof) they pose. There are three common types of concrete crosstie cracking: center, rail seat, and longitudinal (*10*).

Center cracks are located at the crosstie midspan. They typically start on the top of the crosstie and grow vertically in the direction of the bottom, resulting from high center negative bending moments imposed by improper crosstie support under the rail seats. A CSX derailment on Metro-North tracks in the Bronx, NY, in 2013 is an example of center bound concrete crossties being a critical factor contributing to the accident (*15*). Using a finite element (FE) model of a prestressed concrete crosstie, Chen concluded that gaps between the concrete crosstie and ballast at the rail seat region considerably increase the flexural demand at the crosstie center (*16*). For the crosstie type considered in the study, a gap larger than 0.1 in (2.54 mm) resulted in tensile cracking of concrete at the top surface of crosstie midspan. However, predicting the crosstie support conditions to determine the chance of center cracking is nontrivial. McHenry's experiments at TTC revealed significant variability in pressure distribution under concrete crossties, even within the same type of track and between adjacent crossties (*17*).

As the name suggests, rail seat cracks are located under the rail bearing area of the crosstie. In most cases, the crack initiates at the bottom or sides of the crosstie and propagates vertically to its top (*10*). Commonly, rail seat cracking is the result of a combination of stiff track and high impact loads (*18*). Using a FE model, Yu showed that rail seat cracks can occur when the crosstie is supported by a uniform and homogeneous ballast layer (*19*). However, even though published literature indicates it is a frequent deteriorated condition (*20*), focused conversations with railway industry experts showed that rail seat cracking is not a common concrete crosstie problem in North America. While there is not sufficient data to determine the exact occurrence or severity of rail seat cracks, some researchers suggest that rail seat cracks might have more severe consequences for the crosstie deflections and stresses than center cracks (*21*).

The third type of cracks are longitudinal, which, according to the FRA, are "horizontal through the crosstie and extend parallel to its length" (*10*). Commonly associated with high stresses in the vicinity of prestressing wires and the indented wire geometry (*22*-*23*), longitudinal cracks pose a challenge for concrete crosstie manufacturers who consider increasing presstressing forces to improve flexural capacity (*24*). The FRA report on performance of concrete crossties on Amtrak's Northeast Corridor (NEC) indicates that longitudinal cracking was the predominant cracking mode associated with the replacement of crossties on the NEC (*23*).

Improper support conditions, high impact wheel loads, and high stresses at the prestressing wires are not the only causes for concrete crosstie cracking. Chemical reactions (e.g. alkali silica reactivity (ASR) and delayed ettringite formation (DEF)), manufacturing defects, improper design and vibration, and other causes can also result in concrete crosstie cracking. Chemical reactions have been critical causes of crosstie cracking in Sweden, where approximately 500,000 concrete crossties presented various types of cracks due to DEF (*25*). Similarly, ASR contributed to the longitudinal cracking of crossties installed in the 1990's on the NEC (*23*). ASR also caused the failure of more than 350,000 crossties installed in the 1970's by Canadian National (*20*). Similarly, vibration can be an adverse factor for concrete crossties, causing most damage at resonant frequencies of the crosstie's first five modes of vibration (*26*). These frequencies commonly include corrugation-passing frequencies (*27*), meaning that dynamic damage of trains moving on corrugated rail can be worse than it would otherwise be in the presence of other track irregularities.

ANALYSIS OF DATA FROM FRA ACCIDENT DATABASE

One way to determine critical railroad track conditions in terms of causing accidents is to analyze data contained within the FRA accident database. While the specified accident causes depend on the accuracy of each case investigation, and these data are provided by individual railroads, the data are capable of indicating general trends in the U.S. Using the FRA database, an analysis of the accidents caused by infrastructure problems in main lines of Class I railroads from 2004 to 2013 was performed. Six accident codes were considered relevant for this work (Table 3).

TABLE 3 FRA Accident Codes Used in This Study

Code	Description
T110	Wide gage (due to defective or missing crossties)
T111	Wide gage (due to defective or missing spikes or other rail fasteners)
T205	Defective or missing crossties (not resulting in wide gage)
T206	Defective spikes or missing spikes or other rail fasteners (not resulting in wide gage)
T001	Roadbed settled or soft
T105	Insufficient ballast section

First, the average number of cars derailed per accident for each of the six selected codes was computed and compared to the average number of cars derailed per accident for all infrastructure-related codes (Figure 1). Average number of cars derailed will serve as a proxy for accident severity. Second, the total number of accidents of each accident code was compared to the average incidence of all infrastructure accident codes from 2003 to 2014 (Figure 1). These data were plotted on a frequency versus severity graph (Figure 1). The accident causes that were above average for both frequency and severity (i.e. were in the upper right quadrant of the graph) were considered critical and would be further investigated through our experimental study (Figure 1).

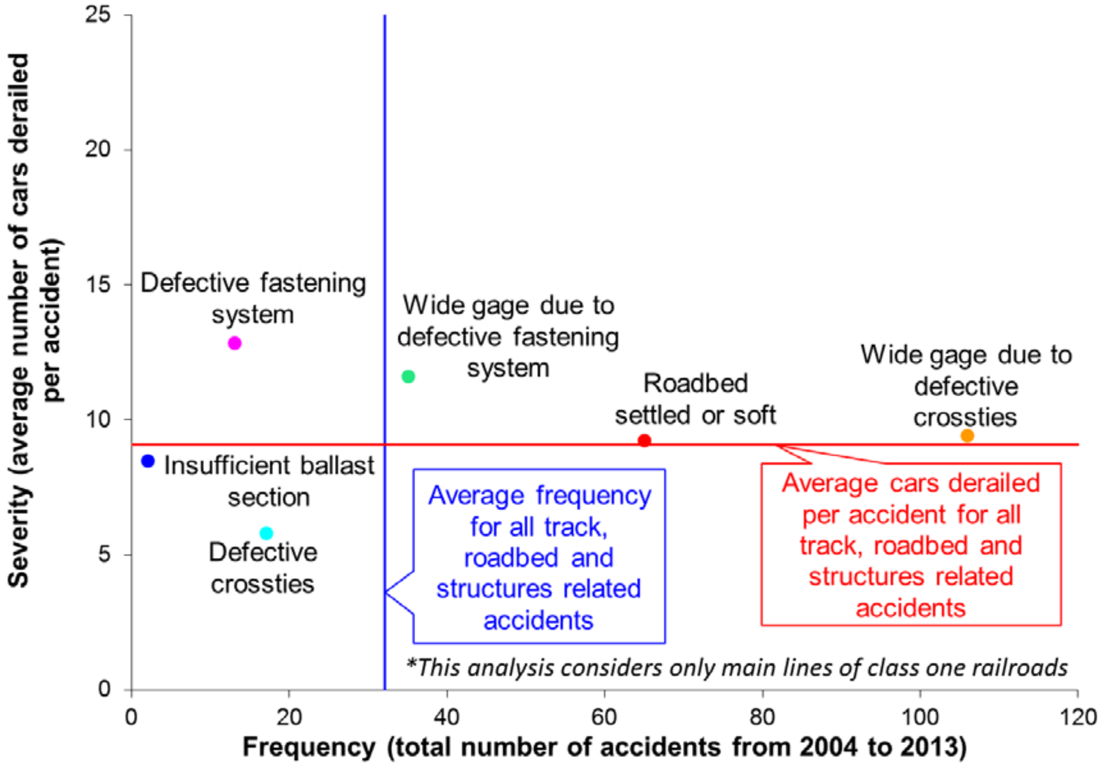

FIGURE 1 Track-Caused Derailment Analysis for All Types of Track

It is important to note that, for an accident or incident to be reportable to the FRA, it has to be classified in one of three primary groups: “Highway-Rail Grade Crossing”, “Rail Equipment” and “Death, Injury and Occupational Illness” (*28*). However, this analysis only accounts for accidents that had material damage above the FRA official reportable threshold ($10,500 for year 2015), which includes all rail equipment related accidents and part of grade crossing related incidents (*28*). With this information, one can conclude that the overall average number of cars derailed is not underestimated due to the influence of accidents with material damage lower than the reportable threshold.

However, this analysis does not differentiate between crosstie materials since the FRA database has no field that relates to crosstie material or type. In order to understand the critical infrastructure related accidents in concrete crosstie track, the type of crosstie had to be manually identified. Therefore, an investigation was conducted to determine the crosstie material for every accident location where one of the six accident codes from Table 3 was named. As a result, a new frequency versus severity plot was developed specifically for concrete crosstie track using only the six accident codes from Table 3 (Figure 2). Additionally, the average number of cars derailed and average incidence in ten years are based on the six studied accident codes, not all infrastructure-related accidents.

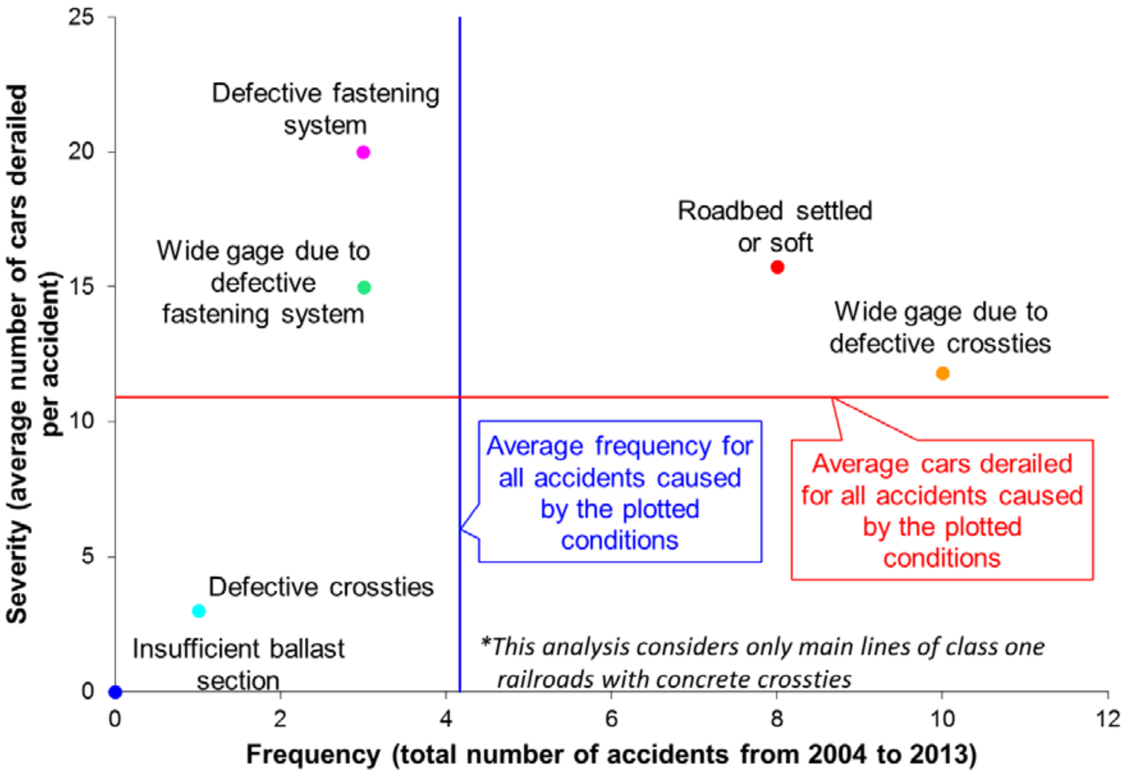

FIGURE 2 Track-Caused Derailment Analysis for Concrete Crosstie Track

When considering all types of track, the problems that rank highest in terms of both severity and frequency are “wide gage due to defective fastening system” (T111), “wide gage due to defective crossties” (T110), and “roadbed settled or soft” (T001). The results are similar for concrete crosstie track, except that “wide gage due to defective fastening systems” has a lower frequency compared to the other cause codes. This difference could indicate that elastic fasteners, which are required for concrete crossties, are more effective in restraining gage than cut spikes in timber crossties.

In addition, the high criticality of “roadbed settled or soft” in both cases is a sign that poor track support conditions is a critical element that should be further explored in laboratory experimentation. In concrete crossties, the effect of poor support conditions can manifest themselves through cracking. Cracking could happen, for example, under center binding or in the presence of substructure with high stiffness (*10*). However, explaining the support conditions of crossties is non-trivial and there is need for additional research in this area.

Derailments on concrete crosstie track due to “wide gage due to defective crossties” occurred at a higher than expected frequency, given concrete crossties are known for holding gage well. However, most of the degraded conditions of concrete crossties can contribute to gage widening. For example, RSD can generate rail cant deficiency, which can allow the rail to roll and alter gage (*12*). Similarly, crossties with reduced flexural capacity from cracking or abrasion of their bottom surface might suffer significant deflections under loading, which also adds to the loaded gage. Therefore, it is likely that wide gage due to defective concrete crossties is a critical problem in the U.S. because multiple factors can contribute to its occurrence.

SURVEY OF RAILWAY INDUSTRY EXPERTS

A survey relating to worn and degraded conditions in concrete crosstie track was developed to identify critical problems of this type of track in North America. In contrast to the broader survey previously cited in this paper (*5*), this survey was shorter and more specific, with only four questions. Like the previous survey, this survey was distributed to experts at railroads, suppliers, and industry and academic research institutions. Topics included the criticality of possible track defects, qualitative assessment of FRA accident codes, the identification of combinations of deteriorated track conditions that can lead to derailments, and noting potential areas of track infrastructure laboratory experimentation and research. Fourteen individuals took the survey, representing railroads, concrete crosstie manufacturers, and research institutions.

Survey Findings

When asked about the criticality of various conditions with respect to the occurance of accidents on concrete crosstie tracks, RSD emerged as the most critical concrete crosstie deterioration condition (Table 4). It should be noted, however, that the first six items are directly related to the condition of concrete crossties and fastening systems, but substructure problems are listed with relatively low criticality.

TABLE 4 Criticality of Track Structure Conditions; Ranked from 1 to 5, with 5 Being the Most Critical

Failure	Rank
Rail seat deterioration and other forms of rail cant deficiency	4.57
Worn or missing shoulder	4.14
Worn or missing insulator	3.79
Missing clip	3.71
Center negative crosstie bending	3.43
Missing rail pad	3.36
Fouled ballast	3.21
Insufficient depth of ballast	3.00
Weak subgrade	3.00
Concrete crosstie with deteriorated bottom	2.93
Rail seat positive crosstie bending	2.43

A similar question was posed regarding the specific FRA accident codes referenced in this paper, and the respective responses are represented in Table 5. In addition, as reported on Table 5, the survey also indicates that “wide gage due to defective or missing crossties” is the top ranked accident code reported to the FRA, confirming the analysis of the FRA database. However, the accident code “roadbed settled or soft” was ranked quite low, which does not align with the findings from the FRA database analysis (Figure 2). This inconsistency may be an indication that “roadbed settled or soft” is perhaps reported to the FRA as an accident cause more often than it should be, or the fact that this term is reflective of a broader set of track conditions than the focus of our investigation (and survey).

TABLE 5 Criticality of FRA Accident Codes for Concrete Crosstie Track; Ranked from 1 to 5, with 5 Being the Most Critical

Code	Description	Rank
T110	Wide gage (due to defective or missing crossties)	4.33
T111	Wide gage (due to defective or missing spikes or other rail fasteners)	4.25
T205	Defective or missing crossties (not resulting in wide gage)	3.64
T206	Defective spikes or missing spikes or other rail fasteners (not resulting in wide gage)	3.42
T001	Roadbed settled or soft	3.25
T105	Insufficient ballast section	3.00

Table 6 indicates pairs of track conditions that the respondents felt could lead to a derailment, Table 6 shows that eleven people responded that the combination of “worn or missing shoulder” and “worn or missing insulator” could lead to a derailment. The same is true for the pair “worn or missing shoulder” and “RSD and other forms of rail cant deficiency”. Second to these, the combination “worn or missing shoulder” with “missing clip” and the pair “center negative crosstie bending” and “concrete crosstie with deteriorated bottom” were considered as potential derailment causes by ten respondents. A common factor that these four pairs have in common is the type of derailment they could potentially lead to: wheel drop due to gage widening.

TABLE 6 Pairs of Problems that Could Lead to a Derailment; Each Number Indicates the Quantity of Votes Received by the Pair Represented in that Cell (out of 14 responses)

	Concrete crosstie with deteriorated bottom	Missing rail pad	Worn or missing insulator	Worn or missing shoulder	Missing clip	RSD and other forms of rail cant deficiency	Rail seat positive crosstie bending	Center negative crosstie bending	Fouled ballast	Insufficient depth of ballast	Weak subgrade
Concrete crosstie with deteriorated bottom		3	3	2	2	8	5	10	5	7	8
Missing rail pad			7	8	5	1	1	2	2	2	4
Worn or missing insulator				11	8	1	0	2	3	1	3
Worn or missing shoulder					10	11	3	2	2	3	4
Missing clip						9	1	4	2	0	4
RSD and other forms of rail cant deficiency							3	4	4	3	7
Rail seat positive crosstie bending								1	2	4	5
Center negative crosstie bending									7	7	7
Fouled ballast										8	8
Insufficient depth of ballast											7
Weak subgrade											

Finally, Table 7 summarizes the most common responses relating to what degraded conditions of track structure the respondents would like to see tested in a laboratory. “Cracked crossties” emerged as the most requested topic for laboratory experimentation on concrete crosstie with four references. This is especially significant considering that this was an essay question where the respondents could freely recommend degraded conditions of concrete crosstie track. It is also worthy to comment that “center negative crosstie bending” can be considered a specific subtopic of “crosstie support condition”, in which case their number of votes could be added together and sum to 6.

TABLE 7 Most Recommended Topics for Laboratory Tests (out of 14 responses)

Topic	Votes
Cracked crossties	4
Crosstie support condition	3
Saturated ballast (wet ballast)	3
Center negative crosstie bending	3
Worn fastening systems	3

CONCLUSIONS

This study focused on identifying critical infrastructure conditions for concrete crosstie track with the objective of informing future laboratory experimentation. In addition to the literature review, an analysis of ten years of data from the FRA accident database and a railway industry survey was conducted. Published literature shows that RSD and concrete crosstie cracking are the most common failures that were noted for concrete crossties. However, rail seat cracking appears to be less frequent than longitudinal and center cracking in the U.S. Based on the analysis of FRA accident data, it was concluded that the accident codes “wide gage due to defective crossties” and “roadbed settled or soft” are both more frequent and more severe than average for concrete crosstie track.

The survey responses indicated that the consulted railway industry experts consider “wide gage due to defective crossties” critical in fact, but the same does not apply to “roadbed settled or soft”. The responses also confirmed the high criticality of RSD as a problem in concrete crosstie track. Moreover, the survey results corroborated the idea that wheel drop due to gage widening might be the leading type of derailment due to combined infrastructure problems of concrete crosstie track. One additional finding from the survey was that crosstie support condition (including center binding) and cracked crossties were the most recurring topics recommended for laboratory experimentation.

As noted by other researchers, the root causes for problems in concrete crosstie track are not always clear (*29*). The broad list of degraded conditions in concrete crosstie track indicates the complexity of the railroad track as a whole and attempting to narrow down the critical conditions could lead to an omission of important terms. To reduce the incidence of these concrete crosstie track problems, further studies are necessary not only to better understand each individual topic, but also to analyze the track as a system.

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