Thrshold Radius for Restraining Rail

Nazmul Hasan*[1]

[1]Senior Track Engr, SNC-Lavalin Inc., Rail and Transit Division,500-745 Thurlow St, Vancouver, British Columbia,Canada. E-mail: nazmul.hasan@snclavalin.com

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Abstract:
This paper deals with the threshold radius that warrants the use of single restraining rail for transit and railroads. Different railways use different threshold radius from 91m to 365m to provide restraining rail. These threshold figures are probably experience driven choices. The need for restraining rail may be related to a so-called derailment alarm coefficient of 1.2 sustained over 2m length (According to UIC leaflet 518 a safe maximum value of Y/Q ratio of 0.8 over the length of 2m is recommended) but it needs a wheel/rail interaction software to estimate derailment coefficient. The author is not aware if it has been done for this purpose. A quick and simple assessment method is developed here. A restraining rail reduces the angle of attack (AOA) to reduce the likelihood of wheel climb derailment and to reduce wear provided it is installed close enough to the inner (lower) rail to prevent flange contact with the outer (higher) running rail. Angle of attack depends on wheel base, curve radius and free play. The threshold radius is formulated by considering these three parameters. An assumption made to derive the equation is that twice the AOA on tangent track due to free play is a critical AOA on circular curves to warrant a restraining rail. The assumption is validated by comparing the threshold radius obtained by the formula with real world examples. It is also shown that curvature resistance of the threshold radius is too high to warrant a restraining rail. If the radius of the curve is less than threshold radius then the restraining rail needs to be extended into the spiral up to a point where the radius matches with the threshold radius. A formula substantially based on current practice is given to determine the extension of single restraining rail into the spiral subject to a minimum requirement.

Keywords: *track Geometry, Track design,Y/Q ratio,wheel/rail interaction, threshold radius*

* Corresponding Author

1. Introduction

The threshold radius for employing guarded track varies between light rail transit agencies. Some transit agencies guard any track curves with radii less than 365 m while others do not guard track in curves with radii larger than 91m (TCRP, 2000). This seems to be an experience driven choice. The need for guard rail may be related to a so-called derailment alarm coefficient of 1.2 sustained over the length of 2m (According to UIC leaflet 518 a safe maximum value of Y/Q ratio (L/V ratio in N. America, Q/P ratio in Japan) of 0.8 over the length of 2m is recommended) but it needs expensive track/vehicle interaction software to estimate exact derailment coefficient by dynamic analysis. The author is not aware if any-one has done this to determine threshold radius.

A quick and simple assessment method is developed here. A restraining rail reduces angle of (flange) attack to prevent wheel climb derailment in addition to reduce gage wear of the outer rail by establishing shared contact between two rails and to reduce chance of rail roll-over by reducing Y/Q ratio on the head of the outer rail provided it is installed close enough to the inner rail to prevent flange contact with the outer running rail. (Ahlf, 2003). Research revealed that a friction moderator applied at wheel/rail interface reduced lateral load (Y) significantly but has no significant effect on the angle of attack Fukagai (2008). Angle of attack mainly depends on wheel base, radius of curve and free play. An equation based on these three parameters has been developed to determine the threshold radius that warrants restraining rail. In fact restraining rail functions more to reduce the propensity for derailment than it does as an absolute necessity to avoid derailment. This refers to a single restraining rail on low side.

2. Derivation of threshold radius

As per UIC Code (UIC 703, 2003) angle of attack (AOA), α is given by

$$\alpha = \frac{B}{2R} + \frac{f_p}{B}$$

in which

$$f_p = G - (a + 2t)$$

For tangent track, $\alpha = \frac{f_p}{B}$ because $R = \infty$.

On tangent track restraining rail is not required. Therefore it can be inferred that for the same value of AOA on the curve restraining rail will not be required to reduce wear of rail/wheel and to prevent derailment. Clearly curves with radius equal to or greater than Klingel radius do not need any restraining rail. In practice a curve with a radius less than the Klingel radius up to a lower limit does not warrant restraining rail. An assumption is made to find out the lower bound radius below which a restraining rail may be required after which the assumption is validated.

Assumption: Critical AOA to warrant a restraining rail for a circular curve is equal to twice the angle of attack on the tangent track. The assumption helps to bring wheel base, an important component, into the picture.

Let R_C be the critical radius that warrants a restraining rail. Angle of attack for this curve would be

$$\alpha = \frac{B}{2R_C} + \frac{f_p}{B}$$

As per assumption,

$$\frac{B}{2R_C} + \frac{f_p}{B} = 2\frac{f_p}{B} \quad . \tag{1}$$

$$\frac{B}{2R_C} = \frac{f_p}{B} \, .$$

In the derivation free play on the tangent and the curved track is assumed to be the same. Keeping the
unit of wheel base in m, and radius in m, and making the unit of free play in mm,

$$R_C = \frac{B^2}{2f_p(m)} = 500\frac{B^2}{f_p(\boldsymbol{m} \quad)} \tag{2}$$

During service life high rail gauge face wear on the curve is more than the gauge face wear on the tangent track. Moreover sometimes gauge on a sharp curve is widened. Thus lateral play on the curve will be more than that on the tangent track due to increased lateral wear and gauge widening. This would increase the angle of attack and would increase the wear of rail and propensity of derailment. This would increase the critical radius. The statement may seem
to be contrary to Eq.(2). In fact it is not because the derivation of Eq.(2) assumes equal free play, f_p on tangent and curved track. It is explained below:

Eq.(1) is re-written with different free play as under:

$$\frac{B}{2R_C} + \frac{f_p}{B} = 2\frac{f_p}{B}$$

in which

f_{p} = free play on curve in mm,

f_{p} = free play on tangent track in mm.

$$\frac{B}{2R_C} = 2\frac{f_p}{B} - \frac{f_p}{B} = \frac{1}{B}\left(2f_p - f_p\right)$$

$$R_C = \frac{B^2}{2\left(2f_p - f_p\right)}$$

The deduction of Eq.(2) is based on the assumption

$f_{p} = f_p = f_p$.

Gauge widening on curve and/or higher wear on gauge face on curve than that on the tangent track would lead to $f_{p} > f_p$ and $f_{p} < f_p$.

These conditions would make $2f_{p} - f_p = f_p - \left(f_p - f_p\right) < f_p$ that would increase the critical radius. Thus a factor of enhancement of 1.3 is suggested and the threshold radius is given by

$$R_{T} = 1.3 * R_C = 650\frac{B^2}{f_p} \qquad (3)$$

The threshold radius, R_T is directly proportional to square of the wheel base, B. Thus the wheel base has significant influence over threshold radius, R_{T}.

3. Validation

The assumption helps to bring the wheel base into picture. The assumption is validated from two different points of view.

(a) Comparison of computed and real life threshold radii.

The threshold radii are calculated in Table 1.

Table 1: Threshold radii for typical values of wheel bases

f_p (mm)	B (m)	E.F	R_C (m)	R_{TS} (m)
18	**1.8**	1.3	90	**117**
18	2	1.3	111	144
18	**2.2**	1.3	134	**175**
18	2.4	1.3	160	208
18	2.6	1.3	188	244
18	2.8	1.3	218	283
18	3	1.3	250	325

It can be seen from the table that for typical values of wheel base from 1.8m ~ 3.0m for a conventional train, the threshold radii comes out to be 120m ~ 325m. For most LRT vehicles, wheel base ranges from 1.8m to 2.2 m (TCRP,2000). Thus for LRT the threshold radii should be in the range of 117m ~ 175 m. For high speed trains, the wheel base is longer for stability e.g. TGV uses a wheelbase of 3m, Shinkansen, 2.5m. On high speed track, restraining rail is not required for shallow radius.

The threshold radius for employing restraining rail varies between light rail transit agencies. Some guard any track curve with radii less than 365 m while others do not guard track in curves with radii larger than 91m (TCRP, 2000). Some examples (TCRP, 2007) are given in Table 2.

Table 2: Examples of restraining rail installation practices

Transit System	Practice
MBTA (Light Rail Line)	Restraining rail is installed on curves with a radius less than 1000 ft (=300m).
Newark City Subway (Light Rail Line)	Restraining rail is installed on curves with a radius less than 600 ft (=180m).
SEPTA (Heavy Rail Line)	Restraining rail is installed on curves with a radius less than 750 ft (=230m).
WMATA (Heavy Rail Line)	Restraining rail is installed on curves with a radius less than 775 ft (=235m).
CTA (Heavy Rail Line)	Restraining rail is installed on curves with a radius less than 500 ft (=150m).
NOTE: MBTA=Massachusetts Bay Transportation Authority.	
SEPTA=Southeastern Pennsylvania Transportation Authority.	
WMATA=Washington Metropolitan Area Transit Authority.	
CTA=Chicago Transit Authority.	

Due to non-availability of data, exact calculation of threshold radii for transit systems in Table 2 is not possible. Despite this, the threshold radii calculated in Table 1 seem to match with current practice as evident from examples in Table 2. Exact calculation of threshold radius for Canada Line and Calgary West LRT project is done and compared. On the Vancouver Canada line, where $B = 2.2m$, restraining rail was used for all curves with $R \leq$ 200m (computed value 175 m). In the Calgary LRT, where $B = 1.8m$, restraining rail was used for all curves with $R \leq$ 100m (computed value 117 m). The threshold radii computed in Table 1 represent super sharp (R<150m), very sharp (200>R≥150m), and sharp (400>R≥200m) curves. The Eq. (3) seems to suggest reasonable value for threshold radius with the fact that it does not at least suggest mild curve for even 3 m wheel base. In the next section, curve resistance is computed to check if a restraining rail is required to share the wear.

(b) Curvature resistance

Curvature is the main source of flanging force. Three curve resistance formulae are discussed below:

The curvature resistance of 0.8 lb/ton/degree is an average standardised value which is applied to all vehicles (freight cars, passenger cars and locomotives) for the purpose of compensating grades in track curvature areas. Hay's book indicates that this value was settled on by AREA after much testing on various railroads in the early decades of the 1900s. The 0.8 lbs/ton/deg is generally applicable for rolling stock having conventional 3-pieces truck and no rail lubrication (Ahlf, 2003). Curvature resistance of 0.8 lbs/ton/degree is equivalent to $\frac{641}{R}$ kg/ton ((=0.8*1763.79/ (2.2*R)).

RÖckl suggests the following formula for curvature resistance, W_k (Lichtberger, 2005):

$$W_K(kg\ /ton) = \frac{k_1}{R - k_2} \quad \text{where} \quad R = \text{radius in meter}$$

Table 3: Factors for the calculation of curvature of resistance[2]

R (m)	k_1	k_2
> 300	650	55
≈ 300	530	35
< 200	500	30

Nederlandse Spoorwegen (English: Dutch Railway) (NS) uses the following formulae for curvature resistance, W_R expressed as N/KN or as %o (Esveld, 2001),

$$W_R = \frac{650}{R - 5} \text{ \%o for 400 m < R}$$

$$W_R = \frac{750}{R} \text{ \%o for 150 m < R <400m}$$

$$W_R = 5 \text{ \%o for 150 m > R}$$

These three formulae calculate resistance on the basis of curvature only. The current curvature resistance formulae do not relate resistance to wheel base, even though it is very important parameter which influences curve resistance. Would a particular curve offer the same resistance to trucks of different wheel bases? Evidently not, as one would expect less resistance for shorter wheel bases. Perhaps this is the reason to recommend systems that have numerous sharp curves to select vehicles with smaller trucks (TCRP, 2007). In Table 1 wheel base is taken into consideration to calculate threshold radii. Using the above three formulae, curvature resistance is calculated in the Table 4 for threshold radii calculated in Table 1.

Table 4: Curve resistance (%o)

R_{TS} (m)	641/R	NS	Röckl
117	5.5	5.0	5.7
144	4.5	5.0	4.4
175	3.7	4.3	3.4
208	3.1	3.6	2.8
244	2.6	3.1	2.5
283	2.3	2.7	2.1
325	2.0	2.3	1.7

It is for sure that no railway does guard a curve with 500m radius. The curve resistance corresponding to 500m radius is calculated and compared with the minimum curvature resistance from Table 4:

Table 5: Severity index of curvature resistance

641/R	NS	Röckl	Remarks
2.0	2.3	1.7	Minimum resistance from Table 3
1.23	1.46	1.46	Resistance corresponding to 500m radius
1.63 (=2.0/1.23)	1.57 (=2.3/1.46)	1.16 (=1.7/1.46)	Minimum Severity Index (MSI)

All three formulae suggest high curvature resistance for the computed threshold radii. The restraining rail is warranted to reduce the high (outer) rail wear by sharing.

4. Limitation

The minimum radius for a guarded curve is related to the dynamic wheel/rail interaction, which depends on geometry (e.g. wheel base, free play, track gauge, wheel/rail profile etc.), operation and maintenance (e.g. speed, cant deficiency, lubrication etc.), truck design, and vehicle configuration. Therefore, the assumption on which the formula is based has its limitations.

The assumption under Section 2 leads to the following condition that warrants a restraining rail:

$$\frac{B}{2R_C} = \frac{f_p}{B}.$$

This means that if the angle of attack due to curvature equals the angle of attack due to free play then the restraining rail is warranted. If for any reason/s, the angle of attack due to curvature is reduced to a lesser value then the angle of attack due to free play restraining rail will not be needed. The curvature resistance and angle of attack are strongly correlated as both are directly proportional to curvature. With the reduction of angle of attack curvature resistance should decrease for which sharing of wear by the restraining rail is not required.

The formula for the angle of attack is based on simple geometry; it does not consider many of the parameters that affect angle of attack e.g. truck design, vehicle configuration, suspension stiffness, rolling radii difference, centre plate lubrication etc. The steering is a complicated discussion. Differently designed trucks of the same wheel base on the same curve may show different angle of attack e.g. radially flexible steerable truck will give less angle of attack than rigid or less flexible truck. The Eurotram low floor motor truck has independent wheels mounted on radial arms. Each wheel is driven by its own small traction motor. A degree of steering is achieved by driving the motors on the outside rail of a curve at a higher speed compared to those on the inside. Advanced design of linkages between car body, side frame and axle set can guide the axle set to a radially steered position that enables the vehicle to enter into a curve with the minimum angle of attack which should be less than the computed angle of attack based on geometry. The Schindler "COBRA" low floor motor truck with radial steering wheelsets uses independent wheels which are physically steered. The steering is provided by a linkage from the articulation between the two body segments. The Schindler COBRA concept was developed with a view to reducing flange wear and curve squeal on the tightly curved routes in Zurich. In theory, a system whose vehicles are equipped with a self-steering radial truck design will not need guarded track (TCRP, 2000). Without restraining rail tramways can operate safely and without excessively wearing rails on radii far below the threshold radius calculated by the Eq. (3), with typical tram wheel bases of around 1.5m. Clearly, the assumption vis-a-vas the formula does not work for all types of vehicle and truck. For example, the CITADIS 301 can negotiate 25m radius without excessively wearing rail. A detailed study of truck/vehicle design and track/vehicle interaction software may be useful to explain the non-applicability of the formula and is beyond the scope of the work.

5. Extension of restraining rail

A clothoidal spiral is assumed. If the radius of curve, R is less than threshold radius, R_s it falls on the transition curve. Consequently restraining rail needs to be extended onto the transition curve by the following equation:

$$L_{ext} = L\left(1 - \frac{R}{R_s}\right).$$

The above equation suggests that no extension is required if $R = R_s$. Some railroads guard both trucks before they enter into the circular curve. So the above equation is restricted to a minimum of truck centre to centre plus wheel base.

6. Conclusion

The threshold radius for transit and rail road is given by

$$R_s = 650\frac{B^2}{f_p}$$

in which

B Wheel base in metres,

f_p standard free play in mm.

The extension of single restraining rail into the spiral is given by

$$L_{ext} = L\left(1 - \frac{R}{R_s}\right)$$

subject to a minimum of truck centre to centre plus wheel base.

7. Abbreviations

a Wheel back to back,

B Wheel base

$E.F$ Enhancement Factor

G	track gauge
f_p	standard free play
L	Transition length
L_b	Pivot pitch of truck (truck c/c)
L_{ext}	extension of single restraining rail inside spiral
$\frac{Y}{Q}$	lateral load/vertical load (in Europe)
R	Radius of curve
R_C	Base threshold radius
R_K	Klingel radius
R_{TS}	Threshold radius for single restraining rail
t	wheel flange thickness,
α	Angle of attack, AOA in rad

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