International Journal of Railway Research, Vol. 6, No. 2, (2019), 13-22

Iran University of Science and Technology

International Journal of Railway Research

ISSN: 2423-3838

Qualification of Track Parameters Based on a Review of Previous Studies

Nazmul Hasan *

Senior Trackwork Engineer, SNC-Lavalin Inc., Rail and Transit Division, Suite 500–745, Thurlow St., Vancouver, British Columbia, Canada

ARTICLE INFO

Article history:
Received: 14.07.2019
Accepted: 18.09.2019
Published: 24.12.2019

Keywords:
Track qualification
Track foundation parameters
Limiting deflection
Track deterioration
Process validation

A B S T R A C T

The objective of this paper is to qualify track parameters systematically over a wide range of categories. The characteristic length is strongly related to all track parameters including deflection. These relations and interrelations among track parameters are used to qualify all other track parameters. As such, the characteristic length is qualified by previous studies, a literature review, and analysis. The qualification of other track parameters is based on the qualification of the characteristic length. The track deflection is defined with reference to the characteristic length and is formulated and qualified as the minimum, optimum, and limiting deflections. The qualification can help design engineers to apply more accurate track parameter values in a consistent manner during the design phase, as well as supporting field engineers to evaluate the track foundation condition and track performance in making maintenance decisions. In addition, the qualification work can aid engineers in judging or inferring the requirements of some track materials. The qualification work is validated against current qualifications and literature.

1. Introduction

The aim of this research is to qualify track parameters, including those that are not yet qualified (e.g., track stiffness and ballast bed stiffness), and deflection systematically over a wide range of categories. Only a few studies qualify track foundation parameters. Esveld [1] qualifies only four track parameters over two categories – "good" and "poor". Ahlf [2] qualifies only track modulus over a wide range of six categories – from "very low" to "very stiff." The current qualification of deflection is not load specific.

The characteristic length represents the characteristic of the track system and it includes single rail bending stiffness as well as the elasticity of the foundation. Thus, it reflects track condition. It is a significant parameter in several track analysis equations. As such, the characteristic length is qualified first—because it is used as a base work for the qualification of other track foundation parameters—through a literature review and analysis.

A field engineer can measure some track parameters in the field easily, such as track stiffness and deflection. The qualification would help these engineers evaluate the track foundation condition and track performance to make maintenance decisions. Track stiffness is a significant parameter from the aspect of designing, construction and maintenance of the track. This parameter represents the basis for calculating stresses in track elements. The field measurement of the track stiffness is easier and quicker than that of the mean track stiffness or the track modulus. With the knowledge of track stiffness, the track modulus may be determined without resorting to the elaborate field procedure [1]. Among all parameters used to describe the

*Corresponding author
Email: nazmul.hasan@snclavalin.com

[DOI: 10.22068/IJRARE.6.2.13]

elastic behavior of the track, the advantage of the track stiffness is that the deformation behavior can be expressed independently of the supporting area of various layers [3]. Track stiffness is a promising field measurement of track's structural condition under vertical loading; it helps determine the cause of certain structural problems [1]. The stiffness of the track itself hardly changes under operational load [3]. Thus, it is worthy to qualify the track stiffness.

Vertical track deflection is the best indicator of track strength, life, and quality [4]. Track deflection is an indicator of track performance. The rail sags and acts as a load distributor due to the elasticity of the railroad. If the deflection is too low (rail road is significantly stiff/rigid), the rail loses its load-distributing effect, resulting in a high load on an individual tie, which causes tie settlement, especially with the sub-soil of low bearing capacity [3]. Thus, the high stiffness of a track has a deteriorating effect on the stability of its geometry. Alternatively, high deflection leads to ballast deterioration through abrasion and powdering of the particles, the formation of water and ballast pockets, muddy and permanent deformation, and increased train resistance [4]. High deflections would cause intensive wear on all track components with accelerated wear of joints, fittings, turnouts, and loose bolts [2]. Thus, it is worthy to qualify the track deflection. Track modulus represents the vertical response of the entire track system below the base of the rail including crossties, fasteners, tie pads, ballast and subgrade (AREMA 2018) [5]. It is also highly important as a measure of track stability and track life [4]. Thus, it is an indicator of the quality and safety of railroad. The qualifications done by Esveld [1] and Ahlf [2] are considered to present a qualification over six categories.

At times, the literature mentions some track parameter values without any qualification. The qualification work would help the readers perceive the status of those parameters, as well as help engineers judge or infer the desirable requirements of some track materials. For example, the modulus of the ballast mat can be inferred from the qualification of foundation modulus because use of ballast mat on a concrete invert reduces the ballast height, and the fastener stiffness can be inferred from the qualification of track or ballast bed stiffness as fasteners are substituted for ballast in a direct fixation (DF) track. The qualification would help design engineers assume or compute more accurate track parameter values in a consistent manner during the design phase.

The qualification is validated against previous studies and information from the current literature.

2. Literature Review

A few studies characterize the conditions of track foundation parameters. For example, Ahlf [2] characterizes the track modulus, which is presented in Table 1.

Table 1. Qualification of track modulus [2]

Type of tie	Track modulus (lbs./in./in.)	Qualification
Wood tie	500	Very low
Wood tie	1,000	Poor
Wood tie	2,000	Fair
Wood tie	3,000	Good
Wood tie	5,000	Very stiff
Concrete tie	7,000–8,000	Very stiff

Ahlf [2] characterizes one foundation parameter under five categories: very low, poor, fair, good, and very stiff. Crossties significantly influence the track modulus through their vertical compressibility in the rail seat region; bending stiffness; tie spacing, length, and bearing area; and fastening system rigidity (toe load) (AREMA 2018) [5]. Ahlf [2] assigns to the track modulus of the wood tie track several different categories (very low to very stiff), while that of the concrete tie track receives only one category (very stiff). Meanwhile, Esveld [1] characterizes four track foundation parameters—foundation modulus (ballast coefficient), spring constant, foundation coefficient (track modulus), and characteristic length—without mentioning the tie type. As shown in Table 2, the parameters are characterized under only two categories: good and poor.

Table 2. Qualification of the condition of track foundation [1]

Quality of support	Unit	Poor	Good
Characteristic length, L	[m]	1.30	0.7
Foundation coefficient, k	[N/mm/mm]	9	90
Spring constant, kd	[N/mm]	5.5	55
Foundation modulus, C	[N/mm^3]	0.02	0.20

Esveld [1] seems to put extreme values of “good” and “poor” on track foundation parameters. Thus, values exceeding “good” values may be qualified as “very stiff” and “poor” values as “very low.” The spring constant in Table 2 is the mean spring constant (mean track stiffness), not track stiffness (total spring rate, or support stiffness). In Ahlf’s [2] study, the “good” track modulus is six times that of the “very low” track modulus with two more categories in between (“poor” and “fair”), whereas in Esveld’s [1] study, the “good” track modulus is ten times that of the “poor” track modulus with no further categories in between. “Good” is qualified as 3000 lbs./in./in. (21 N/mm/mm) and 13,062 lbs./in./in. [90 N/mm/mm] for Ahlf [2] and Esveld [1], respectively. Ahlf [2] qualifies 5000 lbs./in./in. [34 N/mm/mm] as “very stiff’. Esveld [1] explicitly did not qualify any value as “very stiff” but did qualify 13,062 lbs. /in. /in. [90 N/mm/mm] as “good’, which seems to be the extreme point of “good” qualification. Hence, any value over 13,062 lbs./in./in. [90 N/mm/mm] may be qualified as “very stiff”.

2.1. Qualification of Track Parameters

All track foundation parameters (track modulus, track stiffness, etc.) and track deflection are strongly related to the characteristic length. For example, the track modulus relates inversely to the characteristic length of the fourth power. The deflection is directly proportional to a third of the characteristic length’s power. Therefore, the characteristic length is qualified first and the qualifications of the other parameters are based on it.

2.2. The Characteristic Length

A characteristic length reflects the track condition efficiently as it includes both single rail bending stiffness and elasticity of foundation modulus. It is expressed by Esveld [1] as under:

$$L = \sqrt[4]{\frac{4EI}{k}}, \tag{1}$$

in which

L: characteristic length of the track (in., mm),

k: track modulus (lbs. /in. /in., N/mm/mm),

EI: bending stiffness of rail (lbs.in.^{2}, N.mm^2).

Ahlf [2] characterizes the track modulus over a wide range of categories (Table 1). In Table 3, the characteristic length is computed in the fourth column for the 115 RE rail using data from Table 1. For 141 RE rail, the characteristic length would increase by 10%. Thus, the variation is not significant over rail sections.

In Table 2, Esveld [1] uses two end values, 0.7 and 1.3 m, to qualify “good” and “poor” characteristic length, respectively. Thus, a characteristic length shorter than 0.7 m may be qualified as “very stiff” and a characteristic length longer 1.3 m may be qualified as “very poor”. Average 0.7 m [28 in.] and 1.3 m [51 in.] (i.e. 1 m [39 in.]) may be qualified as “good’; Esveld’s [1] “good” may be considered “very good”. A deflection of 1 mm under an axle load of 20-t reflects a good ballasted track. This corresponds to a track stiffness or total spring constant of 50 kN/mm [285,506 lbs./in.] and a track modulus of 26 N/mm/mm [3755 lbs./in./in.]. The characteristic length comes out as 0.966 m [38 in].

Thus, a characteristic length of 1 m [39 in] qualifies as “good”, while significantly shorter characteristic lengths are labeled as “stiff”. Steenbergen and Esveld [6] assume a stiffness of 30X10^6 N/m per tie to account for a high degree of looseness. This corresponds to a total spring rate, k_{tot} of 15 kN/mm. This value reflects a bad track, which corresponds to a track modulus of 5 N/mm/mm [754 lbs./in/in]. The characteristic

Table 3. The characteristic length using data from Table 1 [2]

Type of tie	Track modulus (lbs./in./in.) [N/mm/mm]	Qualification	Characteristic length m [in.]
Wood tie	500 [3]	Very low	1.6 [63]
Wood tie	1000 [7]	Poor	1.35 [53]
Wood tie	2000 [14]	Fair	1.13 [45]
Wood tie	3000 [21]	Good	1.02 [40]
Wood tie	5000 [34]	Very stiff	0.9 [35]
Concrete tie	7000–8000 [48–55]	Very stiff	0.83~0.80 [33~31]

length comes out as 1.4 m [57 in.]. Thus, a characteristic length of 1.4 m [55 in.] qualifies as "poor" and <1.4 m [57 in.] qualifies as "very poor", as it would increase the rail stress over 40% compared to a 1 m [39 in.] characteristic length, which is a typically the value of a good ballasted track. The American Railway Engineering and Maintenance-of-Way Association (AREMA 2018) [5] suggests a value of 1000 lbs./in/in (cf. poor in Table 1) for a newly tamped wood-tie track (cf.754, 1000).

The characteristic length's qualification, based on the previous qualification works, literature review, and analysis, is presented in Table 4.

Henceforth, the qualification of the characteristic length will be the basis for the qualification of other track parameters used to describe the elasticity of the track and deflection.

2.3. Track Modulus

Track modulus is an indicator of the quality and safety of railroad. Track modulus can be defined as the supporting force per unit length of rail per unit deflection. The track modulus is expressed from the Equation (1) in terms of characteristic length to facilitate as follows:

$$k = \frac{4EI}{L^4}. \tag{2}$$

Esveld [1] qualifies a track modulus of 13,000 lbs./in./in. [90 N/mm/mm] and 1,300 lbs./in./in. [9 N/mm/mm] as "good" and "poor," respectively.

Table 4. Qualification of the characteristic length

Characteristic length m [in.]	Qualification
<0.7 [<28]	Very stiff
0.9 [35]	Stiff
1.0 [39]	Good
1.4 [55]	Poor
>1.4 [>55]	Very low

In fact, Esveld [1] puts two extreme values to be "good" and "poor". Thus, a track modulus above 90 N/mm/mm may be qualified as "very stiff" and below 9 N/mm/mm, "very poor". A track modulus value of 2000–2500 lbs./in./in. represents a good conventional track. The value can rise to 7000–8000 lbs./in./in. for tracks on concrete ties [4]. Tie type is not mentioned in the qualification. A track modulus of 5000 lbs./in./in. or above qualifies as 'very good/stiff'. Most of the track modulus in this category would be with a concrete tie track. Most of the track modulus in the "good" type would be with wood tie tracks.

Equation (1) with the above narration and previous studies is used to qualify the track modulus with RE115 and RE 136 rail in Table 5.

This qualification would help engineers to have an idea about a track with a given track modulus.

[DOI: 10.22068/IJRARE.6.2.13]

Table 5. Qualification of the track modulus

Track modulus N/mm/mm [lbs./in./in.]	Qualification
>94 [>13,600]	Very stiff
34–49 [5,000–7,180]	Stiff/very good
23–32 [3,275–4,700]	Good
6–8 [850–1,200]	Poor/soft
<6 [<850]	Very low/very soft

For example, the track modulus with the track structure described can be expected to be in the following range (TCRP 2012): 17–24 N/mm/mm [2500–3500 lbs./in./in.]; well-compacted sub-ballast and heavy stone ballast with a depth of 558 mm [22 in.], and wood ties spaced at 558 mm [22 in.]. This track is closer to a good track than a poor track, as its foundation condition is three times better than a poor or soft track.

2.4. Mean Track Stiffness

The mean track stiffness may be expressed as follows [1]:

$$k_d = ka, \tag{3}$$

in which

k_d: mean track modulus (lbs. /in., N/mm),

k : track modulus (lbs./in/in, N/mm/mm),

a : tie spacing (in., mm).

In Table 6, the mean track stiffness is qualified by multiplying the values in Table 5 by a tie spacing of 24 in. [610 mm] (assumed). The spring constants of 55 N/mm and 5.5 N/mm are qualified as “good” and “poor”, respectively, to characterize the foundation’s condition ([2], re: Table 2). Esveld [2] puts two end values as “good” and “poor”. Thus, mean track stiffness above 55 N/mm may be qualified as “very stiff”.

2.5. Track Stiffness

The importance and advantages of using the track stiffness is discussed in the introduction. Very stiff track means very low track elasticity, which causes high ballast pressure that can lead to possible ballast destruction and an unstable track position. Alternatively, poor track means very high track elasticity; the rail sag will be too high and may cause high stress in relation to its fatigue strength.

Table 6. Qualification of the mean track stiffness

Mean track stiffness kN/mm [lbs./in.]	Qualification
>57.34 [>326,400]	Very stiff
20.74–29.89 [120,000–172,320]	Stiff
14–19.52 [78,600–112,800]	Good
0.006–0.008 [20,400–28,800]	Poor/soft
<0.006 [<20,4000]	Very low/very soft

Note: Tie spacing = 24 in. [610 mm].

From the qualification, the optimum track stiffness may be assessed. Thus, the track stiffness deserves qualification, though it is unknown if any study has done so. The track stiffness may be expressed in terms of characteristic length [1] as:

$$k_{tot} = \frac{8EI}{L} \tag{4}$$

in which:

k_{tot} : track stiffness (lbs./in., N/mm).

The qualification of the characteristic length is based on previous studies on a rational basis; hence, the qualification done is unlikely to be irrational. As track stiffness has not been qualified in previous studies, however, the qualification work will be judged against some information from the current literature, given below: Simulation calculations give the general result that the optimum track stiffness is within the range of 50–100 kN/mm [3].

The formation of the high-speed ballast tracks of the Germany railway company Deutsche Bahn (DB) has been highly compacted without upper limit; it has the properties of a concrete track formation. Measurement showed deflection values of only 0.3–0.45 mm [3]. The track is expected to be very stiff. Assuming an axle load of 200 kN, and 50% load on tie under the axle, the track stiffness comes out as 111–

167 kN/mm, which falls under the "very stiff" category as per qualification in Table 7.

Table 7. Qualification of the track stiffness

Track stiffness, kN/mm [lbs./in.]	Qualification
>132 [>750,000]	Very stiff
62–89[366,647–527,300]	Stiff
45–65 [265,000–380,000]	Good
16–24[94,000–135,000]	Poor/soft
<16 [<94,000]	Very low/very soft

White spots with ground ballast occurred in several places because of the high ballast pressure. The hard bedding also led to unpleasant noises in the Intercity-Express (ICE). The situation improved only after the insertion of soft rail pads, which led to a settlement of 0.8 mm [3]. Thus, a very stiff track does not perform well and therefore is not desirable.

Steenbergen and Esveld [6] assumed a stiffness of $30X10^6$ N/m per tie to account for a high degree of looseness. This corresponds to a total spring rate (track stiffness), of 15 kN/mm, which is qualified as poor/soft in Table 7. The qualification work done seems to be acceptable. Inference of the fastener stiffness may be drawn from the qualification of the track stiffness. A very stiff track is not desirable. Usually, the stiffness of a direct fixation (DF) track is three times that of the fastener, so a fastener stiffness above 44 kN/mm (=132/3) is not desirable at all. Conversely, a fastener stiffness of 15–22 kN/mm (=45/3–65/3) should be acceptable. A fastener stiffness below 8 kN/mm (=24/3) would be too poor to use.

2.6. Ballast Bed Stiffness

Laboratory or in-situ tests and requirements on ballast bed stiffness are rare [1]. However, one can compute the ballast bed stiffness from the track stiffness. The tie on which the wheel is standing usually takes up 40% of the wheel load; both neighboring ties together take up 50% and both following ties together take up 10% [3]. Thus, the ballast bed stiffness would be 0.4 times the track stiffness. In Table 8, the values in Table 7 are multiplied by 0.4 to qualify ballast bed stiffness. In a DF track, ballast is replaced by the DF fastener. Obviously, the fastener stiffness shall be similar to that of the ballast bed. The popular stiffness range of standard fastener (TCRP 2012) is 15.8–24.5 kN/mm [90,000–140,000 lbs./in.], which almost matches the ballast bed stiffness under the "good" category in Table 8. In the DB standards for slab track, the vertical stiffness is 22.5 kN/mm [128,477 lbs. /in.] with a spacing 650 mm [26 in.] [1].

Table 8. Qualification of the ballast bed stiffness

Ballast bed stiffness, kN/mm [lbs./in.]	Qualification
>53 [>300,000]	Very stiff
25–35[140,000–200,000]	Stiff
18–26 [102,800–148,000]	Good
7–10 [37,600–54,000]	Poor/soft
<7 [<37,600]	Very low/very soft

2.7. Foundation Modulus (Coefficient of Ballast)

The stiffness of the ballasted track grid is described by the foundation modulus (coefficient of ballast, ballast bed modulus). For road construction, this parameter is measured by the plate load-bearing test according to the following correlation:

$$C = \frac{p}{y} \tag{5}$$

in which

C: coefficient of ballast (lbs./in.^{3}, N/mm^3),

p: surface pressure under the loaded plate (psi, N/mm2), and y: settlement of the loaded plate (in., mm).

The foundation modulus is calculated by linearizing the curve, which is measured under increasing load. The railroad shows many deviations from the round plate used in the plate load-bearing test, such as pressure distribution over the ties in strips and cavities under the ties

[DOI: 10.22068/IJRARE.6.2.13]

[3]. The foundation modulus is the ratio of surface pressure and deflection (N/mm^3).

The deflection of the tie depends on the tie spacing, the resistance of rail to bending, the ballast bed and sub-soil properties, and the spring constant of the rail fastenings. For the purpose of qualification, the foundation modulus is expressed in terms of the track modulus as follows:

$$C_{tb} = \frac{k_d}{A_{tb}} = \frac{k.a}{A_{tb}} \tag{6}$$

in which

C_{tb}: foundation modulus at contact area between tie and ballast (lbs./in.^{3}, N/mm^3),

k: track modulus (lbs. /in./in., N/mm/mm),

a: tie spacing (in., mm), and A_{tb}: contact area between tie and ballast bed for half time (in.^{2}, mm^2).

Assuming a tie length of 2,515 mm, a tie width of 254 mm at the bottom, and a tie spacing of 610 mm, the foundation modulus are expressed as:

$$C_{tb} = \frac{k.a}{A_{tb}} = \frac{610k}{(0.66*2515*254)*0.5} = 0.003k \tag{7}$$

Equation (6) is used to qualify the foundation modulus in Table 9.

Table 9. Qualification of the foundation modulus

Foundation modulus N/mm^3 [lbs./in.^{3}]	Qualification
>0.28 [>1036]	Very stiff
0.10–0.15 [381–547]	Stiff
0.07-0.1 [250–358]	Good
0.018–0.024 [65–91]	Poor/soft
<0.018 [<65]	Very low/very soft

A concrete tie of length 2,590 mm, a bottom width of 300 mm, and a tie spacing of 750 mm would produce the same values given in Table 9. The disadvantage of this type of calculation is that it depends on the area of the tie support—a value that is known only approximately. Some professionals suggest using two-thirds of the foot print area of a tie as the support area, while some suggest using half.

The following literature review validates the qualification done in Table 9.

Esveld [1] qualifies a foundation modulus of 0.02 N/mm^3 [73 lbs./in.^{3}] as "poor" and one of 0.2 N/mm^3 [736 lbs./in.^{3}] as "good". In fact, Esveld [1] puts two end values under "good" and "poor". Thus, a foundation modulus above 0.2 N/mm^3 [736 lbs./in.^{3}] may be qualified as "very stiff". The high ballast coefficient (0.4 N/mm^3 [1472 lbs./in.^{3}]) of classic railroads on high-speed lines is extremely unfavorable. It reduces rail stress but has a negative effect on the stability of the track geometry [3].

The foundation modulus is within a very narrow range of 0.05–0.1 N/mm^3 [184 -368 lbs./in.^{3}] [3].

Typical coefficients of ballast are:

- Very poor subsoil (bogland, fine grained sand) 0.02 N/mm^3 [73 lbs./in.^{3}],
- Poor subsoil (cohesive soft to stiff clay) 0.05 N/mm^3 [182 lbs./in.^{3}],
- Good subsoil (coarse sand/gravel) 0.1 N/mm^3 [368 lbs./in.^{3}], and
- Very good sub-soil (gravel, rock) 0.15N/mm^3 [522lbs./in.^{3}] (Lichtberger 2005).

One option to reduce vibration is the insertion of a resilient ballast mat between the bottom of the ballast and the tunnel invert. The ballast mat can save extra cost, weight, and height associated with extra ballast to achieve the same noise reduction target [1]. Thus, one can infer the requirement of the ballast mat's foundation modulus from the qualification presented in Table 9. It is sensible to use a soft ballast mat to achieve vibration attenuation. However, while a foundation modulus between 0.018 and 0.024 N/mm^3 [65–91 lbs./in.^{3}] might seem to be the right choice, too soft a mat would increase the track deflection. From the above review, it seems that the foundation modulus of the ballast mat should be below 0.1 N/mm^3 [368 lbs./in.^{3}] for the intended purpose of vibration isolation. In fact, typical ballast mat values are within the range of 0.025–0.03 N/mm^3 [92–110 lbs./in.^{3}] [1].

3. Qualification of the Track Deflection

Vertical track deflection is the best indicator of track strength, life, and quality [4]. Track deflection is an important parameter for track design and maintenance, as well as an important

[DOI: 10.22068/IJRARE.6.2.13]

indicator of track performance. The track deflection is defined with a reference to the characteristic length and is formulated and qualified as the minimum, optimum, and limiting deflection. Thus, it is worthwhile to qualify track deflection for guidance. As the characteristic length was already qualified in Table 3, it is necessary to relate the deflection with the characteristic length to qualify the former. The relationship is derived as follows:

The deflection under the wheel load in [1] is given by:

$$w = \frac{Q}{2kL}, \tag{8}$$

in which

w: deflection under the wheel (in., mm),

Q: wheel load (lbs., N),

k: track modulus (lbs./in./in., N/mm/mm), and

L: characteristic length of the track (in., mm).

Incorporating Equation (1) in Equation (8):

$$w = \frac{QL^3}{8EI}. \tag{9}$$

Equation (9) is used to qualify track deflection considering the track condition, wheel load and single rail bending stiffness. The deflection is qualified into three categories: the minimum deflection, the optimum deflection, and the limiting deflection considering track condition, wheel load, and single rail bending stiffness.

3.1. Minimum Deflection

The railroad is defined as significantly rigid/stiff if the deflection corresponds to a characteristic length of <0.7 m [28 in.]. Some values of deflection are computed with different axle loads:

Under a 10-t axle load (light rail transit, (LRT)), a deflection <1.14 mm [0.045 in.] for 115RE would represent a significantly rigid track.

Under a 33-t axle load (heavy haul (HH)), a deflection <0.8 mm [0.03 in.] for 136 RE would represent a significantly rigid track.

The track formation of DB's high-speed ballast tracks has been highly compacted without upper limit; it has the properties of a concrete track formation. Measurement showed deflection values of only 0.3–0.45 mm. White spots with ground ballast occurred in several places because of the high ballast pressure. The hard bedding also led to unpleasant noises in the ICE. The situation improved only after the insertion of soft rail pads, which led to a settlement of 0.8 mm [3]. Therefore, the track would be significantly rigid if the deflection is <1 mm [0.04 in.]. A significantly rigid track is not desirable, so the target deflection value should be above 1 mm [0.04 in.].

4. Optimum Deflection

The deflection corresponding to a characteristic length of 1 m [39 in.] is qualified as an "optimum" deflection. The design should target an optimum deflection value. Some optimum values of deflection are computed with different axle loads and compared with the values available in the literature:

For a 10-t axle load (LRT), a deflection of 1.2 mm [0.05 in.] for 115RE rail comes out as optimum.

For a 15-t axle load (heavy rail transit (HRT)), a deflection of 1.6 mm [0.064 in.] for 115RE rail comes out as optimum.

For a 20-t axle load, a deflection of 2.2 mm [0.085 in.] for 115RE rail and 1.5 mm [0.06 in.] for 136 RE rail come out as optimum. Simulation calculations give the general result that the optimum track stiffness is within the range of 50–100 kN/mm. The optimum range of settlement stated is 1.2–1.5 mm [3]. The Société Nationale des Chemins de Fer uses 1.5 mm settlement values under 20 t axle loads as target values [3].

For a 25-t axle load (passengers car (PC)), a deflection of 2.7 mm [0.11 in.] for 115RE rail and 1.9 mm [0.075 in.] for 136 RE rail come out as optimum.

For a 27.5-t axle load (UK and select European limit PC), a deflection of 3.0 mm [0.12 in.] for 115RE rail and 2.1 mm [0.081 in.] for 136 RE rail come out as optimum. Under a 27.5-t axle load, the quasi-static track deflections should be around 3 mm [0.12 in.] [1].

For a 33-t axle load (North American free interchange limit), a deflection of 3.6 mm [0.14 in.] for 115RE rail and 2.5 mm [0.097 in.] for 136 RE rail come out as optimum.

[DOI: 10.22068/IJRARE.6.2.13]

The normal maximum desirable deflection for a heavy track is in the range of 0.125 in. [3 mm]~0.2 in. [5 mm] to give a requisite combination of flexibility and stiffness [4]. Therefore, the deflection corresponding to 1 m [39.36 in.] characteristic length may be accepted as an optimum deflection value and may be used as a design input. The optimum deflection may be labeled as 'desirable' deflection too.

4.1. Limiting Deflection

The deflection corresponding to a characteristic length of 1.4 m [55 in.] qualifies as a "limiting" deflection. Some optimum deflection values are computed with different axle loads and compared with the values available in the literature:

For a 10-t axle load (LRT), a deflection of 3 mm [0.12 in.] comes out as limiting deflection for 115RE rail.

For a 15-t axle load (HRT), a deflection of 4.5 mm [0.18 in.] for 115RE rail and 3.1 mm [0.13 in.] for the 136 RE rail come out as limiting deflections.

For a 20-t axle load (PC or freight wagon (FW)), a deflection of 6.0 mm [0.24 in.] for 115RE rail and 4.23 mm [0.167 in.] for the 136 RE rail come out as limiting deflections.

For a 25-t axle load (HH), a deflection of 7.6 mm [0.3 in.] for 115RE rail and 5.3 mm [0.21 in.] for the 136 RE rail come out as limiting deflections.

For a 27.5-t axle load (HH), a deflection of 8.3 mm [0.33 in.] for 115RE rail and 5.8 mm [0.23 in.] for the 136 RE rail come out as limiting deflections. Under a 25-t axle load, the quasi-static track deflections should be around 3 mm [0.12 in.] with a limiting deflection of 4–5 m [0.16–0.20 in.] under a static load. Higher values would cause intensive wear and fatigue of track components and a quick deterioration of the track geometry [1]; the values seem too stringent.

For a 33-t axle load (HH), a deflection of 10 mm [0.4 in.] for 115RE rail and 7 mm [0.28 in.] for the 136 RE rail come out as limiting deflections. If the deflection is over 10 mm [0.4 in.], the track will deteriorate quickly [4].

According to Talbot, no main line track should have deflections that exceed 0.25 in. [6 mm]; therefore, a high level of maintenance is required [4].

The deflection corresponding to a characteristic length of 1.4 m [55 in.] may be treated as a limiting value for the purpose of track maintenance. Track maintenance needs to be initiated at the deflection above the limiting value. Increasing the track support modulus may be easier, less expensive, and more lasting than increasing rail weight alone [4] to control track deflection. The limiting deflection may be labeled as 'undesirable' deflection too. Table 10 qualifies some deflection values.

Table 10. Qualification of track deflection

Axle load, tons	Status	Rail section	Optimum deflection, mm [in.]	Limiting deflection mm [in]	Room for track maintenance
10	LRT	115 RE	1.2 [0.05]	3.0 [0.12]	1.8 [0.07]
15	HRT	115 RE	1.6 [0.06]	4.5 [0.18]	2.9 [0.11]
20	PC/FW	115 RE	2.2 [0.09]	6.0 [0.24]	3.7 [0.15]
25	HH	136 RE	1.9 [0.07]	5.3 [0.21]	3.3 [0.13]
27.5	HH	136 RE	2.1 [0.08]	5.8 [0.23]	3.7 [0.15]
33	HH	136 RE	2.5 [0.10]	7.0 [0.28]	4.4 [0.18]

4.2. Current and Proposed Qualification of Deflection

Most of the deflections in the ballasted track result from deformation of the ballast and sub-grade. To minimize deflections, AREMA suggests that total deflections for ballasted tracks are kept under a 6 mm [0.25 in.] limit (TCRP 2012) [7]. The American Railway Engineering Association (AREA) suggests a maximum rail deflection of 6 mm [0.25 in.] for a stable track [4]. This implies that AREMA recommends a service limit value of 6 mm [0.25 in.]. A deflection of 6 mm [0.25 in.] is the recommended basis for track design by AREMA [2]. The author is unsure if 6 mm [0.25 in.] is the design value or service limit value; it seems to be design value as AREMA labels a deflection of 18 mm [0.75 in.] as "high" deflection [2] which may be considered as a "limiting" value. Table 11 shows qualification of deflection values by

[DOI: 10.22068/IJRARE.6.2.13]

AREMA and this paper for 25, 27.5 and 33 tons axle loads from Table 10.

Table 11. Comparative study of qualification of deflection

AREMA [2]	Author (Table 10)
"low"	**"Minimum"**
1.25 mm [0.05 in.]	1.0 mm [0.04 in.]
"Design"	**"Optimum"**
6.0 mm [0.25 in.]	1.9 mm [0.07 in.]
6.0 mm [0.25 in.]	2.1 mm [0.08 in.]
6.0 mm [0.25 in.]	2.5 mm [0.10 in.]
"High"	**"Limiting"**
19 mm [0.75 in.]	5.3 mm [0.21 in.]
19 mm [0.75 in.]	5.8 mm [0.23 in.]
19 mm [0.75 in.]	7.0 mm [0.28 in.]

Track will deteriorate quickly after a deflection of 10 mm [0.4 in.] if it is not maintained well [2]. All welds require meeting or exceeding a deflection of 19 mm [0.75 in.] for high strength grade steel under slow bend test (AREMA 2018). Thus, the deflection of 0.75 in. labeled as "high" seems unreasonably high for a revenue track in the context of the aforementioned review and analysis under "Limiting Deflection". Thus, AREMA provides a large room of 13 mm [0.50 in.] for track maintenance which is not reasonable; large room means less frequent maintenance. The qualification does not seem to be based on a theoretical basis. The AREMA value is meant for heavy haul and it is not specific to different axle loads (e.g., 30, 33, 36 tons). AREMA may review its design value and high or limiting value. The proposed qualification considers track condition, wheel load, and single rail bending stiffness and hence, applicable for light rail to passenger car to heavy haul. Thus, the proposed qualification of deflection has advantages over the current one for design and maintenance.

5. Conclusions

The qualification of track foundation parameters was done in a consistent and systematic manner over five categories. Track deflection was defined and formulated with reference to the characteristic length, wheel load, and single rail bending stiffness and qualified as the minimum, optimum, and limiting deflection. The optimum and limiting deflection values may be seen as desirable and undesirable values. Design engineers may compute and use the optimum deflection value as an input for track design, as well as compute the minimum deflection value to avoid the consequences of a very stiff track. The field engineers may compute the limiting deflection value and use it as a maximum service limit for maintenance purposes beyond which maintenance to be initiated.

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[DOI: 10.22068/IJRARE.6.2.13]