Models to evaluate riding comfort on curved track in a railway system

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Improvement of riding comfort in the railway is a key to improve railway passengers' amenity. But, there are few systematic papers done about riding comfort, because this concept is equivocal and not easy to quantify. This paper offers new simple models to evaluate riding comfort on a curved track. Measures to evaluate riding comfort are analyzed. The effect of curve radius, train speed, length and type of transition curve, lateral acceleration, rate of change of cant, and jerk on riding comfort has been also studied. New technical measures to improve riding comfort have been introduced.

تعتبر عمليات التحسينات والتي تنفذ بغرض زيادة راحة الركاب على السكك الحديدية من أهم العوامل لزيادة الطلب على هـــذا النوع من النقل ، وبالتالي زيادة طاقتها الإنتاجية. وتعتبر عملية تقييم راحة الركاب علي خطوط السكك الحديدية من العمليـــات الصعبة، ولذلك يوجد القليل من الأبحاث والتي تهتم بهذا النوع من الدراسات. إن الهدف الرئيسي من هذا البحث هو بناء نماذج رياضية جديدة لتقييم راحة الركاب على الخطوط المنحنية لأنظمة السكك الحديدية. وفي هذه النماذج تم دراسة تـــأثير طـــول ونوع منحنيات الانتقال، وسرعة القطارات، والعجلة الخارجية، ومعدل تغيير الظهر عن البطن، وكذلك معدل تغيـــير العجلـــة الخارجية (jerk) . واخيرا تم عرض وسائل تكنيكية حديثة لتحسين راحة الركاب على الخطوط المنحنية لأنظمـــة السكك الحديدية .

Keywords: Riding comfort, Transition curves, Lateral acceleration, Jerk

1. Introduction

It is very important for railway passengers' amenity to improve riding comfort of the railway system. The term "riding comfort" is defined as a feeling that is prescribed by many factors; such as vehicle vibration, noise, and seating. In this paper, this term means the feeling that is caused by only vehicle vibration.

Investigation of the dynamics of train movement on curved track indicated that passenger comfort and the extend of the intermittent lateral force generated by the moving mass depend on the nature and the shape of the curvature function of the transition curve. On the transition curve section, the vehicle is apt to vibrate. The length of the transition curve is decided for three purposes: preventing the derailment caused by the three wheels support on the track torsion, maintain good riding quality under increased elevation, and maintain good riding quality under increased deficiency of the elevation.

The purposes of this paper are to develop new models to evaluate riding comfort on curved track in a railway system, as well as to introduce technical measures to improve riding comfort.

This paper is divided into four major sections. The first section identifies the main factors affecting riding comfort. The second section presents and analyzes measures to evaluate riding comfort. In the third section new models to evaluate riding comfort on a curved track in a railway system has been derived. The forth section introduces new technical measures to improve riding comfort.

2. Factor affecting riding comfort

There are two categories of factors that affect riding comfort in a railway system, these are:

- Track geometrical factors, and
- Vehicle dynamic factors.

The track geometrical factors may be summarized as:

- Radius of horizontal curve,
- Length of circular curve,
- Track cant,
- Cant deficiency,

- Curving speed,
- Gradient of curvature on transition curve,
- Type and length of transition curve,
- Gradient of cant on superelevation ramp,
- Type of superelevation ramp,
- Radius of vertical curve,
- Length of vertical curves, and
- Type of vertical curve.

The vehicle dynamic factors include:

- Suspension coefficient,
- Yaw velocity (magnitude, and duration),
- Yaw acceleration,
- Roll velocity,
- Lateral acceleration (magnitude and duration),
- Rate of change of lateral acceleration, and
- Vertical acceleration.

3. Measures to evaluate riding comfort

In the railway engineering the riding comfort may be evaluated by the following measures:

- Vibration acceleration measure,
- Stationary lateral acceleration measure, and
- Roll motion measure

3.1. Vibration acceleration measure

There are some possibilities by which the magnitude of vibration can be expressed: such as displacement, velocity, and acceleration. Among them adopting of acceleration is generally more popular. It is convenient, because many standards advocate that the severity of human vibration exposures could be expressed in terms of the vibration acceleration [1].

Railway vehicles have 6 types of motion: 3 types of linear motion and three types of rotational motion. As shown in fig. 1, Linear and rotational vibrations may be created in the direction of longitudinal (X), lateral (Y), and vertical (Z) axes. The rotational vibrations are called rolling (around X-axis), pitching (around Y-axis), and yawing (around Z-axes).

To evaluate the riding comfort of a railway system, amplitude and frequency of vibration acceleration may be considered [2].

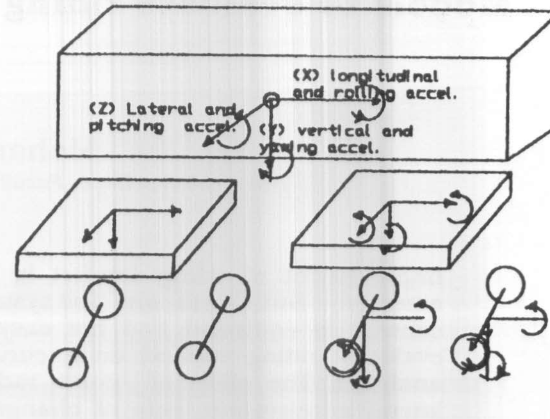

Fig. 1. Linear and rotational vibration acceleration of a railway vehicle.

3.2. Stationary lateral acceleration measure

The stationary lateral acceleration, SLA, (it has also other names such as: quasi static lateral acceleration, sustained acceleration, and steady acceleration in lateral direction) is the acceleration which may be created in a railway curve. It can be defined as follows: In the case where the vehicle runs through a horizontal curve section, a component parallel to car-body floor of the acceleration in lateral direction is generated steadily at the circular curved part. The absolute value of the SLA (m/sec^2) in the horizontal plane equals to:

$$a = C_{max} * v^2 , \qquad (1)$$

where;

C_{max} is the maximum value of curvature, (1/m)

v is the speed, (m/sec)

A part of SLA may be compensated through the superelevation design, and other uncompensated (a_u) part of the lateral acceleration which causes a passenger discomfort should be not exceed 0.66 of the total one, i.e.,

$$a_{umax} \leq (2/3) * a ,$$

$$a = a_u + (U * g) / n,$$

$$a = a_u + U/153, \qquad (2)$$

where;

a_u is the uncompensated lateral acceleration (m/sec^2) ,
U is the normal cant in mm,
g is the gravitational acceleration, 9.81m/sec^2,
n is the distance between the center line of the rails of a track, (equals 1500 mm for standard gauge 1435 mm) .

Human physiology considerations, therefore, determine the maximum value of lateral acceleration as its rate of change. There is a general agreement that the a_{umax} should never exceed 0.1* g [3]. In Japan, this value is limited by 0.8-0.9 of SLA in m/sec^2.

The uncompensated lateral acceleration and its rate of change can be considered as important measures of riding comfort in the railway systems.

3.3. Roll motion measure

This measure may be used for tilting train, and is conducted that riding comfort of a standing passenger at a curve entrance and exit can be evaluated by the waveform of the roll motion.

The proposed allowable limit of the roll angular velocity is about 0.1 rad/sec (5 degrees/sec), and roll acceleration is 0.3 rad/sec^2 (15 degrees/sec^2).

Fig. 2 summarizes the SLA and roll motion measures to evaluate the riding comfort.

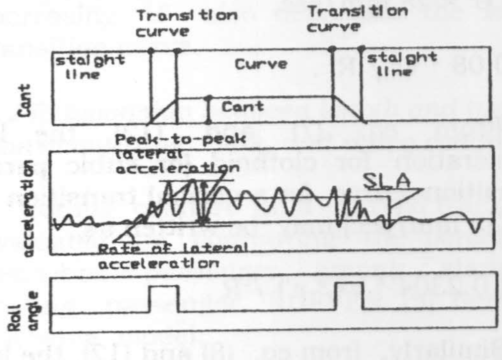

Fig. 2. SLA and roll motion measures to evaluate the riding comfort.

4. Analytical model to evaluate riding comfort in a curved track

Riding comfort in a curved track is affected mainly by lateral acceleration occurred and jerk (time derivative of lateral acceleration). The lateral acceleration depends not only on the cant deficiency (U_d) but also on the roll coefficient of the vehicle (f_r) . The roll factor expresses the ratio between the lateral acceleration in the vehicle body and the lateral acceleration in track plane. The equilibrium cant of a curve (amount of cant that eliminates the lateral acceleration in the track plane), train speed, and length of transition curve are other factors that affect the riding comfort in a railway system. The goal of this section is to derive a new analytical model to evaluate riding comfort in a curved track, tacking into consideration the previous important factors.

4.1. Relationship between length and type of transition curve, speed of train, and the lateral acceleration

Let C is a curvature function of a circular curve, C' is the derivative function of it, and L is the length of its transition curve. In a transition curve the curvature rises regular from zero to C_{max}. Fig. 3 indicates the well-known curvature function and the differentiation curve of a clothoid (cubic parabola) and cosine transition curve. From this curve, the curvature function may be written as:

for clothoid (or cubic parabola) transition curve;

$$C = (C_{max} / L) * X,$$
$$C' = dC/dX,$$
$$C'_{max} = C_{max} / L,$$
$$L = C_{max} / C'_{max}, \quad (3)$$

for cosine transition curve;

$$C = (C_{max}/2) * \{1 - \cos(\Pi / L) X\},$$
$$C' = (C_{max}/2) * (\Pi/L) * \sin(\Pi/L) X,$$
$$C' = C'_{max} \text{ at } X = L/2,$$
$$C'_{max} = (C_{max}/2) * (\Pi/L) * \sin\{(\Pi/L) * (L/2)\},$$
$$C'_{max} = (\Pi/2) * (C_{max}/L),$$
$$C'_{max} = 1.57 * (C_{max}/L) \text{ , and}$$
$$L = 1.57 * C_{max} / C'_{max}. \quad (4)$$

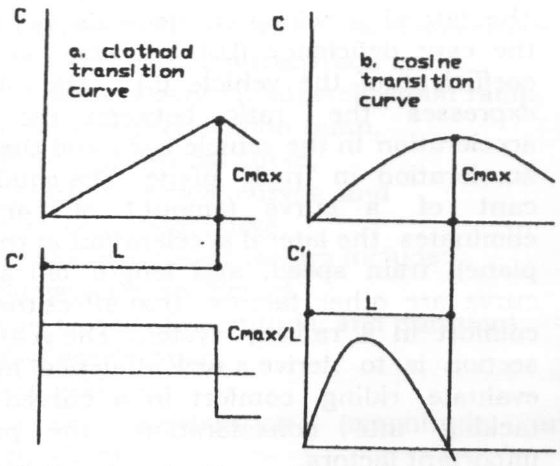

Fig. 3. Curvature function and the differentiation curve of a clothoid (cubic parabola) and cosine transition curve.

According to the eq. (1);

$$C_{max} = a / v^2 , \quad (5)$$

where:

v is the train speed m/sec, and
a is the lateral acceleration m/sec².

GUB'AR [4] defined the relationship between jerk and the differentiation function of curvature as:

$$C'_{max} = a' / v^3, \quad (6)$$

where a' is the time derivative of acceleration (jerk), m/sec³.

The relationship between the length of the transition curve, the lateral acceleration, and the jerk may be derived from eqs. (3), (4), (5), and (6) as follows:
for clothoid (or cubic parabola) transition curve:

$$a = (L * a') / v , \quad (7)$$

or

$$a = (3.6 * L * a') / V,$$

for cosine transition curve:

$$a = (L * a') / (1.57 * v), \quad (8)$$

or

$$a = (3.6 * L * a') / (1.57 * V), \text{ and}$$

$$a = (2.29 * L * a') / V,$$

where v in m/sec, and V in km/sec.

The relationship between the length of a transition curve L, rate of change of cant U' (time derivative of cant in mm/sec), and the normal cant U is:

$$L = (U * v) / U' , \quad (9)$$

$$U = (8 V^2) / R, \quad (10)$$

where:
U is the cant in mm,
L is the length of transition curve in m, and
R is the radius of curve in m.

In geometrical design of track the value of the rate of change of cant U' may take the values of 46 mm/sec, 35 mm/sec or 28 mm/sec [5].

Substituting eq. (10) in (9),
-for U' = 46 mm/sec,

$$L = 0.048 * V^3 /R, \quad (11)$$

-for U' = 35 mm/sec,

$$L = 0.064 V^3 / R, \text{ and} \quad (12)$$

-for U' = 28 mm/sec,

$$L= 0.08 * V^3 / R . \quad (13)$$

From eq. (7) and (12), the lateral acceleration for clothoid (or cubic parabola) transition curve for a normal transition curve (U'=35 mm/sec) may be written as:

$$a = (0.2304 * V^2 * a') / R . \quad (14)$$

Similarly, from eq. (8) and (12), the lateral acceleration for cosine transition curve may be concluded as:

$$a = (0.146 * V^2 * a') / R . \quad (15)$$

Eqs. (14) and (15) represent important relationships between the lateral acceleration occurred in a curved track as a function of train speed, jerk, and radius of curve for a clothoid (or cubic parabola) and cosine transition curve respectively.

In order to analyze the effect of length and type of transition curve, and speed of train on the lateral acceleration occurred on a curved track, and consequently on the degree of riding comfort, the models in (7), (8), and (12) have been drawn in fig. 4 for a' = 0.4 m/sec^3, and R = 500 m and in fig. 5 for the same a' and 1000 m curve radius. These figures indicate that cosine transition curves have minimal lateral acceleration and consequently better riding comfort than clothoid or cubic parabola curves. Increasing of train speed results an increase in the lengths of transition curve and the lateral acceleration and consequently worsen the riding comfort for both the clothoid and cosine transition curves. Increasing of radius of curves reduces lateral acceleration and improving riding comfort for the same train speed for both cosine and clothoid or cubic parabola transition curves.

In order to study the effect of the rate of change of cant U' on the length of transition curves and also on the lateral acceleration, the eqs. in (7), (8), (11), (12), and (13) have been drawn in fig 6 for R=1000 m, a' = 0.4 m/sec^3. This Figure illustrates the importance of increasing the rate of change of cant in decreasing the lateral acceleration, for clothoid and cosine transition curves, and consequently increasing the riding comfort. Increasing U' also decreases the length of transition curve.

4.2 Relationship between length and type of transition curve, jerk, and riding comfort

Riding comfort in a curved track may be evaluated by computing the percentage of disturbed passenger among standing or seating passenger. KUFVER [5] derived the following model;

$$P_{st}=\{0.1867*U_d*f_r+0.0376*U_d*f_r*(V/L)\} +5.75*10^{-6}\{|U_{eq}-f_r*U_d|*(V/L)\}^{2.283} \quad (16)$$

$$P_{seat}=\{0.0587*U_d*f_r+0.0176*U_d*f_r*(V/L)\}+73.96*10^{-6}\{|U_{eq}-f_r*U_d|*(V/L)\}^{1.626} \quad (17)$$

where:

- P_{st} is the percentage of disturbed Passenger among standing passenger (%),
- U_d is the cant deficiency (mm),
- f_r is the effective roll factor,
- V is the train speed (km/hr.),
- L is the length of transition curve (m),
- U_{eq} is the equilibrium cant (mm),
- P_{seat} is the percentage of disturbed, passenger among seating passenger (%).

The effective roll factor is defined as:

$$f_r = (15 * a_l) / U_d, \quad (18)$$

where:

- a_l is the lateral acceleration in percentage of g ,
- U_d is the cant deficiency (mm),

but,

$$a_l = (100 * a) / (9.81), \quad (19)$$

substituting eq. (19) in (18):

$$f_r = (153 * a) / U_d. \quad (20)$$

From eq. (16), (17), and (20), the following model may be derived.
For standing passenger:

$$P_{st} = \{28,56 * a + (5.57 * a * V)/L\} + 5.75 * 10^{-6}*\{|U_{eq}-153a|*(V/L)\}^{2.283}. \quad (21)$$

For seating passenger:

$$P_{seat} = \{8.98 * a + (2.69*a*V)/L\} + 73.96 * 10^{-6} * \{|U_{eq} - 153a| * (V/L)\}^{1.626}. \quad (22)$$

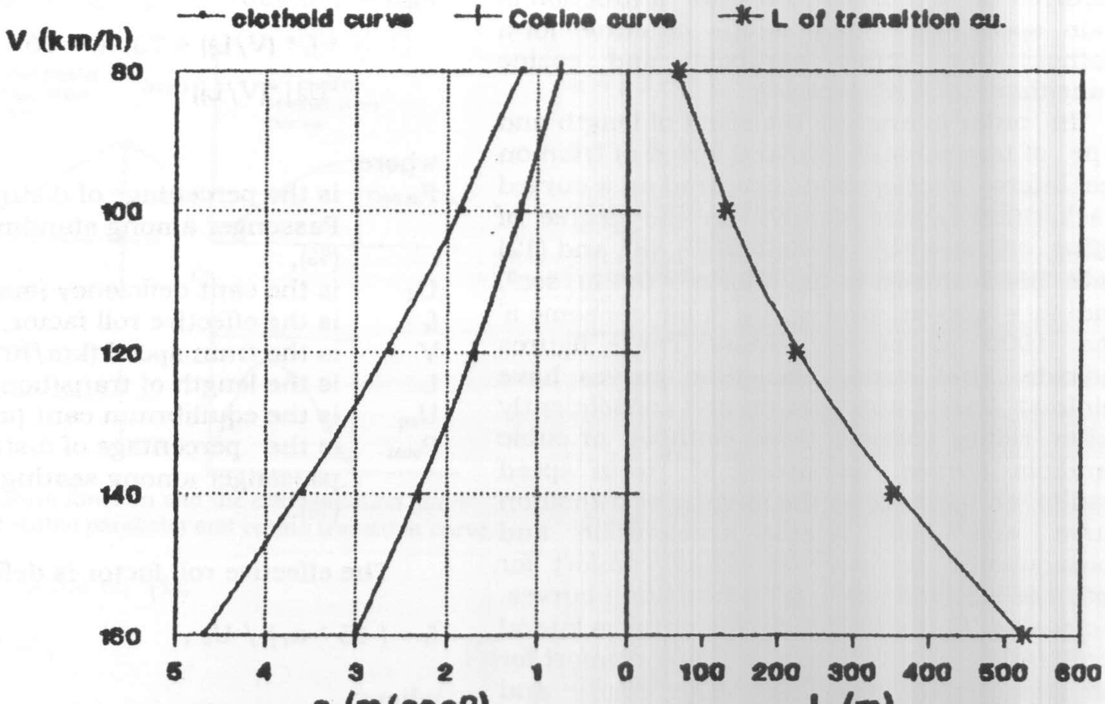

Fig. 4. Effect of type and length of transition curve, and train speed on lateral acceleration (R = 500m, a' = 0.4m/sec³, U'=35 mm/sec) .

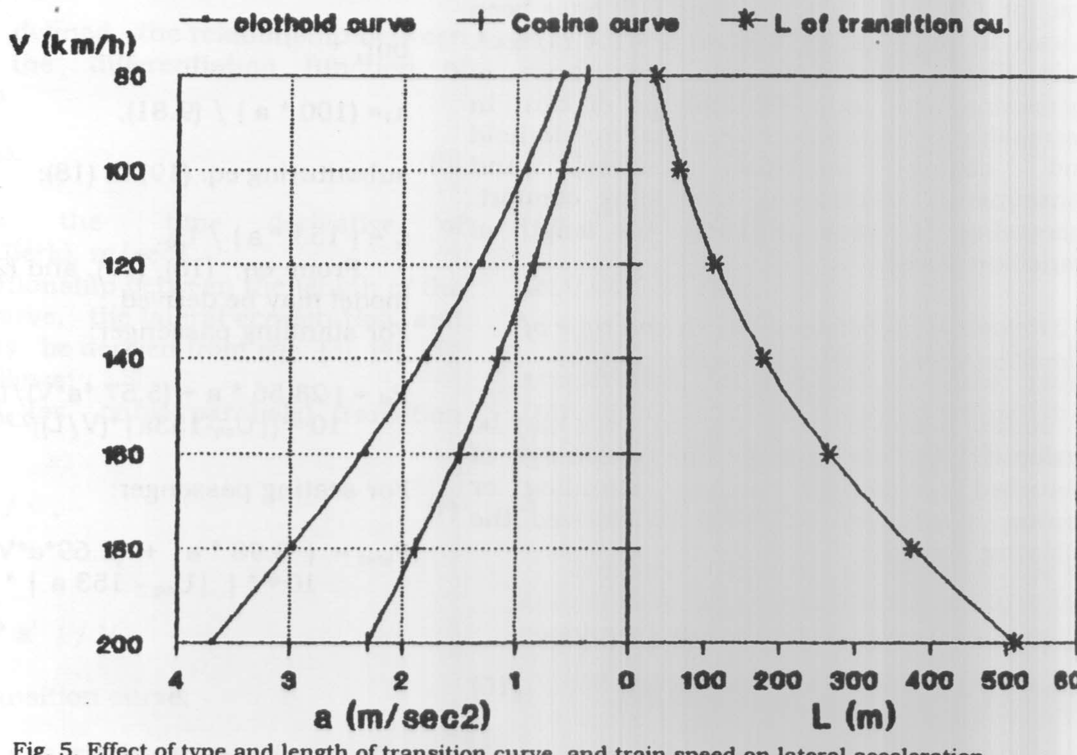

Fig. 5. Effect of type and length of transition curve, and train speed on lateral acceleration (R = 1000m, a' = 0.4 m/sec³, U'=35 mm/sec)

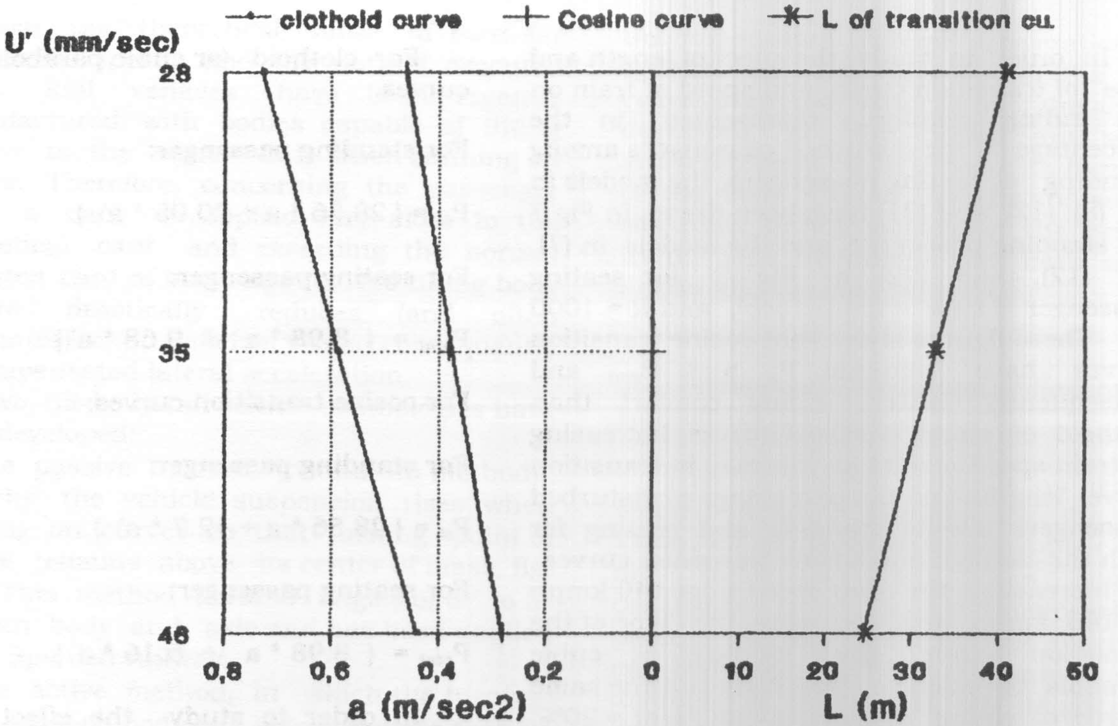

Fig. 6. Effect of rate of change of cant on the length of transition curve, and train speed on lateral acceleration (V =80km/h, a' = 0.4 m/sec³ , R=1000m).

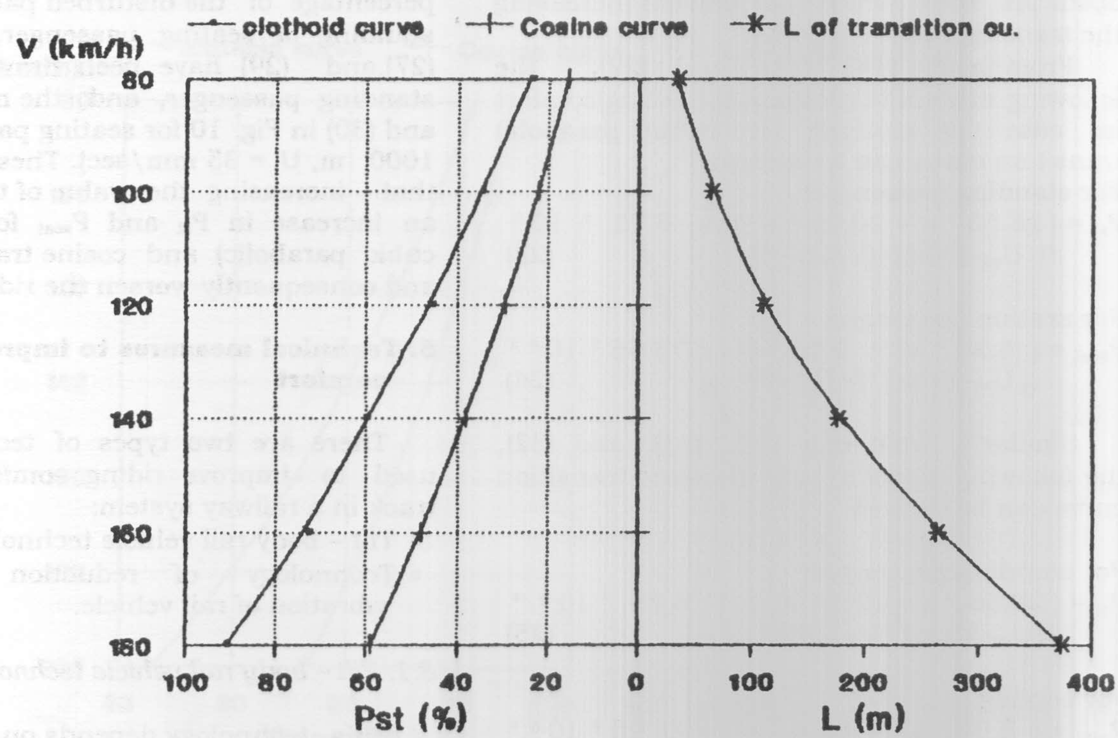

Fig. 7. Effect of type and length of transition curve, and train speed on riding comfort (Pst%, R=1000m, a'=0.4 m/sec³,U'=35 mm/sec).

In order to study the effect of length and type of transition curve, and speed of train on the riding comfort, represented in the percentage of the disturbed passengers among standing or seating passengers, the models in (7), (8), (12), and (21) have been drawn in Fig 7 for standing passenger, and the models in (7), (8), (12), and (22) in Fig 8 for seating passenger (for a' = 0.4 m/sec^3, and R = 1000 m). These figures show that cosine transition curves have minimal P_{st} and P_{seat} and consequently better riding comfort than clothoid or cubic parabola curves. Increasing of train speed results an increase in transition curve lengths and the percentage of disturbed passengers among standing and seating for both the clothoid and cosine transition curves.

Increasing the train speed from 140 kmph to 180 kmph with changing the type of the transition curve from clothoid or cubic parabola to cosine curve may result the same degree of riding comfort, giving Pseat = 20%. This result can be considered as an important conclusion for upgrading rail-lines where obstacles exist which may prevent increasing the transition curve lengths.

From eqs. (14), (21), and (22), the following models to evaluate the riding comfort in case of clothoid (or cubic parabola) transition curve can be derived.

For standing passenger:

$$P_{st} = \{ 28.56 * a + 20.05 * a' \} + 5.75 * 10^{-6} *\{ | U_{eq} - 153a | * (V/L)\}^{2.283}. \quad (23)$$

For seating passenger:

$$P_{seat} = \{ 8.98 * a + 9.68 * a' \} + 73.96 * 10^{-6} * \{ | U_{eq} - 153a | * (V/L)\}^{1.626}. \quad (24)$$

Similarly, from eqs. (15), (21), and (22), the following model in case of cosine transition curve can be derived:

For standing passenger;

$$P_{st} = \{ 28.56 * a + 12.7 * a' \} + 5.75 * 10^{-6} * \{ | U_{eq} - 153a | * (V/L)\}^{2.283}. \quad (25)$$

For seating passenger:

$$P_{seat} = \{ 8.98 * a + 6.16 * a' \} + 73.96 * 10^{-6} * \{ | U_{eq} - 153 a | * (V/L) \}^{1.626}. \quad (26)$$

The second term in eqs. (23), (24), (25), and (26) is small and may be neglected. This may conclude the following simple models:

For clothoid (or cubic parabola) transition curves.

For standing passenger:

$$P_{st} = \{ 28.56 * a + 20.05 * a' \}. \quad (27)$$

For seating passenger:

$$P_{seat} = \{ 8.98 * a + 9.68 * a' \}. \quad (28)$$

For cosine transition curves:

For standing passenger:

$$P_{st} = \{ 28.56 * a + 12.7 * a' \}. \quad (29)$$

For seating passenger:

$$P_{seat} = \{ 8.98 * a + 6.16 * a' \}. \quad (30)$$

In order to study the effect of jerk on riding comfort for both clothoid and cosine transition curves, represented in the percentage of the disturbed passenger among standing or seating passenger, the models in (27),and (29) have been drawn in fig. 9 for standing passenger, and the models in (28), and (30) in Fig. 10 for seating passenger (R = 1000 m, U' = 35 mm/sec). These figures show that increasing the value of the jerk results an increase in P_{st} and P_{seat} for clothoid (or cubic parabolic) and cosine transition curves and consequently worsen the riding comfort.

5. Technical measures to improve riding comfort

There are two types of technologies that used to improve riding comfort on curved track in a railway system:

- Tilt – body rail vehicle technology,
- Technology of reduction of flexural vibration of rail vehicle.

5.1. *Tilt – body rail vehicle technology*

This technology depends on compensating of the excess in lateral acceleration (uncompensated lateral acceleration) that exists due to cant deficiency (the difference between the theoretical value of cant for maximum speed and the normal executed cant). Rail vehicles have been recently manufactured with bodies capable of tilting relative to the wheel - base when running on curves. Therefore, concerning the passenger level, a cant is applied very close to the theoretical cant and exceeding the normal executed cant of track layout. This tilting body feature drastically reduces (and often eliminates) cant deficiency and consequently uncompensated lateral acceleration.

Two tilt-body rail vehicle technologies have been developed:

- The passive method (pendulum method), whereby the vehicle suspension rises when running on curves so that turning point of vehicle remains above its center of mass, fig. 11 . This method permits angles of 3 ° to 5° between body and axle and has been applied to the Spanish railway.
- The active method, in which the turning angle between body and axle is greater than 8° ≈ 10° and is set as a function of the uncompensated lateral acceleration. In this system, as the train enters the transition curve from the straight line, the acceleration developed at the bogies are sensed by accelerometers. Instructions to begin rotation of the body around its axis are issued by an electronic device located at the head of the train. This technique has been applied by Italian and German railways.

5.2. Technology of reduction of flexural vibration of rail vehicle.

This technology depends on reducing of vertical flexural vibration of the car-body. Visco –elastic layer (damping rubber sheet of 2 mm thickness, and 1.2-m width) and constraint layer (5 mm thickness) may be pasted partially on the outside sheeting of the car body, fig. 12. The optimum length of the damping layer depends on its characteristic [6].

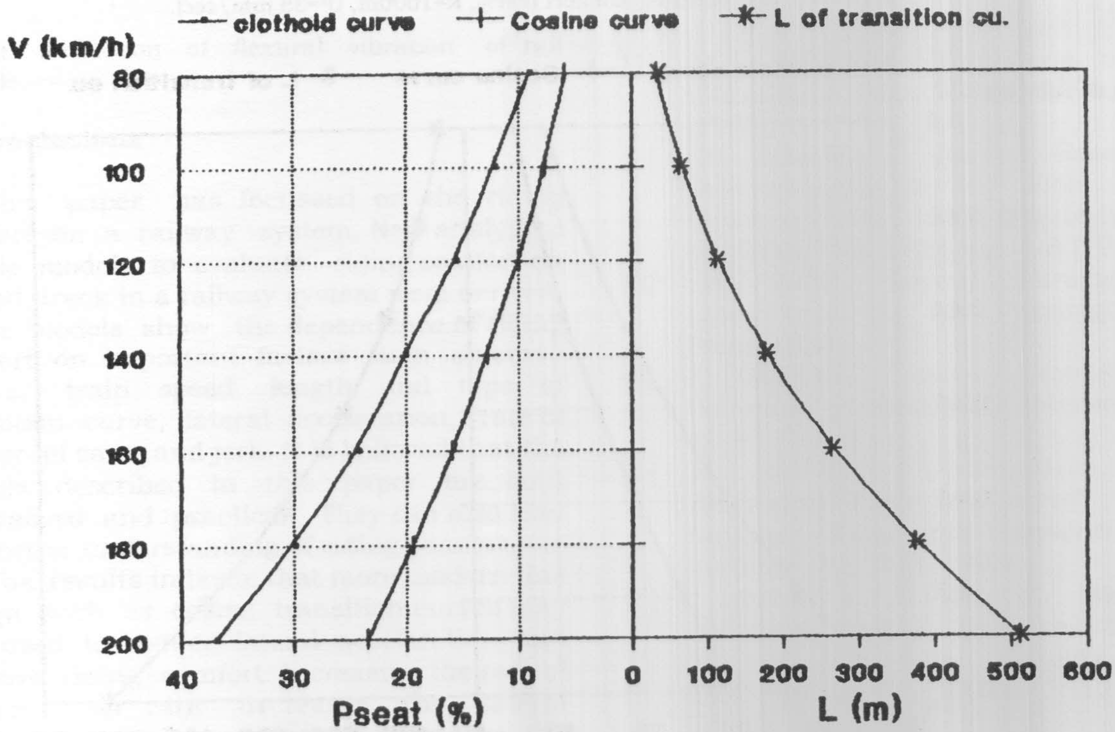

Fig. 8. Effect of type and length of transition curve, and train speed on riding comfort ($Pseat\%R$=1000m,a'= 0.4 m/sec^3, U'=35 mm/sec).

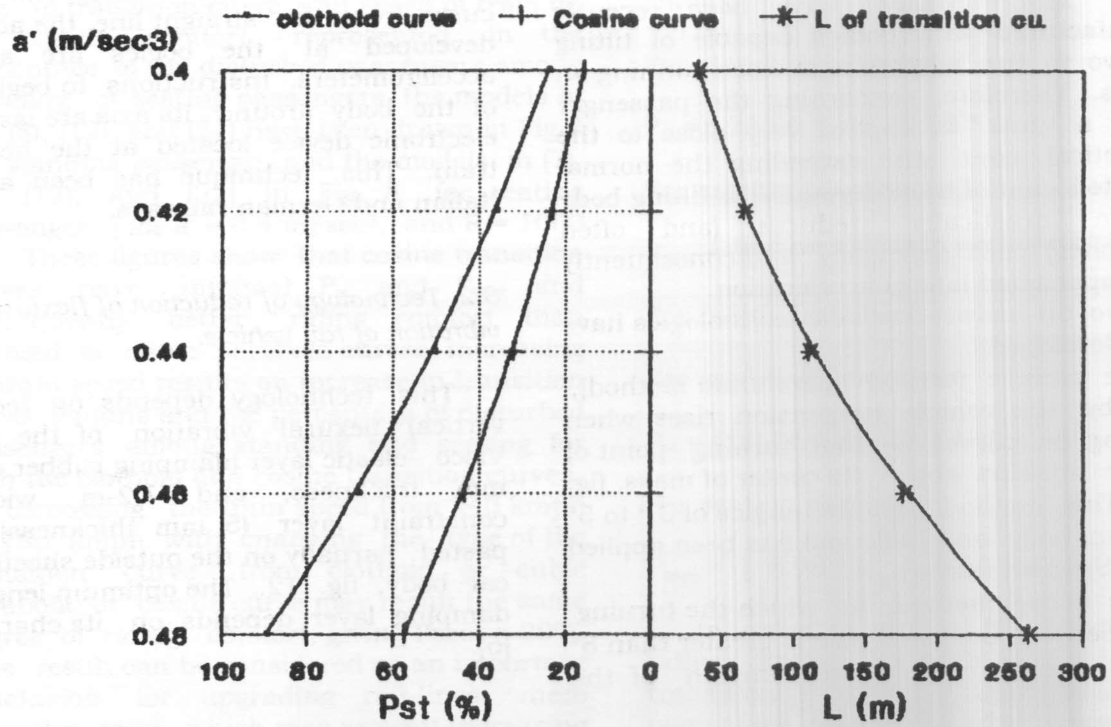

Fig. 9. Effect of jerk on riding comfort (Pst%, R=1000m, U'=35 mm/sec).

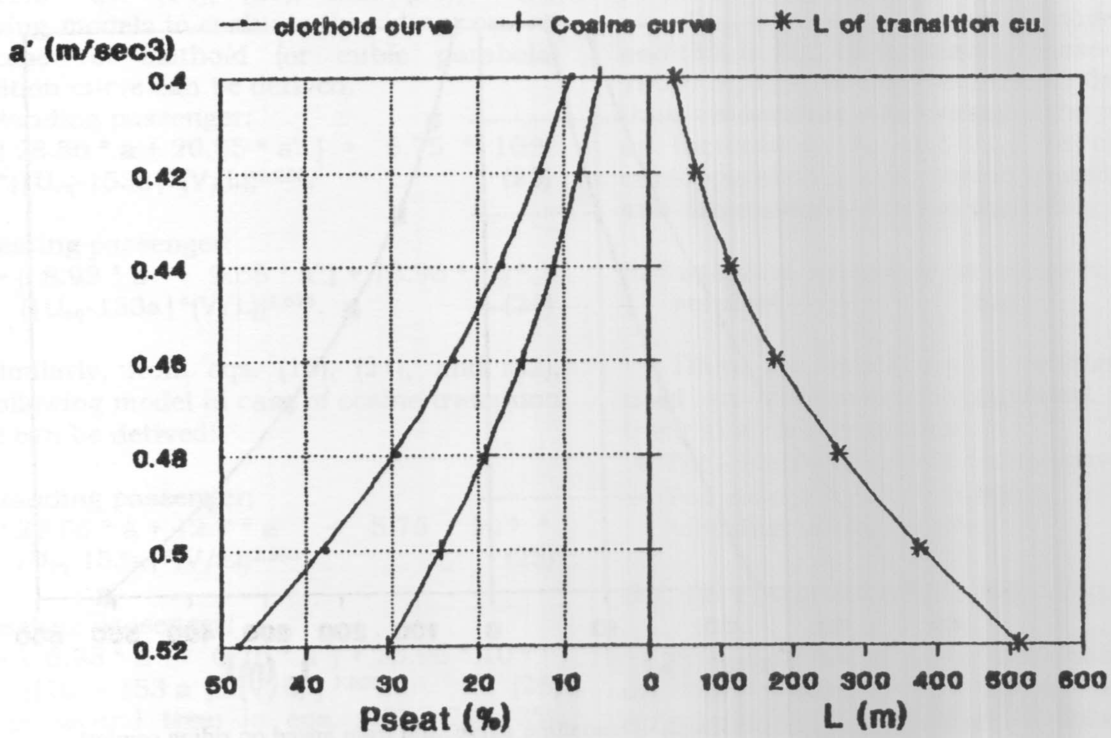

Fig. 10. Effect of jerk on riding comfort (Pseat%, R=1000m,U'=35 mm/sec).

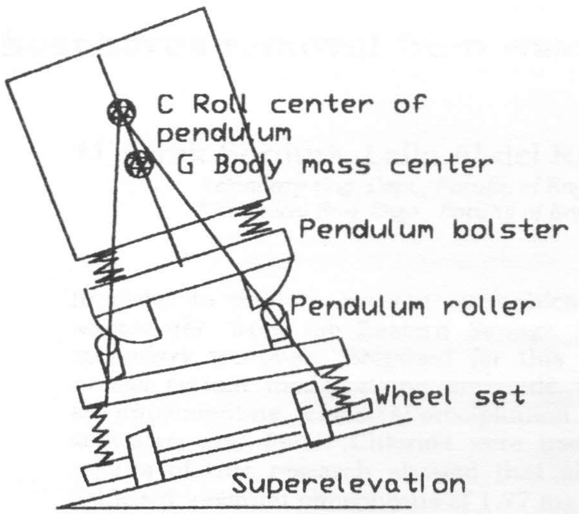

Fig. 11. Pendulum tilt-body rail vehicle technology.

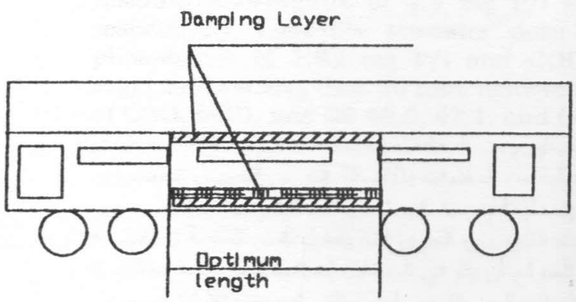

Fig.12. Reduction of flexural vibration of rail Vehicle.

6. Conclusions

This paper has focussed on the riding comfort on a railway system. New analytical simple models to evaluate riding comfort on curved track in a railway system were derived. These models show the dependence of riding comfort on important factors such as curve radius, train speed, length and type of transition curve, lateral acceleration, rate of change of cant, and jerk. It is believed that the models described in this paper are both generalized and practical. They can also lead to a better understanding of riding comfort.

The results indicate that more modern line design such as cosine transition curves may be used to reduce lateral acceleration and improve riding comfort. Increasing the rate of change of cant decreases the lateral acceleration and consequently increases the riding comfort. Cosine transition curves have mimimal percentage of disturbed passengers among standing and seating (P_{st}, P_{seat}) and better riding comfort than clothoid or cubic parabola transition curves. Increasing of train speed results an increase in transition curve lengths and the percentage of disturbed passengers among standing and seating for both the clothoid and cosine transition curves.

Increasing the train speed from 140 kmph to 180 kmph with changing the type of the transition curve from clothoid or cubic parabola to cosine curve may result the same degree of riding comfort (Pseat = 20%). This result can be considered as an important conclusion for upgrading rail-lines where obstacles exist that may prevent increasing the transition curve lengths.

Increasing the value of the jerk results an increase in P_{st} and P_{seat} for clothoid (or cubic parabolic) and cosine transition curves and consequently worsens the riding comfort.

Using of tilt - body rail vehicle and vehicles equipped with measures to reduce flexural vertical vibration may be other methods to improve riding comfort in a railway system.

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