Optimisation of clothoid lengths – simulations of dynamic vehicle reactions on horizontal curves with track irregularities


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KEYWORDS: Alignment, Clothoids, Radii, Track irregularities, Transition curves, Vehicle dynamics

ABSTRACT
In this study, equally costly alignment alternatives are compared. The cost is assumed to be correlated to the extent to which existing obstacles along a new alignment need to be removed. Hence, different combinations of radii and clothoid lengths are located in predefined terrain corridors.

An X2000 power car, a tilting X2000 coach and a non-tilting Eurofima coach have been studied. Vehicle reactions have been simulated in the time domain with non-linear vehicle/track models using 46 degrees of freedom for each vehicle.

Vertical wheel/rail forces, track shift forces and wheel climbing ratios have been used in boundary conditions, with limits suggested by UIC and CEN. Passenger comfort has been used as the object function. It has been found that in curve design, the most suitable single value is Comfort on Curve Transitions \( P_{CT} \) since this takes into account the combined effects of lateral acceleration, lateral jerk and roll velocity of the vehicle body.

The simulations are focused on the influence of the (design) alignment, but the track model also includes lateral, vertical, cant and gauge irregularities measured with the Swedish track recording vehicle STRIX.

INTRODUCTION
When increasing permissible train speeds on existing lines, the horizontal alignment is often the binding constraint. Therefore, the present study is focused on dynamic vehicle reactions when running through horizontal curves.

The alignments that are compared are selected in order to fit predefined terrain corridors. All alignment alternatives passing the same set of obstacles are assumed to be equally costly to build (Kufver, 1997a & 1998a). If an "obstacle" can be removed at no cost, it should not be classified as an obstacle, and vice versa if two compared alignment alternatives are not equally costly to build, this must be explained in differences in obstacles to be removed.

The concept of equally costly alignment alternatives and obstacles has been used in studies of the usefulness of S-shaped superelevation ramps (Kufver, 1999) and in studies of optimal combinations of radii and lengths of transition curves (Kufver, 1997b), (Kufver & Andersson, 1998), (Kufver & Gåsemyr, 1999a-b). The innovative feature in the present study is the presence of track irregularities.
ALIGNMENT ALTERNATIVES
In the present study, four predefined alignment corridors have been evaluated. In each corridor, there must be a single curve (a clothoid/circle/clothoid combination), which may be defined by the radius $R$ and the length of each transition curve $L_t$. The curves are located between tangent tracks, where the change in direction is 0.1 rad for two of the corridors, and 0.5 rad for the other two. The corridors enable the use of clothoid lengths of 180 m and radius 1888 m, which is the smallest curve radius for 200 km/h operation with conventional trains, according to Swedish track standards. (Certain vehicles, including tilting trains, may pass $R=1888$ m at a higher speed than 200 km/h.)

The binding obstacles defining the edges of the corridors are placed either in the middle of the curve or at the end. The latter cases may consist of turnouts on the adjacent tangent tracks, which should remain straight and without cant, see Figure 1.

![Figure 1. A double slip at Älvsjö (8 km south of Stockholm C) as a binding endpoint obstacle.](image)

Largest possible curve radius $R$ as a function of clothoid length $L_t$ is shown in Figure 2.

![Figure 2. Largest possible curve radius $R$ as a function of clothoid length $L_t$, in the four terrain corridors.](image)
VEHICLE MODELS

In the present study, the evaluation of different alignment alternatives is based on dynamic vehicle reactions. For economic and practical reasons, the dynamic vehicle reactions are estimated through simulations instead of measurements in full-scale tests. Such tests are expensive, but it also too difficult to control background variables such as vehicle speed, friction in wheel/rail contact, track stiffness and track irregularities.

The simulations have been conducted with the multibody code GENSYS. This code is used in a wide range of applications concerning track/vehicle interaction. Descriptions of the software and its performance in benchmark tests are published in Iwnicki (1999).

In the present study, the vehicles are modelled with seven rigid bodies (a vehicle body, two bogies and four wheelsets), each having six degrees of freedom, see Figure 3.

![Figure 3. Degrees of freedom in the vehicle models.](image)

The track model consists of a lumped mass connected to each wheelset. Each mass has one degree of freedom, lateral displacement. Vertical flexibility is introduced by a spring, representing a lumped flexibility, in wheel/rail contact, Figure 4. Data for dampers and horizontal springs in the track model are published in Kufver (1997b). Friction in the wheel/rail contact patches has been set at 0.4.

![Figure 4. Flexibility between wheel and track and between track and ground in the model.](image)

The following three vehicles have been studied:

1. The Eurofima coach (UIC-ZI), a non-tilting standard coach, used by several railway companies in Europe.
2. The SJ UA2 coach, a tilting coach used in the Swedish X2 trainsets (also called X2000).
3. The SJ X2 (X2000) power car, representing a modern, high speed locomotive.
Public vehicle data are published in Kufver (1997b).

EVALUATION VARIABLES
In the present study, it has been decided to follow recent CEN (1995 & 1999) and UIC (1999) draft standards on evaluation of track/vehicle interaction as closely as is possible and relevant. In wheel/rail contact, vertical wheel forces $Q$, track shift forces $\Sigma Y$ and climbing ratios $Y/Q$ have been evaluated, see Table 1.

Table 1. Variables in wheel/rail contact, processing and limits.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low-pass filter</th>
<th>Statistics</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical wheel force, $Q$</td>
<td>30 Hz</td>
<td>99.85-percentiles</td>
<td>180 kN</td>
</tr>
<tr>
<td>Track shift force, $\Sigma Y$</td>
<td>30 Hz, 2 m averaging</td>
<td>99.85-percentiles</td>
<td>10 kN+static axle load/3</td>
</tr>
<tr>
<td>Climbing ratio, $Y/Q$</td>
<td>30 Hz, 2 m averaging</td>
<td>99.85-percentiles</td>
<td>0.8</td>
</tr>
</tbody>
</table>

According to CEN (1999) and UIC (1999), the quantities in Table 1 should be evaluated at a slightly higher speed than the planned operating speed, but this has not yet been done. Further simulations are planned and will be presented during autumn 2000.

Passenger (dis)comfort is expressed as $P_{CT}$, passenger comfort on curve transitions. This measure takes into consideration the combined effect of lateral acceleration, lateral jerk and roll velocity of the vehicle body when passing transition curves (CEN, 1995). The signals are 2 Hz low-pass filtered and averaged during 1 second according to CEN. There are two $P_{CT}$ functions, one of which is validated for seated passengers and the other for standing passengers. In this paper, $P_{CT}$ for standing passengers will be shown. The $P_{CT}$ values indicate the percentage of the passengers who consider the level of comfort to be low.

TRACK IRREGULARITIES
Two sets of track irregularities were used in the present study, denoted Track A and Track B. They were selected on the criteria that the data sets are to represent poor track quality for 200 km/h operation, and that they are to be approximately equally poor over the entire length used in the simulations. The latter criterion was difficult to fulfil. Neither of the selected tracks contains any switches or crossings.

Track A contains irregularities from a compound curve on the up line from Malmö to Stockholm (southern main line in Sweden) at chainage 153+800 (km+metres). However, the curve is classified only for 130 km/h (165 km/h for tilt operation). The track quality just matches the maintenance limit for a
140 km/h track, and the limit is exceeded if standards for 145 km/h (and above) are applied. On the tangent track before the curve, the gauge is approximately 1430 mm, and on the transition curve, the gauge widens. On the circular portions of the curve, the gauge is approximately 1440 mm. In the simulations, the track irregularities were superimposed so that the start of the transition curve in the design alignment was in phase with the start of the transition curve in the file containing the irregularities. Appendix A shows irregularities plotted against chainage and power spectral density (PSD) for Track A.

Track B contains irregularities from tangent track on the up line from Gothenburg to Stockholm (western main line in Sweden) at chainage 158+000 (km+metres). The track is classified for 160 km/h (190 km/h for tilt operation). The track quality matches the maintenance limit for 145 km/h (and above). The limit is exceeded slightly for vertical irregularities, but there is a small margin for cant irregularities. The gauge is approximately 1433 mm. Appendix B shows irregularities plotted against chainage and PSD for Track B.

When superimposing track irregularities, the forces (99.85-percentiles) increase. Figure 7 shows Q forces and Y forces (plotted against distance along track) from a simulation of the Eurofima coach on tangent track with track irregularities, Track A.

![Figure 7a-b](image1.png)

Figure 7a-b. Vertical Q forces [kN] and lateral Y forces [kN] of two wheels of the Eurofima coach running on tangent track at a speed of 200 km/h. Irregularities from Track A are used in the simulation.

An overview of the effects of the irregularities on the vertical Q forces is shown in Table 2. (The length of the simulations on straight track is the same as for the two corridors with a change in direction of 0.1 rad.)

<table>
<thead>
<tr>
<th></th>
<th>No irregularities</th>
<th>Track A</th>
<th>Track B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurofima coach, 200 km/h</td>
<td>58.0 kN</td>
<td>71.2 kN</td>
<td>74.3 kN</td>
</tr>
<tr>
<td>SJ UA2 coach, 250 km/h</td>
<td>59.6 kN</td>
<td>78.5 kN</td>
<td>79.6 kN</td>
</tr>
<tr>
<td>SJ X2 power car, 250 km/h</td>
<td>90.2 kN</td>
<td>121.4 kN</td>
<td>118.8 kN</td>
</tr>
</tbody>
</table>

Measured irregularities from the outer rail of Track A have always been superimposed on the outer rail in the simulations. Track B, which contains irregularities from a tangent track, has been used twice for each alignment alternative, so that irregularities from the left rail and right rail have both been superimposed on the outer rail in the simulations.
**SIMULATIONS ON CURVES**

The vehicle reactions were estimated on the alignment alternatives in the terrain corridors, as defined in Figure 2. The circular curves were provided with 150 mm cant. The cant varied linearly on the clothoids, the ramps coinciding with the transition curves.

The non-tilting Eurofima coach passed the curves at a speed of 200 km/h. At the clothoid length $L_t=180$ m, cant deficiency is $I=100$ mm and rate of cant is $dD/dt=46$ mm/s, which are the limits according to Swedish track standards for conventional vehicles. On longer transition curves, the cant deficiency $I$ exceeds the limit, while on shorter transition curves (and superelevation ramps), the rate of cant $dD/dt$ exceeds the limit.

The resulting $P_{CT}$ values are shown in Figures 8-9. Each alignment alternative has been evaluated without irregularities, once with Track A and twice with Track B.

The vanes in the wheel/rail contact were all below their limits. This may be a consequence of the low cant deficiency in the reference alternative ($I=100$ mm). Certain railway administrations accept a cant deficiency of approximately 150 mm for this vehicle.

The tilting SJ UA2 coach passed the curves at a speed of 250 km/h. At the clothoid length $L_t=180$ m, cant deficiency is $I=241$ mm, which is slightly below the limit (245 mm) according to Swedish track standards for tilting trains. However, the rate of cant deficiency is $dI/dt=91$ mm/s, which is above the Swedish limit (78 mm/s). When lengthening the clothoids, cant deficiency $I$ exceeds the limit of 245 mm.

The resulting $P_{CT}$ values are shown in Figures 10-11. Again, each alignment alternative has been evaluated without irregularities, once with Track A and twice with Track B.
For the SJ UA2 coach, the track shift forces do not exceed the limit if cant deficiency is less than 297 mm for Track A (track quality for 140 km/h operation!) and 344 mm for Track B. The most critical case is the corridor with a change in direction of 0.5 rad and an endpoint obstacle, since this corridor generates the smallest radii (see Figure 2).

Vertical $Q$ forces and the wheel climbing ratios $Y/Q$ of the SJ UA2 coach did not exceed their limits.

The SJ X2 power car is heavier than the SJ UA2 coach and hence the limit for track shift forces $\Sigma Y$ is higher. Figure 13 shows that track shift forces (in relation to the limit) are not worse for the power car than the tilting coach.
Figure 13a-b. Track shift forces $\Sigma Y$ (worst wheelset, 99.85-percentiles) of the SJ X2 power car (speed 250 km/h). Terrain corridors with an angle of 0.5 rad.

Vertical $Q$ forces reach the limit of 180 kN at a cant deficiency of 320 mm for Track A and 370 mm for Track B. Such high cant deficiencies were only used in the terrain corridor with an angle of 0.5 rad and an endpoint obstacle ($R=1573$ m/Lt=340 m and $R=1414$ m/Lt=420 m, respectively). Wheel/climbing ratios $Y/Q$ were lower than the limit 0.8 in all alignment alternatives.

DISCUSSION AND CONCLUSIONS

The results from the present study confirm earlier observations and conclusions published in Kufver (1997b), Kufver & Andersson (1998) and Kufver & Gåsemyr (1999a-b). The clothoid lengths of a single curve that minimise comfort disturbances ($P_{CT}$) depend on:

1. The angle between the adjacent tangent tracks. A larger angle results in longer optimal clothoids.
2. The position of the binding obstacles. A binding obstacle in the middle of the curve normally results in a longer optimal clothoid than a binding obstacle at the end.
3. Vehicle characteristics. Tilting vehicles result in longer optimal clothoids than non-tilting vehicles.

The $P_{CT}$ values are generally higher for track with irregularities than without, and are generally higher for Track A than Track B. However, the clothoid lengths $L_{t^*}$ that minimise $P_{CT}$ are in most cases the same, independent of the track irregularities.

A small percentage of passengers suffer from symptoms of motion sickness when travelling in a tilting train. The contribution from different types of motion is unclear (Förstberg & Ledin, 1996), but results from Japan (Koyanagi, 1985), (Ohno, 1996) and Sweden (Förstberg, 1996) indicate that roll motions are important. In Japan, it has been found that when limiting roll velocity of the vehicle body to 0.1 rad/s and roll acceleration to 0.3 rad/s$^2$, tendencies to motion sickness have been reduced, although they have not been completely eliminated (Ohno, 1996). In the present study, roll velocities are lower than 0.1 rad/s when the clothoids are 140 m or longer for the 0.1 rad curves, and 180 m or longer for the 0.5 rad curves. In the four evaluated terrain corridors, roll velocities for of the tilting SJ UA2 coach become less than 0.1 rad/s when $P_{CT}$ is minimised.

In planning new railways and realigning of existing ones, the following two aspects should be taken into consideration:

1. The optimal alignments are not the same for tilting vehicles compared to non-tilting vehicles. The optimal transition curves are longer for tilting trains.
2. For tilting trains, the desire for long transition curves (due to passenger comfort) must be balanced against the desire for large curve radii (due to wheel/rail forces).
ACKNOWLEDGEMENTS

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REFERENCES


Figure A. *Track A*: Irregularities as a function of distance along track and as PSD.
Figure B. Track B: Irregularities as a function of distance along track and as PSD.
Statens väg- och transportforskningsinstitut (VTI) har kompetens och laboratorier för kvalificerade forskningsuppdrag inom transporter och samhällsekonomi, trafiksäkerhet, fordon, miljö samt för byggande, drift och underhåll av vägar och järnvägar.

The Swedish National Road and Transport Research Institute (VTI) has laboratories and know-how for advanced research commissions in transport and welfare economics, road safety, vehicles and the environment. It also has research capabilities for the construction, operation and maintenance of roads and railways.

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