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Horizontal Curve Design of Railway Tracks Incorporating Safety Criteria

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In this study, a new approach for the evaluation of horizontal curve design in railway tracks integrating safety criteria is proposed. A vehicle-track interaction model is developed in ADAMS/Rail engineering software. Simulation of dynamic vehicle response from derailment point of view is followed. Using this model, sensitivity analyses are made on the main geometry parameters of horizontal curves, including radius, super-elevation and transition length, considering different speed. Consequently, the influences of each parameter are investigated on governing derailment criteria i.e. Overturning, Nadal and Prud'homme indexes. The results form the basis for further practical charts by which, both the geometry design and safety evaluation of railway horizontal curves can be determined. A practical use of the new approach is finally presented to indicate its performance and applicability.

1. Introduction

Tangent sections of a rail track in need to be connected in a manner that steers the trains safely, ensuring that the passengers are comfortable and the cars and track perform well together [1]. To meet these expectations, significant emphasis in geometry design codes is considered on horizontal curve parameters especially for high-speed trains. The current design approaches for railway horizontal curves are mainly used to calculate the amounts of each geometrical parameter considering the region topography, operational condition as well as design speed within the allowable limits. After selecting the super-elevation and the design speed, other parameters such as curve radius and transition length can be determined [2]. Therefore, the safety control is conducted with the minimum radius select as well as transition curve length. However, safety, from an analytical point of view, can also be assessed through the simulation of dynamic vehicle responses via vehicle-track interaction analyses [3]. Evaluation criterion of the alignment geometry in terms of safety is derailment. Derailment is based on interaction forces caused by the traveling vehicles and cannot be obtained by the usual geometry design approaches [4]. Hence, the necessity of developing a new method for complementary evaluation of horizontal curve design from safety outlook can be revealed.

This research is a response to the need and presents a new approach in which, the parallel evaluation of governing safety criteria as well as horizontal curve design parameters becomes possible. Moreover, the modification of design parameters to meet the safe traveling speed increment can be predictable. To begin, a literature survey on current design approaches of railway horizontal curves is made with the focus on rapid railways. Consequently, the

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general design scheme of horizontal curves, the effective parameters as well as their allowable variation ranges are concluded. Then, a vehicle-track interaction model in ADAMS Rail engineering software is prepared. Using this model, sensitivity analyses are made in order to investigate the main parameters influencing the derailment of rail vehicle. The parameters include radius, super-elevation, transition length, and vehicle speed. The correlation of these parameters with safety criteria is then obtained as integrated practical design charts. The Overturning, Nadal and Prud'homme indexes are the main criteria used in the development of correlations. These are then used to present a new horizontal curve design approach. The applicability of the new method for Tehran-Mashhad line, as the most important railway line in Iran, is also discussed.

2. Current Horizontal Curve Design Methods in Railways

Horizontal curves are one of the two important transition elements in geometric design of railways. A horizontal curve provides a transition between two tangent sections of railroad, allowing a vehicle to negotiate a turn at a gradual rate rather than a sharp cut [5]. The design of the curve is dependent on the intended design speed for the railway, as well as other factors including track class, train type and operational conditions [6].

Railways of different countries use various specifications to design horizontal curves. Among these standards with emphasis on high speed trains, it can be referred to BV (Sweden) [7], DB (German) [8], SNCF (France) [9], JR (Japan) [10], TSI (European Countries)[11] as well as IR394 (Iran) [12]. However, the general algorithm governed on the design procedure in different standards is similar, which is presented in Figure 1. As illustrated in the figure, after specifying the speed and the operational condition for the track, the values of cant, equilibrium cant, and cant deficiency are selected. Then, the minimum radius of curve and its transition length can be calculated. These parameters put the final design of a horizontal curve in a safe manner. Some examples of these practices are presented in Table 1. As presented in the table, none of the requirements of current approaches can directly evaluate or control safety level from dynamic vehicle response point of view.

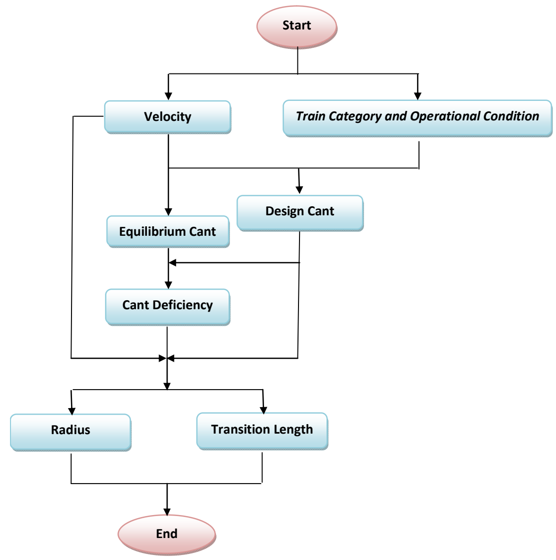

Figure 1. General algorithm governed on the horizontal curve design in railways

3. Parametric Study on Vehicle-Track Interaction at Horizontal Curve

Railway vehicle motion causes the dynamic response, which is due to geometrical variations and track irregularities. Each parameter, which exceeds the allowable value, is a negative factor to achieve the travel safety [13]. Although the allowable and limit ranges of effective parameters in railway standards have been presented, the influence of each single parameter compared to the others as well as simultaneous evaluation of all parameters are questionable. Exact evaluation of dynamic effects caused by contact between wheel and rail is not possible without simulation of derailment phenomenon by using the train-track interaction models. Thus, in this section, the multi-body system (MBS) theory has been used. This theory is a strong process and a high-usage tool for the analytical calculation of the railway vehicle dynamic behavior moving on an arbitrary track [3]. With application of this theory, parametric studies of each geometry factor in horizontal curves are followed and discussed.

3.1. Safety Measures

The governing safety criteria must be firstly defined as a basis for the evaluation of analysis outputs. Failure of traveling safety, in a way, appears to be connected to the derailment

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Table 1. Current equations used for the horizontal curve design in railways

Standard	Design basis	Cant	Radius	Spiral length
BV	Train category (A,B,S) [a]	h_d $h_t \le 150$ mm	$R_{rec,\min} = \frac{(1.3v_{\dim})^2 * 11.8}{h_{eq}}$ $R_{\min} = \frac{V_{\dim}^2 11.8}{h_{eq}}$	$L_t \ge 0.4.\Delta h_{t,mm}$ $V_{\lim} \le \frac{L_t.1000}{q_t.\Delta h_{t,mm}}$ $V_{\lim} \le \frac{L_t.1000}{q_d.\Delta h_{d,mm}}$
DB	Without permission or Permission necessary [b]	h_d $h_t \le 180$ mm h_{eq}	$R_{\min} = \frac{V_{\dim}^2 11.8}{h_{eq}}$	$L_t \ge 0.4.\Delta h_{t,mm}$ $V_{\lim} \le \frac{L_t.1000}{8.\Delta h_{t,mm}}$ $V_{\lim} \le \frac{L_t.1000}{4.\Delta h_{d,mm}}$
TSI	Traffic categories and velocity [c]	h_d $h_t \le 190$ mm h_e dht/dx dht/dt	$\frac{V_{\dim}^2 11.8}{h_t + h_d} \le R \le \frac{V_{\dim}^2 11.8}{h_t - h_e}$	$\frac{V_{\max}}{3.6} \Delta h_d \left(\frac{dh_d}{dt}\right)_{\lim}^{-1}$ $\Delta h_t \left(\frac{dh_t}{dx}\right)_{\lim}^{-1}$
IR 394	Train velocity [d]	h_d $h_t \le 120$ mm h_{eq}	$R_{\min} = \frac{V_{\dim}^2 11.8}{h_{eq}}$ $R_{\min} = 0.0625\ V_{\max}^2$	$L_t = \frac{Vt}{3.6}$ $L_t = \frac{Vh_t}{100}$

h_e: Equilibrium cant *h_d:* Cant deficiency *h_t:* Actual cant *t:* time of first oscillation of train. (1.5 sec)

a. Train category:
- A: conventional vehicles with older running gear and freight trains
- B: vehicles with improved running gear, according to approval
- S: vehicles with improved running gear and carboys tilt system

b. With or without permission:
-Without permission: consist of recommended and limited values
- Permission necessary: consist of permission and exception values

c. Traffic categories and Velocity:
-Mixed traffic lines designed for passenger train $200 < V \le 300$
-Mixed traffic lines with passenger train $V \le 230$ (or 250 on upgraded lines) with vehicles incorporating special technical design characteristics.
-High-speed lines with dedicated passenger traffic $250 \le V \le 300$

d. Train velocity:
-High-speed lines $160 \le V \le 250$

phenomenon. The main reason is because of generating high lateral forces at horizontal curves, which are due to the motion mechanism of wheels on rails [4]. Assuming that there is no irregularity on track, this phenomenon at the horizontal curves falls into three categories: climbing of a wheel flange on a rail (Nadal criterion), track shifting (Prud'homme criterion) as well as vehicle overturning. Table 2 presents the governing equations and limiting values for these three types of derailment. The acceptable limits for safety measures have been detailed in UIC518 [14].

3.2. Modeling and Validation Process

The non-linear dynamic stability simulation of vehicle on the track is made by using ADAMS/Rail engineering software due to the availability and reliability of the outcome. This software produces a virtual environment for the sake of a complete simulation of the track–vehicle interaction. For simulation of the wheel–rail contact forces in contact patch, the Fastsim model developed by Kalker [15] is used.

3.2.1. Model Geometry and Mechanical Features

A single passenger wagon consisted of MD523 bogie is selected due to its widespread application and compatibility for higher running speed [16]. To model the vehicle, the properties

Table 2. Selected safety measures and the governing equations

Safety measure	Equation	Limiting value	Effective parameters
Overturning	$\eta_{\lim} = \frac{\sum_{bogie} Q_{i(left)} - \sum_{bogie} Q_{i(left)}}{\sum_{bogie} Q_{i(left)} + \sum_{bogie} Q_{i(left)}}$	0.9*	∑Ql : Sum of the vertical wheel forces, left wheel ∑Qr : Sum of the vertical wheel forces, right wheel
Nadal	$\frac{Y}{Q} = \frac{\tan\alpha - \mu}{1 + \mu \tan\alpha} \le \left(\frac{Y}{Q}\right)_{\max}$	0.8	α = Flange contact angle μ = Friction coefficient
Prud'homme	Ymax,lim = k1 (10 + 2Q0/3)	│∑Ylim│ ≤ Ymax,lim	2Q0 is the static vertical axle load. [KN] k1 = 0.85 │∑Ylim│ is the absolute value of Yl and Yr (The lateral forces of rail track)

including mass, inertia, stiffness, and damping coefficient are used [17]. The axle load is considered constant (i.e. 100 KN). However, to evaluate the effect of traveling speed as an important design parameter, it varies in a range of 160 to 250 km/hr.

For track modeling, the rail properties and the main curve parameters, which have significant influences on the traveling safety, are considered. The UIC60 profile is selected because of its common usage. The possible effective parameters include curve radius, transition length and cant. According to the limiting values of geometry standards, the curve radius is selected in a range of 500 to 4500 m. Transition length is also selected in between 30 to 130 m, while the cant is considered from 80 to 300 mm.

3.2.2. Verification Process

Due to the lack of real data on rolling stock forces, the model is verified by using BS EN 14363 standard (Testing for the Acceptance of Running Characteristics of Railway Vehicles)[18]. Hence, a basic model is developed in software and vehicle-passing performance is evaluated under certain track geometry and operational conditions (i.e. radius of 500 m, cant of 200 mm and speed of 125 km/h). The output from the dynamic analysis are indicative of the rolling stock stability and the generated model is validated in compliance with this standard.

3.3. Sensitivity Analyses and Interpretation of the Results

Sensitivity analyses of the interaction model is made in order to evaluate the effect of each parameter on the dynamic forces induced by the wheel loads. Hence, the safety measures versus curve parameters at different speed can be estimated. To conduct the sensitivity analyses, all parameters except one (that needs to be varied) are considered to have constant sizes. Then, the effect of the varying parameter on the results is investigated. Data in Tables 3-5 present the results. In these tables, R is the curve radius in meters, L is the transition length in meters, and H is the cant in millimeters.

3.3.1. Overturning Criterion

As in Table 3, the overturning at the sharpest curve (i.e. with a radius of 500 m) and for the higher speed is destined to occur. Therefore, it does not depend on the cant and the transition length variations. However, for the higher curve radiuses at different speed, the maximum overturning criterion happens where both the minimum transition length and the maximum cant are simultaneously present.

3.3.2. Nadal Criterion

The results of Nadal criterion, as presented in Table 4, are not critical compared with overturning at the sharpest radius.

Table 3. Overturning results versus curve parameters at different speed

R	H	L	Over turning	R	H	L	Over turning	R	H	L	Over turning	R	H	L	Over turning	R	H	L	Over turning
Velocity = 160 km/hr																			
	80	30	1.00		80	30	0.32		80	30	0.31		80	30	0.32		80	30	0.31
	80	80	1.00		80	80	0.23		80	80	0.08		80	80	0.13		80	80	0.16
	80	130	0.98		80	130	0.16		80	130	0.12		80	130	0.11		80	130	0.15
	135	30	0.85		135	30	0.46		135	30	0.50		135	30	0.71		135	30	0.66
500	135	80	0.86	1500	135	80	0.16	2500	135	80	0.22	3500	135	80	0.28	4500	135	80	0.32
	135	130	0.83		135	130	0.32		135	130	0.19		135	130	0.23		135	130	0.28
	190	30	0.95		190	30	0.62		190	30	0.81		190	30	1.00		190	30	0.91
	190	80	0.71		190	80	0.55		190	80	0.37		190	80	0.43		190	80	0.47
	190	130	0.73		190	130	0.43		190	130	0.34		190	130	0.37		190	130	0.42
Velocity = 200 km/hr																			
	80	30	1.00		80	30	0.46		80	30	0.35		80	30	0.32		80	30	0.31
	80	80	1.00		80	80	0.43		80	80	0.21		80	80	0.16		80	80	0.14
	80	130	1.00		80	130	0.20		80	130	0.22		80	130	0.13		80	130	0.13
	135	30	1.00		135	30	0.62		135	30	0.86		135	30	0.75		135	30	0.69
500	135	80	1.00	1500	135	80	0.36	2500	135	80	0.27	3500	135	80	0.24	4500	135	80	0.30
	135	130	1.00		135	130	0.29		135	130	0.24		135	130	0.16		135	130	0.23
	190	30	1.00		190	30	0.94		190	30	1.00		190	30	1.00		190	30	0.99
	190	80	1.00		190	80	0.32		190	80	0.32		190	80	0.53		190	80	0.48
	190	130	1.00		190	130	0.48		190	130	0.32		190	130	0.34		190	130	0.41
Velocity = 250 km/hr																			
	80	30	1.00		80	30	0.91		80	30	0.49		80	30	0.41		80	30	0.38
	80	80	1.00		80	80	0.77		80	80	0.43		80	80	0.31		80	80	0.24
	80	130	1.00		80	130	0.11		80	130	0.38		80	130	0.25		80	130	0.19
	135	30	1.00		135	30	0.80		135	30	0.77		135	30	0.78		135	30	0.63
500	135	80	1.00	1500	135	80	0.69	2500	135	80	0.48	3500	135	80	0.35	4500	135	80	0.42
	135	130	1.00		135	130	0.21		135	130	0.32		135	130	0.20		135	130	0.16
	190	30	1.00		190	30	1.00		190	30	1.00		190	30	1.00		190	30	1.00
	190	80	1.00		190	80	0.71		190	80	0.53		190	80	0.43		190	80	0.54
	190	130	1.00		190	130	0.38		190	130	0.24		190	130	0.21		190	130	0.32

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Table 4. Nadal results versus curve parameters at different speed

R	H	L	Nadal	R	H	L	Nadal	R	H	L	Nadal	R	H	L	Nadal	R	H	L	Nadal
Velocity = 160 km/hr																			
	80	30	0.24		80	30	0.20		80	30	0.16		80	30	0.14		80	30	0.20
	80	80	0.22		80	80	0.18		80	80	0.08		80	80	0.12		80	80	0.11
	80	130	0.20		80	130	0.13		80	130	0.08		80	130	0.13		80	130	0.12
	135	30	0.22		135	30	0.21		135	30	0.23		135	30	0.25		135	30	0.32
500	135	80	0.24	1500	135	80	0.19	2500	135	80	0.15	3500	135	80	0.16	4500	135	80	0.17
	135	130	0.23		135	130	0.18		135	130	0.11		135	130	0.16		135	130	0.15
	190	30	0.35		190	30	0.22		190	30	0.35		190	30	0.38		190	30	0.37
	190	80	0.29		190	80	0.11		190	80	0.17		190	80	0.23		190	80	0.22
	190	130	0.25		190	130	0.22		190	130	0.17		190	130	0.20		190	130	0.22
Velocity = 200 km/hr																			
	80	30	0.25		80	30	0.21		80	30	0.17		80	30	0.16		80	30	0.22
	80	80	0.20		80	80	0.19		80	80	0.17		80	80	0.10		80	80	0.10
	80	130	0.19		80	130	0.11		80	130	0.15		80	130	0.10		80	130	0.11
	135	30	0.21		135	30	0.22		135	30	0.33		135	30	0.31		135	30	0.30
500	135	80	0.18	1500	135	80	0.20	2500	135	80	0.14	3500	135	80	0.14	4500	135	80	0.18
	135	130	0.18		135	130	0.18		135	130	0.13		135	130	0.14		135	130	0.15
	190	30	0.23		190	30	0.34		190	30	0.39		190	30	0.38		190	30	0.38
	190	80	0.24		190	80	0.20		190	80	0.20		190	80	0.24		190	80	0.26
	190	130	0.23		190	130	0.21		190	130	0.14		190	130	0.17		190	130	0.21
Velocity = 250 km/hr																			
	80	30	0.84		80	30	0.20		80	30	0.21		80	30	0.20		80	30	0.21
	80	80	0.83		80	80	0.19		80	80	0.21		80	80	0.18		80	80	0.15
	80	130	0.16		80	130	0.11		80	130	0.19		80	130	0.18		80	130	0.14
	135	30	0.76		135	30	0.27		135	30	0.25		135	30	0.29		135	30	0.33
500	135	80	0.75	1500	135	80	0.20	2500	135	80	0.19	3500	135	80	0.17	4500	135	80	0.20
	135	130	0.19		135	130	0.15		135	130	0.19		135	130	0.13		135	130	0.13
	190	30	0.52		190	30	0.33		190	30	0.66		190	30	0.65		190	30	0.55
	190	80	0.49		190	80	0.25		190	80	0.23		190	80	0.19		190	80	0.29
	190	130	0.18		190	130	0.20		190	130	0.17		190	130	0.15		190	130	0.19

Table 5. Prud'homme results versus curve parameters at different speed

R	H	L	Prud' homme	R	H	L	Prud' homme	R	H	L	Prud' homme	R	H	L	Prud' homme	R	H	L	Prud' homme
Velocity = 160 km/hr																			
	80	30	6.11E+04		80	30	2.70E+04		80	30	1.11E+04		80	30	1.81E+04		80	30	1.67E+04
	80	80	6.14E+04		80	80	2.07E+04		80	80	9.41E+03		80	80	8.02E+03		80	80	9.17E+03
	80	130	5.86E+04		80	130	7.53E+03		80	130	6.84E+03		80	130	6.49E+03		80	130	5.90E+03
	135	30	6.44E+04		135	30	3.30E+04		135	30	2.32E+04		135	30	2.85E+04		135	30	3.37E+04
500	135	80	6.08E+04	1500	135	80	1.73E+04	2500	135	80	8.62E+03	3500	135	80	1.38E+04	4500	135	80	1.51E+04
	135	130	5.97E+04		135	130	1.39E+04		135	130	8.58E+03		135	130	1.03E+04		135	130	1.32E+04
	190	30	6.30E+04		190	30	3.62E+04		190	30	3.18E+04		190	30	3.87E+04		190	30	3.96E+04
	190	80	6.21E+04		190	80	1.09E+04		190	80	1.44E+04		190	80	2.26E+04		190	80	2.23E+04
	190	130	6.08E+04		190	130	2.07E+04		190	130	1.01E+04		190	130	1.43E+04		190	130	1.49E+04
Velocity = 200 km/hr																			
	80	30	9.81E+04		80	30	3.90E+04		80	30	2.03E+04		80	30	2.35E+04		80	30	2.50E+04
	80	80	8.54E+04		80	80	3.49E+04		80	80	1.88E+04		80	80	1.39E+04		80	80	1.07E+04
	80	130	7.42E+04		80	130	7.87E+03		80	130	1.51E+04		80	130	1.33E+04		80	130	9.32E+03
	135	30	9.90E+04		135	30	4.69E+04		135	30	2.69E+04		135	30	4.52E+04		135	30	4.17E+04
500	135	80	8.20E+04	1500	135	80	3.30E+04	2500	135	80	1.04E+04	3500	135	80	1.43E+04	4500	135	80	1.63E+04
	135	130	7.92E+04		135	130	1.39E+04		135	130	1.34E+04		135	130	9.85E+03		135	130	1.28E+04
	190	30	9.27E+04		190	30	6.16E+04		190	30	6.08E+04		190	30	5.38E+04		190	30	4.60E+04
	190	80	7.25E+04		190	80	2.95E+04		190	80	1.91E+04		190	80	2.90E+04		190	80	2.55E+04
	190	130	7.93E+04		190	130	2.13E+04		190	130	1.28E+04		190	130	1.71E+04		190	130	1.92E+04
Velocity = 250 km/hr																			
	80	30	1.29E+05		80	30	6.37E+04		80	30	5.35E+04		80	30	4.11E+04		80	30	2.89E+04
	80	80	1.12E+05		80	80	5.48E+04		80	80	4.73E+04		80	80	3.15E+04		80	80	2.71E+04
	80	130	9.45E+04		80	130	1.58E+04		80	130	4.22E+04		80	130	3.03E+04		80	130	2.14E+04
	135	30	1.23E+05		135	30	8.32E+04		135	30	6.40E+04		135	30	6.12E+04		135	30	8.47E+04
500	135	80	1.10E+05	1500	135	80	5.33E+04	2500	135	80	3.33E+04	3500	135	80	3.05E+04	4500	135	80	2.08E+04
	135	130	9.03E+04		135	130	1.09E+04		135	130	3.34E+04		135	130	1.86E+04		135	130	1.23E+04
	190	30	1.18E+05		190	30	8.28E+04		190	30	6.22E+04		190	30	9.39E+04		190	30	1.04E+05
	190	80	1.08E+05		190	80	4.97E+04		190	80	2.88E+04		190	80	1.93E+04		190	80	3.26E+04
	190	130	8.86E+04		190	130	1.86E+04		190	130	2.45E+04		190	130	1.39E+04		190	130	1.73E+04

This means that overturning in a curve with a radius of 500 meters will happen before the climbing of the wheel flange on the rail. For higher curve radiuses however, the maximum values of this criterion resulted again where the minimum transition curve length and the maximum track cant exist simultaneously.

3.3.3. Prud'homme Criterion

Table 5 demonstrates that the Prud'homme criterion decreases as the curve radius increases and the vehicle speed decreases. Here again, the combination importance of both cant and transition length parameters is illustrated. This measure also is not critical like Nadal criterion in comparison with overturning at the sharpest

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radius. It should be noted that the limited value of track shift force is equivalent to 36800 Newton based on the equation given in Table 2 and the vehicle specifications.

4. Integrated Design Approach Incorporating Safety Measures

In this section, comparisons between different curve conditions against safety measures are presented in an integrated manner. In Figures 2 to 4, each safety measures in relation to the curve radius and cant gradient are presented at different speed. Cant gradient is the ratio of cant to transition length (H/L) in terms of [mm/m]. This parameter is defined due to the multiplicity of parameters as well as the importance of combined cant and transition length role. For the derivation of the mentioned practical charts in a simple way, surface charts of 3D data, shown as contour lines in a plan XY view is used. Like a topographic map, the colors and patterns in this chart indicate areas that contain the same range of values. With application of these charts, the optimum combinations between two sets of data can be resulted. Therefore, the evaluation of vehicle safety at different speed and the possible speed increment for the governed conditions can be achieved.

At this stage, the development of a new design approach incorporating safety measures can be attempted. The algorithm for the proposed method of the design of horizontal curves incorporating the estimation of the track safety meausres is presented in Figure 5. This new approach includes an extra sub-section in the design algorithm of railway horizontal curves, which enable us to evaluate the safety levels, directly. This evaluation can be done with application of safety charts that were explained. For this purpose, after choosing the speed, curve radius, design cant, and transition length for the selected vehicle, cant gradient can be calculated. By considering the cant gradient and curve radius values and using the safety charts, derailment probability can be evaluated. Moreover, with this assumption that the vehicle is safe against the derailment, the radius and cant gradient can be optimized. Thus, speed increment capability on the curve can be estimated with a high accuracy.

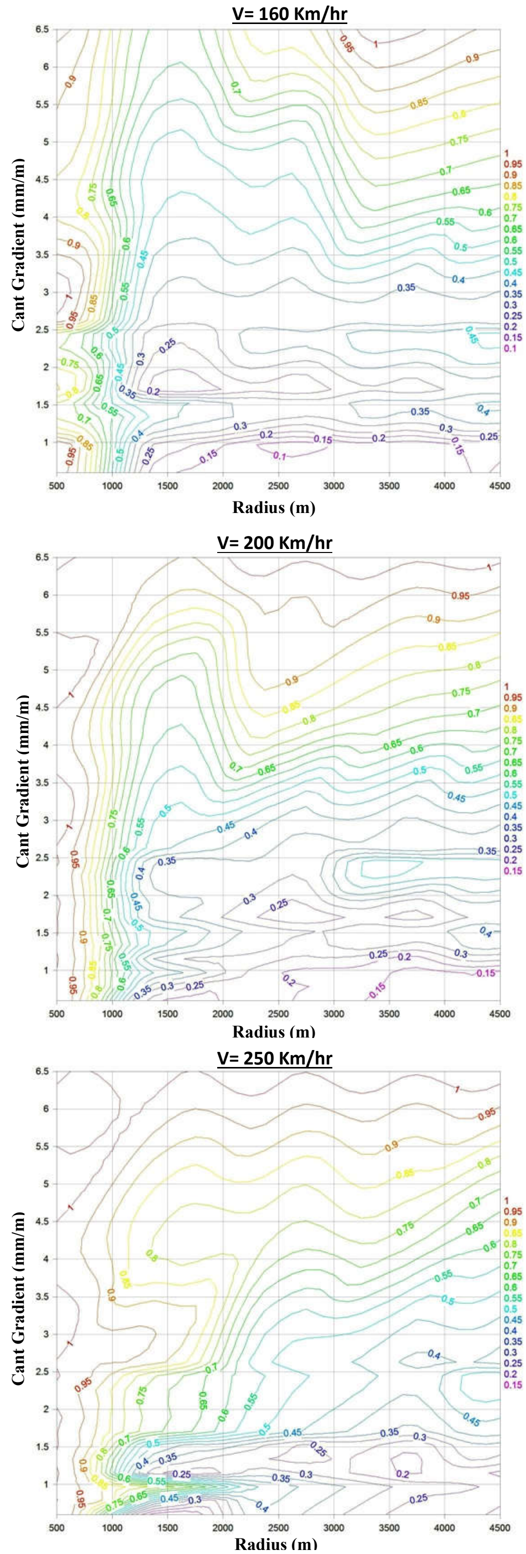

Figure 2. Surface charts of Overturning

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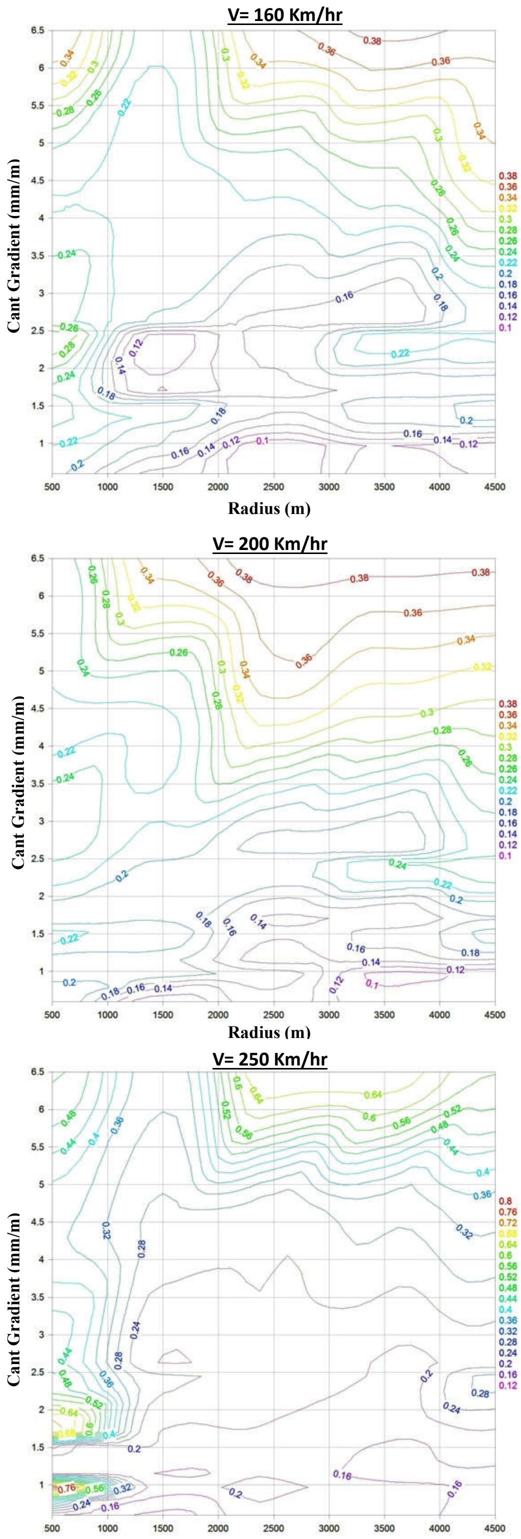

Figure 3. Surface charts of Nadal

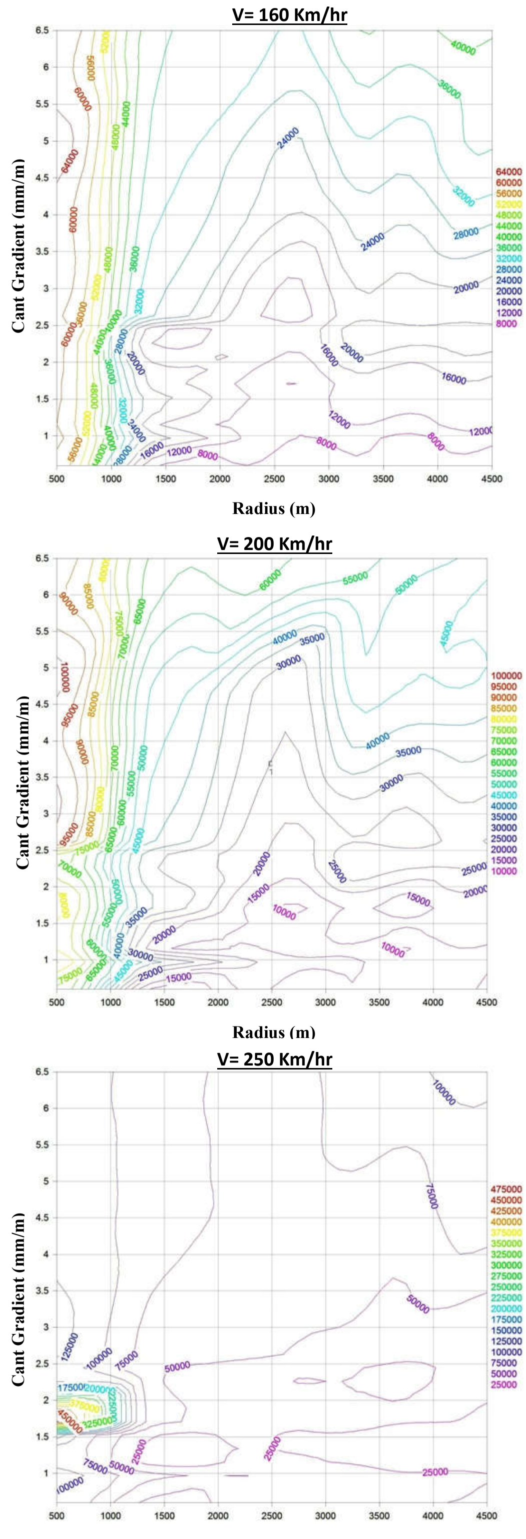

Figure 4. Surface charts of Prud'homme

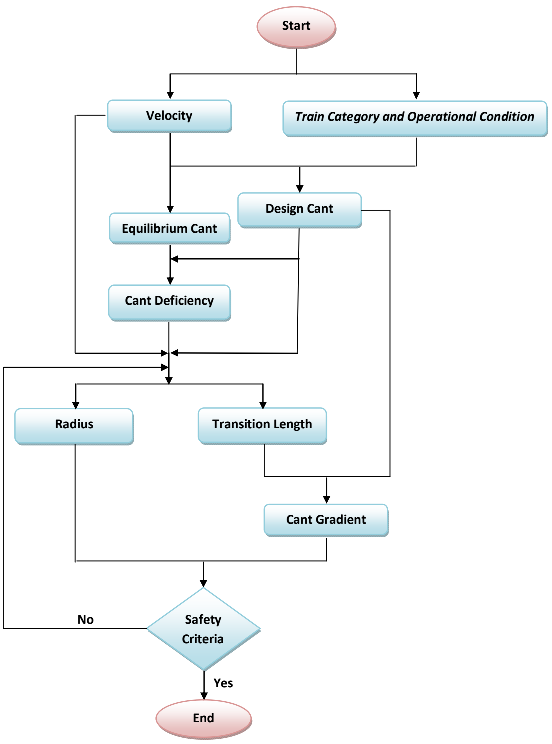

Figure 5. The proposed algorithm of horizontal curve design incorporating safety measures

5. Numerical Example

To demonstrate the versatility of the new approach, Tehran-Mashhad line as one of the most important railway routes in Iran is considered. This line was upgraded for the speed increase from 120 km/hr up to 160 km/hr. Therefore, the feasibility of the speed improvement is determined for 3 main horizontal curves within this route. The specifics for these curves are presented in Table 6. By using the new design approach and calculating the cant gradient for each curve, the safety design charts can be served to evaluate the derailment criteria for different speed. The prediction results are presented in Figure 6.

The predicted results for the first curve with 700 m radius present that, although the Nadal measure is acceptable, the Prud'homme as well as the overturning criteria are critical and outdo

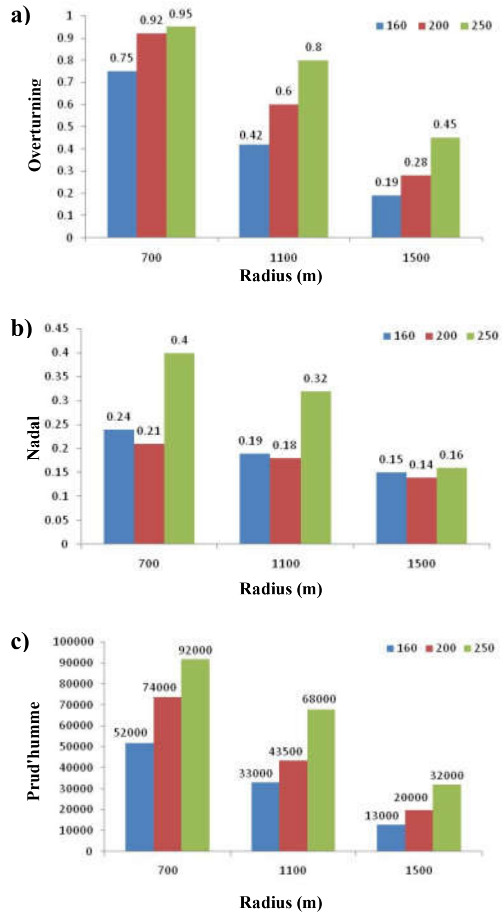

Figure 6. Prediction of derailment criteria for (a) Overturning, (b) Nadal, and (c) Prud'homme

the aloable sizes. Hence, the speed increase cannot be followed for this curve. Investigation of the derailment for 1100 meter curve also shows that, despite the derailment safety predictions by the Overturning and Nadal in all speed ranges, the wagon is in a critical Prud'homme condition for the speed of 200 and 250 km/hr. Therefore, only the increase of speed up to 160 km/hr is safe for this curve. At the curve with a radius of 1500 meters however, the rail vehicle can pass the curve without the prediction for the derailment of any type. Therefore, the speed can be increased up to 250 km/h, without changing the track geometry.

Therefore, the curve radius, variation of cant versus curve length, and the train running speed

Table 6. Specifications of three main horizontal curves in Tehran-Mashhad railway line

Curve No.	Km	Radius (m)	Cant (mm)	Transition Length (m)	Cant Gradient (mm/m)
1	45+300	700	120	75	1.6
2	50+455	1100	100	100	1
3	63+100	1500	60	90	0.7

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are the influential track design parameters, as expected.

6. Conclusions

The influences of horizontal curve parameters on the safety condition of railway vehicles were investigated in this research. Derailment criteria including Overturning, Nadal and Prud'homme were referenced for the safety evaluation. Results obtained from the simulation of dynamic vehicle response (using a vehicle–track interaction model) were then used for the development of safety design charts. According to these charts, the current design approach for railway horizontal curves can be improved. This provides the possibility of being able to make a prediction about the overall safety conditions of the curved track in different speed. It becomes a useful option when the speed increment of a railway line is followed.

According to the results, the curve radius, the variation of the cant versus transition curve length (e.g. the cant gradient), as well as the vehicle speed are the most important parameters on safe design approach of railway horizontal curves. Moreover, the comparison of safety criteria proves that for the sharp curves with radiuses such as 700 and 1100 meters, the governing measure for the derailment in current research conditions is Prud'homme, whereas the Nadal criterion is less influenced.

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