Proceedings of the 2016 Joint Rail Conference
April 12-15, Columbia, South Carolina, USA

DRAFT

JRC2016-5725

FOULED BALLAST DEFINITIONS AND PARAMETERS

Radim Bruzek
ENSCO, Inc.
Springfield, VA, USA

Timothy D. Stark
University of Illinois at Urbana-Champaign
Urbana, IL, USA

Stephen T. Wilk
University of Illinois at Urbana-Champaign
Urbana, IL, USA

Hugh B. Thompson II
Federal Railroad Administration
Washington, D.C., USA

Theodore R. Sussmann, Jr.
Volpe National Transportation Systems Center
Cambridge, MA, USA

ABSTRACT

Ballast fouling is a potentially problematic track condition that can lead to inadequate ballast performance. Prioritizing remediation of fouled ballast sites is difficult because no relationship between ballast fouling and track performance exists and fouled ballast performance depends on the amount, grain-size, type, plasticity, and moisture content of the fouling material. This paper provides results of an international railroad industry survey on fouled ballast definitions, parameters, limits/standards, and laboratory test results to aid development of a procedure for quantitatively assessing ballast fouling and assessing the ability to: transmit applied train loads to the subgrade, allow drainage, and/or maintain proper track geometry as required under §213.103.

INTRODUCTION

Ballast is one of the primary railroad track structure components and refers to the coarse rock particles placed underneath railroad crossties. In the United States, Federal Track Safety Standards (FTSS) establish minimum safety requirements for track. The FTSS are not design or maintenance standards. The ballast safety standard set forth under §213.103 requires ballast to perform the following functions [1]:

- Transmit and distribute the load of the track and railroad rolling equipment to the subgrade;
- Restrain the track laterally, longitudinally, and vertically under dynamic loads imposed by railroad rolling equipment and thermal stresses exerted by the rail;
- Provide adequate drainage for the track; and
- Maintain proper track crosslevel, surface, and alinement.

This means no federal specifications on ballast type or gradation exist in the United States as long as the ballast performs the above functions.

Fouled ballast typically refers to the ballast condition in which fine particles fill the voids of the ballast matrix and is often associated with ballast that is unable to perform the functions specified by §213.103. However, the fouling limit at which ballast is unable to perform the functions specified by §213.103 is unclear, which makes it difficult to predict ballast performance based on observations of fouled ballast in track. For example, the amount, grain-size, type, plasticity, and moisture content of fouling material all affects ballast performance and these can be difficult to measure without large sample masses, reconstituting, and testing equipment.

§213.103 does not specifically refer to the term "fouled ballast" nor is it defined by a supplemental document to guide to determine whether or not a fouled ballast location should be remediated. FRA guidance states that ballast must maintain the track in accordance with the FTSS and advises that fouled ballast occurs when the track exhibits "inadequate" drainage and/or is not "maintaining proper track geometry."

The lack of specification can make it difficult for railroads to determine when and how to prioritize fouled ballast repairs. To emphasize this point, Figure 1 displays track with various levels of fouling. Figures 1(a) and (b) show fouled track with track geometry defects, Figure 1(c) shows track with a drainage defect, and Figures 1(d) and (e) show fouled track but the track and track geometry remain in good condition. The two questions that arise from these photos are whether these sites meet the objectives of §213.103 and whether the presence of the fouling requires remediation.

This literature survey compiles fouling definitions and parameters to assist in the creation of a procedure to measure and quantify a fouling parameter that corresponds to inadequate transmission of train loads to the subgrade, poor drainage, and/or inability to maintain proper track crosslevel, surface and alinement as required under §213.103.

Selecting or developing a fouling parameter for U.S. railroads will be difficult because it requires finding a balance between the testing complexity and adequate prediction of ballast and track performance under future traffic. It is expected that U.S. railways will not regularly perform complex field or laboratory testing to determine the fouling parameter but some quantitative metric is desirable for a more consistent application of the ballast regulation. The following sections review existing fouling parameters and track maintenance or performance limits along with laboratory test results to aid development of a U.S. definition of fouled ballast.

EXISTING FOULED BALLAST PARAMETERS

Fouled ballast is usually defined as a ballast condition where voids in the ballast are filled with relatively finer materials or fouling agents. New procedures and definitions should: (1) be relatively easy to measure, (2) predict ballast performance under future traffic and a range of environmental conditions, and (3) reliably predict track performance and safety.

Purpose of Fouled Ballast Parameter

This subsection investigates fouling parameters that have been proposed for correlating the level of ballast fouling with future ballast and track performance. For example, ballast with a hypothetical fouling parameter value of zero (0) should have no fouling material and the track will perform the four functions under §213.103. Conversely, ballast with a fouling parameter significantly greater than zero would imply a significant reduction in ballast and track performance because of the presence of ballast fouling material. Such a fouling parameter could be used to objectively classify ballast performance as "acceptable" or "unacceptable" for a given speed and track geometry limit.

Percent Passing:

Existing literature [2-4] presents a number of fouling parameters that are a slight variation of the "Percent Passing" concept, which is defined as the percentage of material by weight of particles passing or finer than a certain grain-size diameter. For example, if fouling material is defined as particles passing the No. 4 sieve and the material by weight of a sample passing the No. 4 sieve is 20% of the total sample weight, the "Percent Passing" is 20%. "Percent Passing" is also commonly referred to as "Percent Fouling" [4,5] and Percent Passing is useful because it reminds the user/reader to inquire about the grain-size diameter that is being used to define the fouling material.

A number of grain-size diameter thresholds have been proposed or adopted by railroads in various countries to define "fouling material" using the Percent Passing concept. For example, material passing the No. 4 sieve (4.75 mm) is typically considered "fouling material" in the U.S. based on the Fouling Index (FI) proposed by Selig and Waters [2]. Alternatively, European railroads use a grain-size diameter of 22.4 mm (1 inch) as fouling material while railroads in South Korea use a threshold of 0.075 mm (0.003 inch) which corresponds to the No. 200 sieve [6].

Selecting a grain-size diameter for fouling material is important because it has implications for the testing required and thus usefulness of the index. For example, using a grain-size diameter of 22.4 mm (1 inch) to define fouling material could be practical because it can be determined by visual inspection. However, this grain-size limit could be problematic for U.S. railroads because some U.S. track uses ballast particles sizes less than 22.4 mm (1 inch) so these locations would be considered completely fouled under this definition even though they may be functional for the intended level of service.

Unfortunately, using the Percent Passing with a particular grain-size diameter also does not provide an insight to the composition, plasticity, and behavior of the fouling material. For example, ballast fouled with sand-sized particles will probably exhibit better drainage, strength, and compressibility properties than ballast fouled with plastic fine-grained particles even though they have similar values of Percent Passing a particular grain-size diameter.

Fouling Index:

To emphasize the importance of silt and clay-sized fouling particles (<0.075 mm), Selig and Waters [2] propose the Fouling Index (FI). This parameter defines "fouling material" as the particles that pass the No. 4 sieve (4.75 mm) and includes the influence of fines content, i.e., particles passing the #200 sieve, because fine-grained particles (<0.075 mm) were observed to reduce ballast performance to a greater extent by weight than coarse-grained fouling particles (0.075 mm to 4.75 mm). As a result, FI is defined by [2] as:

$$\mathrm{FI} = \mathrm{P}_4 + \mathrm{P}_{200}$$

where P_4 is the percentage of particles passing the No. 4 sieve (4.75 mm) and P_{200} is the percentage of particles passing the No. 200 sieve (0.075 mm) by weight. Therefore, FI reflects the importance of fines content by adding the fines content twice to the FI through P_{200} and P_4. The FI parameter has been adopted by railroads in the Australian state of New South Wales (NSW) and is widely used in academic research.

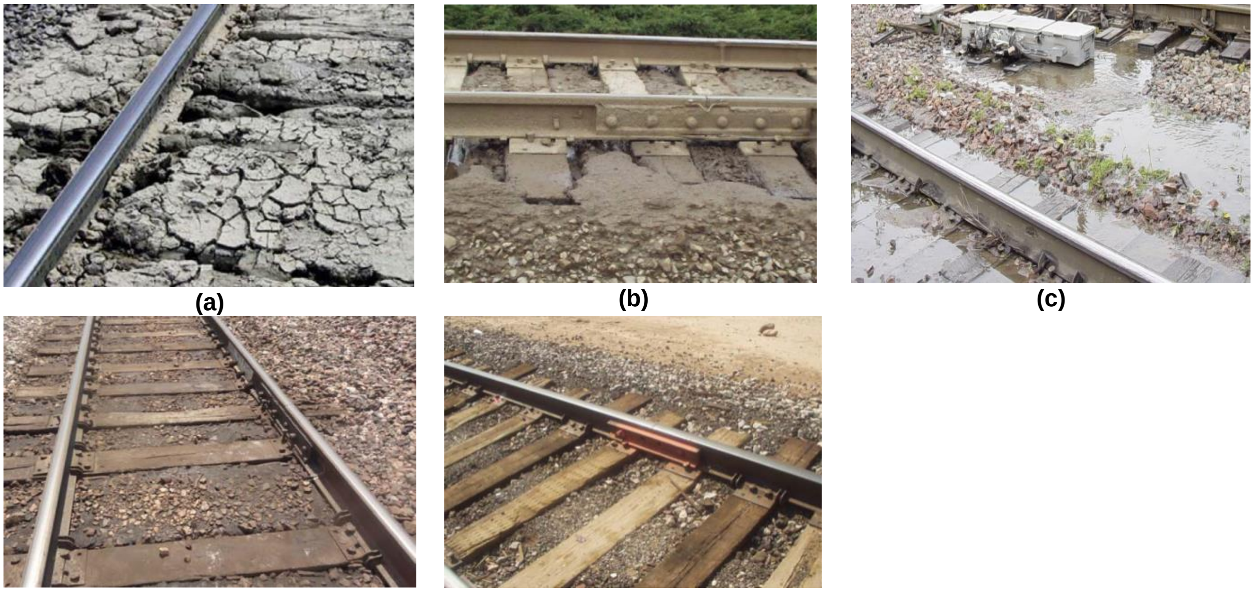

FIGURE 1 – PHOTOGRAPHS OF TRACK WITH VARIOUS FOULING LEVELS AND TRACK GEOMETRY (PHOTOS COURTESY OF DAVID JAMIESON).

Percentage Void Contamination

Another commonly used ballast parameter is "Percentage Void Contamination" (PVC), which expresses fouling as a percentage of volume instead of a percentage of sample weight [3]. The development of PVC was in response to the inadequate predictions made using "Percent Passing" and FI for ballast fouled with coal ash. This inadequacy results from the specific gravity of coal ash (~1.28) being about one-half of most rock or soil particles (~2.76), meaning the volume of coal ash in the fouled ballast will be twice that of most rock or soil particles for the same value of "Percent Passing" because it is based on weight not volume. PVC defines "fouling material" as the particles passing the 9.5 mm (3/8 inch) sieve by volume not weight as shown below [3]:

$$\mathrm{PVC} = \frac{\mathrm{V_2}}{\mathrm{V_1}} * 100\%$$

where V_1 is the void volume between clean ballast particles (>9.5 mm) for a given density and V_2 is the total volume of fouling material (<9.5 mm) that fills V_1. For example if V_1 is one-half of V_2, one-half of the voids are filled with fouling material (<9.5 mm). The PVC parameter is frequently used in Australia and South Africa where the primary fouling material is coal ash.

The primary benefit of PVC over FI is the ability to predict fouled ballast behavior when coal ash is the fouling material. This is evident from cyclic triaxial compression tests comparing the permanent strains of ballast fouled with coal ash and ballast fouled with crushed ballast particles [7]. Identical fouling volumes of coal ash and crushed ballast were added to identical ballast material. This results in equal values of PVC but FI values of 10 and 20 for ballast fouled with coal ash and crushed ballast, respectively. This is problematic because both ballast samples exhibited similarly unacceptable large permanent strains during cyclic triaxial loading even though the coal ash sample would be expected to exhibit better performance because the value of FI is one-half (10) the FI of the crushed ballast sample (20). This suggests that parameters based on volume, e.g., PVC, are better indicators of fouled ballast performance than fouling parameters based on weight, e.g. "Percent Passing" and FI, especially when coal ash is involved. However, parameters based on volume will require laboratory testing, which is problematic because of difficulties in obtaining and reconstituting a representative ballast sample in the laboratory. Under ASTM D75/D75M and ASTM C136/C136M [8,9], about 300 lbs (140 kg) of ballast is required to obtain a representative sample, which is about 7 to 8 five (5) gallon buckets of ballast based on a unit weight of 110 pcf (17.3 kN/m3).

Void Contaminant Index:

More complicated parameters expressing fouling as a volume instead of weight have also been proposed such as void contaminant index (VCI) [4]. This index is a modification of PVC by using void ratio, specific gravity, and dry mass of the fouling and clean ballast material to calculate volume. This parameter will not be emphasized in the literature survey because the testing required is not considered practical for U.S. railroads but is included herein for completeness. The definition of VCI is [4]:

$$VCI = \frac{(1+e_f)}{e_b} * \frac{G_{sb}}{G_{sf}} * \frac{M_f}{M_b} * 100$$

where e_b is void ratio of clean ballast, e_f is void ratio of fouling material, G_{sb} is the specific gravity of clean ballast, G_{sf} is the specific gravity of fouling material, M_b is the dry mass of clean ballast, and M_f is the dry mass of fouling material.

Even with additional testing, none of these proposed fouling parameters account for differences in fouling material mineralogy, plasticity, and moisture content all of which can have a significant effect on ballast performance as discussed below.

Comparison of Fouling Parameters:

Table 1 presents values of percent passing the No. 4 sieve (4.75 mm), percent passing the three-quarters inch sieve (19 mm), and FI for the following ballast conditions stated by Selig and Waters (1994) and Indraratna et al. (2011) [2,10]: clean, moderately clean, moderately fouled, and fouled. These types of comparisons are useful for comparing the standards of various railroads because of the range of fouling definitions used in practice. This also allows the maintenance and safety limits used in other locations, i.e. Europe, to be translated to fouling parameters used in the United States.

TABLE 1 – COMPARASION OF PERCENT PASSING VARIOUS SIEVES AND FI FOR MULTIPLE BALLAST CONDITIONS.

Category	Percent Passing (4.75 mm sieve)	Percent Passing (3/4" sieve)	Fouling Index (FI)
Clean	<2	-	<1
Moderately Clean	2 to <9.5	-	1 to <10
Moderately Fouled	9.5 to <17.5	25 to 35	10 to <20
Fouled	17.5 to <34	40 to 50	20 to <40
Highly Fouled	>34	>50	>40

TABLE 2 – COMPARASION OF MAINTENANCE LIMITS USED BY DIFFERENT COUNTRIES

Reference	Country	Parameter	Maintenance Limit	Sieve Size	Comments
[12]	Australia (Aurizon, Queensland)	PVC	30%	9.5 mm	If fouling is pumped clay from the subgrade, maintenance is often performed earlier
[12]	South Africa (Transnet)	Depth of competent ballast	120 mm	-	Similar to 30% PVC
[6]	South Korea	% Fouling	35%	0.075 mm	Immediate maintenance occurs if a track geometry problem accompanies fouling. If no track geometry problem exists, maintenance is pushed until next fiscal year.
[17]	Great Britain	% Fouling	30%	14 mm	
[17]	Europe	% Fouling	30%	22.4 mm	ERRI value, some countries adopt some do not

Existing Fouled Ballast Standards

This subsection reviews existing fouled ballast standards to illustrate how other countries define fouled ballast and the safety limits used for fouled ballast areas. Most sources specify "maintenance limits" instead of "safety limits" with the distinction being "maintenance limits" are set by individual railroads for maintenance purposes and "safety limits" are set by regulatory agencies to ensure track safety.

A review of existing "maintenance limits" for fouled ballast reveals a lack of consensus on grain-size diameter and fouling parameter used for fouled ballast (see Table 2). Based on this review, most maintenance limits correspond to a Percent Passing of 10 to 20% assuming fouling is defined as material passing the No. 4 sieve (4.75 mm). Australia, South Africa, Great Britain, and most European Countries require ballast cleaning immediately after surpassing the maintenance limit. South Korea is the notable exception to this statement because maintenance is delayed until the next fiscal year if a track geometry defect is not detected for the fouling location [6].

Data on "safety limits" are less available than "maintenance limits". However, safety limits typically assume a lack of ballast performance once the voids are at or near full with fouling material. FI values of 30 to 40 are typically cited as a safety limit [2,11] while PVC values of 75% or greater have been proposed as a safety limit [4,12].

Defining Possible Fouling Parameter in the U.S.

Defining a fouling parameter for U.S. railroads requires finding a balance between complexity of testing required and adequate prediction of future ballast performance. It is not expected that U.S. railways will regularly perform complex field or laboratory testing to determine the fouling parameter but having some quantitative metric is desirable to increase consistency of identifying locations of reduced performance ballast. The advantages and disadvantages of the Percent Passing, FI, and PVC parameters discussed above are discussed in the following paragraphs.

The "Percent Passing" parameter has the advantages of: being simple to understand, easy to measure, and possibly being able to be determined in the field. However, Percent Passing does not account for varying mineralogy or plastic behavior of the fouling material both of which can significantly affect ballast performance. If a grain-size diameter less than 1 inch (22 mm) is used, the Percent Passing may be determinable in the field. However, using a grain-size diameter less than No. 4 sieve (4.75 mm) will likely require a mobile laboratory with a sieve shaker or physically transporting large ballast samples (about 300 lbs or 140 kg) to a laboratory [13].

The "Fouling Index" parameter has the advantage of quantifying the influence and importance of fine-grained fouling material, i.e., % passing No. 200 sieve, which provides a better prediction of ballast behavior than just Percent Passing. However, FI requires a laboratory sieve analysis to be performed and does not differentiate between differences in specific gravity and mineralogy or plasticity of the fouling material. FI may be best parameter in the U.S. because it is commonly used and easy to calculate. However, FI may not be well suited for ballast performance assessment if coal ash is expected to be the fouling material. A simple solution may be doubling the FI value if coal ash is the primary fouling material.

The Percentage Void Contamination (PVC) parameter has the advantages of accounting for the specific gravity of the fouling material leading to more consistent ballast behavior predictions. However, PVC will require a sieve analysis and water-volume measurements to determine the volume of ballast void and fouling material for the field compaction condition. PVC also does not account for differences in fouling material grain-size so it cannot differentiate between ballast filled with sand- or clay-sized particles. This parameter may be best suited if a wide range of fouling materials and specific gravities are expected, such as, coal ash.

EFFECT OF FOULING ON BALLAST BEHAVIOR AND PERFORMANCE

This section reviews the effect of fouling on ballast behavior and performance. The first subsection focuses on laboratory ballast testing while the second subsection focuses on field ballast failure mechanisms.

Laboratory Fouled Ballast Testing

While ballast in the United States can be any particle size that satisfies the service requirements in §213.103, it typically consists of 0.75 inch to 3 inch sized rock particles. This range of particle-size is desirable for railroad track because it offers high strength and stiffness due to the high frictional resistance between ballast rock particles. In addition to high strength and stiffness, the large voids between the ballast particles allow drainage of water from the ballast.

When fouling material accumulates on the ballast particles and/or within the ballast voids, the strong frictional contact between the ballast particles is reduced and replaced by a weaker frictional contact between the ballast and/or fouling particles. The reduced strength behavior of fouled ballast has been demonstrated using laboratory ballast box testing [5] and triaxial compression testing [7,14], which shows increased compressibility and/or permanent strain. These data suggest that ballast strength, compressibility, and stiffness are dependent on the engineering properties and moisture content of the fouling material.

In general, increasing the moisture content of the fouling material decreases the laboratory [5] and field [15] measured strength and stiffness of the fouled ballast. For example, laboratory ballast box testing show significant increases in ballast settlement as clay-sized fouling material goes from dry to wet [5]. Seismic surface wave testing also shows a reduction in Young's Modulus by a factor of two when the same section of fouled ballast was soaked with a fire hose [15].

Laboratory tests measuring settlement and permanent axial strain also observed that ballast with dry fouling material exhibits similar settlement behavior as clean ballast [5,7], which is in agreement with seismic surface wave measurements [15]. For example, seismic surface wave tests show higher Young's Modulus values for dry fouled ballast than clean ballast because the dry fouling material fills the voids of the ballast yielding a stiffer material [15]. This suggests that dry fouled ballast may not require the same attention as wet fouled ballast unless the area is subject to precipitation. This means fouling in drier regions, e.g. New Mexico, may not be as problematic as fouling in wet regions, e.g. Oregon. This also implies that track behavior may significantly change if a precipitation event occurs soon after inspection.

The grain-size diameter of the fouling material will also affect the drainage characteristics of the fouled ballast. For example, some drainage will still occur if the ballast is fouled with sand-size particles. However, drainage may be completely prevented if the ballast matrix is filled with clay-sized particles especially if the clay-sized particles exhibit some plasticity.

In summary, this brief review of laboratory ballast testing shows that fouled ballast behavior is dependent upon the amount, grain-size diameter, and moisture content of the fouling material. Therefore, the fouling definition and parameter should try to incorporate the amount, grain-size diameter, plasticity, and moisture content of the fouling material. If moisture content is incorporated in the fouled ballast definition and parameter, an additional consideration is moisture content will vary with time at a particular location because of variations in precipitation and evaporation rates. This means moisture content at the time of inspection may not represent the worst case track scenario [11].

Field Fouled Ballast Failure Mechanisms

The previous section focused on the effect of fouling on laboratory measured ballast strength, stiffness, and drainage. This section focuses on five potential track failure mechanisms that can occur because of fouled or reduced ballast performance. These five failure mechanisms are not meant to represent a complete list but mechanisms that should be considered during selection of safety limits for track safety.

The first potential failure mechanism is the progressive failure of fouled ballast. This will occur when the ballast voids are filled with fouling material, causing the ballast particles to lose contact with each other and essentially "float" within the fouling material. If the fouling material is weak, e.g. low to medium plasticity fine-grained particles, "ballast flow" will occur when the applied tie force pushes the fouled ballast into and upwards out of the area under and around the tie. This can cause complete loss in ballast support and the track will be unable to perform the four functions in §213.103, especially if the fouling material is wetted.

A second failure mechanism is bearing capacity failure of the fouled ballast and possibly the underlying subgrade. This occurs when the frictional resistance in the ballast and underlying subgrade are unable to resist the applied tie loads resulting in a loss of strength along a bearing capacity failure surface in the fouled ballast. This is different than the previous "ballast flow" mechanism because this bearing capacity failure mechanism will cause an instantaneous and permanent settlement of the track instead of the previous progressive failure.

A third failure mechanism is the reduction of interface strength between the bottom of the tie and top of the ballast. This reduces the lateral and longitudinal support provided by the ballast to the tie and may allow the tie and track to move in the lateral direction. This reduction in interface strength is due to the weaker fouling material covering the ballast particles and bottom of the tie causing a weak tie/ballast interface.

A fourth failure mechanism is full saturation of the track substructure because the fouling material prevents drainage of precipitation and other liquids. Full saturation of the fouling material can also result in an increase in pore-water pressures within the fouling material during repeated tie loading by passing traffic. For example, tie loading will try to compact the fouled ballast and compress water-filled voids in the fouling material. Because the water cannot drain quickly from the fouled ballast during rapid loading, compression of the water-filled void causes an increase in pore-water pressure and a reduction in the confining stress and strength of the fouled ballast. If the reduction in strength is great enough, it can cause ballast bearing capacity failure. This mechanism is also important because pore-water pressures can accumulate with each passing car or tie load, resulting in a progressive weakening of the ballast during train passage. This may explain why many freight train derailments usually occur during the last one-third of the train [16].

The last mechanism addresses the potential negative impact of ballast fouling on the entire track system. In the case of fouling only under a single tie, greater ballast settlements are expected under that tie than surrounding ties. This will result in a gap between the bottom of the tie and top of the fouled ballast because the rail and connecting ties will be supported by the adjacent clean ballast that experience less settlement. This is similar to the hanging ties often observed in transition zones or other significant changes in track support. The hanging tie will cause redistribution of the applied wheel load to adjacent ties. The increase in load applied to adjacent ties will cause ballast compression and degradation and a tie/ballast gap to develop and progressively increase until it is similar to the initially hanging tie. This mechanism is important because the redistribution of wheel load can accelerate deterioration of other track components as well as the ballast, such as, spike pull out, reduced tie load on elastic fasteners, tie deterioration, and tie plate wear. Therefore, a safety limit could be developed for fouled ballast that considers the impacts and loads applied to other track components such as ties, tie fastening systems, and/or the rail.

Considering the performance of the entire track system, instead of just the presence of fouled ballast, could be beneficial for future regulation. Field data relating the length and extent of fouling to tie and track performance is the focus of subsequent tasks of this research project and will provide insight to potential safety limits for the length and extent of fouling at a particular location.

SUMMARY

This paper summarizes fouling definitions, parameters, and maintenance limits used by railroads in various countries to help develop a new fouling parameter that relates ballast fouling to track performance and safety. Some of the key observations from this literature survey are:

- The fouling definition should correspond to a safety limit and not a maintenance or serviceability limit for the ballast.
- The fouling definition and parameter should help develop an approach for U.S. Railroads that can relate ballast condition to track performance. This will require the new definition and parameter to account for the wide range in ballast particle size, fouling material, and environmental conditions present in the U.S.
- Fouling Index "FI" or some variation of it

represents a fouling grain-size size parameter that appears suitable for U.S. railroads. Advantages of this parameter include it can be determined from a sieve analysis, emphasizes the negative effects of fine-grained fouling material, and has safety limits already associated with it [2]. However, the sieve analysis needed to determine FI will require more extensive testing than Percent Passing.

- A multi-tiered approach that includes a fouling parameter and a performance limit that reflects the type of fouling material, length of fouling, and track operation factors can better address the wide range of environmental, ballast, and fouling conditions experienced in the U.S. would be beneficial.

ACKNOWLEDGMENTS

The literature review of ballast fouling parameters and definitions was sponsored by the U.S. Department of Transportation's FRA ORDT.

The authors also acknowledge David Jamieson of David W Jamieson, LLC for his experience and insights in preparing this paper.

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