Optimisation of the railway alignment considering vehicle reactions

Paper presented at the International seminars on infrastructure and vehicle/infrastructure interaction, 18-19 February 1998 at the Hong Kong Convention and Exhibition Centre, Hong Kong, China, organised by the Institution of Civil Engineers

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OPTIMISATION OF THE RAILWAY ALIGNMENT CONSIDERING VEHICLE REACTIONS

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Background

The alignment of a railway has a high degree of permanence. When the alignment is altered, other technical subsystems, as superstructure, substructure, catenary systems etc., must be altered as well. Therefore, changes in alignment are normally associated with high costs. This indicates that the alignment of new railways should be designed to meet future demands, but an unnecessarily high standard may make the project too expensive and cause an undesirable impact on the environment. These facts lead to the conclusion that the alignment should be optimised with great care when building new lines (ref. 1).

Levels of analysis

Three levels of analysis have been identified. At Level One, the horizontal alignment (radii of horizontal curves, lengths of transition curves) is fixed and the track engineer is able only to choose the amount of cant.

At Level Two, there are obstacles (existing structures etc.) along the route which must be passed with a predefined clearance. There are possibilities to vary radii and transition lengths, and all alignment alternatives which pass the same set of obstacles (with at least the predefined clearance) are assumed to be equally costly to build. In comparisons between different alignments, each of these should be evaluated with its most suitable cant according to analysis at Level One.

At Level Three, the obstacles may be removed, in which case the alignment alternatives will be associated with different construction costs. In such an analysis, it is reasonable to compare the best alignment alternative at each cost level, derived from analysis at Level Two. In this paper, analysis on Level Three will not be described.

Models

Vehicle reactions have been quantified with two different methods:

1. A simplified analysis assumes that lateral acceleration within the vehicle body is proportional to the lateral acceleration in the (superelevated) track plane. An effective roll factor \( f_r \) describes the relation between the two accelerations. The effective roll factor is assumed to be 1.2 for a conventional passenger coach (Eurofima) and 0.3 for an X2000 tilting coach. In the simplified analysis, the roll angle of the vehicle body and the lateral acceleration are assumed to change linearly on the transition curves.

2. A dynamic analysis is conducted with the multibody computer code GENSYS. Vehicle bodies, bogies and wheelsets are modelled as rigid bodies and have six degrees of freedom each (see Figure 1). The track is modelled as a rigid body connected to each wheelset and there is one degree of freedom for each track body: lateral displacement. Hence, this model contains 46 degrees of freedom for each vehicle.

Springs and dampers in the GENSYS model are non-linear. Track and vehicle data are published in ref. 1. Simulations are conducted in the time domain.
Variables and criteria

It has been concluded that, whenever possible, the same variables, the same filtering, the same statistical evaluation and the same limits should be used when evaluating alignments as when evaluating vehicles (ref. 2). UIC 518 OR (ref. 3) and CEN TC 256 WG 10 (ref. 4) are working on evaluation of track/vehicle interaction and have issued draft standards suggesting evaluation of vertical wheel/rail forces, guiding forces, track shift forces and wheel climbing ratios. The following limits from ref. 3 were applied:

- Vertical wheel/rail forces (99.85-percentiles) 170 kN
- Track shift forces (99.85-percentiles) 10 kN + static axle load/3
- Wheel climbing ratio (99.85 percentiles) 0.8

A provisional Swedish limit of 45 kN was used for the 99.85-percentiles of the guiding forces, since both UIC and CEN suggest that only median values of guiding forces be evaluated.

However, in this study, it was considered that in most cases it is not of crucial importance for a railway company to reduce these variables to absolute minima. Instead, it is preferable to use passenger comfort as the object function, in order to minimise the comfort disturbances when passing the curve at a relatively high speed.

Ride comfort

Passenger comfort is of a complex nature. In curve design, where radii, cant and transition lengths are to be chosen, the most suitable single value is Comfort on Curve Transitions ($P_{CT}$) which takes into consideration steady state lateral acceleration, lateral jerk and roll velocity of the vehicle body (ref. 1).

The $P_{CT}$ functions show the percentage of the passengers who regard the lateral ride as "very uncomfortable" or "uncomfortable" on a five-level scale (ref. 5). There is one $P_{CT}$ function for seated passengers and another for standing passengers. The latter, which is used in this study, is:
\[ P_{CT} = \max(2.80 \cdot \dddot{y} + 2.03 \cdot \dddot{y} - 11.1, 0) + 0.185 \cdot (\ddot{\theta})^{2.283} \]

where \( \dddot{y} \) = maximum absolute value of low-pass filtered lateral acceleration of the vehicle body, expressed in per cent of g

\( \dddot{y} \) = maximum absolute value of low-pass filtered lateral jerk of the vehicle body, expressed in per cent of g per second

\( \ddot{\theta} \) = maximum absolute value of low-pass filtered roll velocity of the vehicle body, expressed in degrees per second

\( g \) = gravitational acceleration

**Analysis of single curves (clothoid - circle - clothoid combinations)**

The analysis assumes the lateral positions of the adjacent straight lines to be fixed in positions which are the same for all curve combinations. The analysis also assumes that the lengths of the transition curves are the same at both ends. On these assumptions, the curve geometry can be defined with two variables, and in this case it is reasonable to use the radius (\( R \)) and the length of a transition curve (\( L_t \)). In reality, it may be possible to create compound curves, to have different transition lengths and to alter the positions and directions of the adjacent straight lines. However, sooner or later in the design process the straight lines will be fixed, and normally compound curves are neither desirable nor necessary. The element combination and the assumptions made in this discussion correspond to the most frequent case in a design process.

Figure 2 shows a permissible zone for comparing equally costly alignment alternatives, when a number of obstacles along the alignment are considered. The best alignment alternative may be expected to be found on the border defined by the obstacles, since an \( R-L_t \) combination within the zone may be improved by larger radius and/or longer transition curves. At the border, increased lengths of the transition curves always result in a smaller radius.

![Figure 2](image-url)  
**Figure 2.** Equally costly alignment alternatives in the \( R-L_t \) plane.
It has been found that obstacles in the middle of the curve and at the end constitute the extremes, requiring the smallest and the largest compensations of radius, when lengthening the transition curves. It has also been found that a smaller angle between the adjacent straight lines requires a larger compensation of radius than a larger angle between the straight lines.

In order to clarify the relations, only one binding obstacle is used in the figures below, and it is placed either in the middle of the curve or at the end. The curve radius (R) at Lt=180 m is in the figures 1888 m and these values correspond to the smallest radius and shortest transition for conventional trains running at 200 km/h.

Figure 3 shows $P_{CT}$ values according to the simplified analysis, for a curve with an obstacle in the middle of the curve and an angle of 0.5 rad between the adjacent straight lines. $P_{CT}$ (for standing passengers) is calculated for conventional vehicles ($fr=1.2$) running at 160, 200 and 220 km/h and for tilting vehicles ($fr=0.3$) running at 220 and 250 km/h. All alignment alternatives are evaluated with the optimal cant (resulting in the lowest possible $P_{CT}$ value), but an upper limit of 150 mm has been applied.

![Figure 3](image-url)

Figure 3. Simplified $P_{CT}$ on a curve with an angle of 0.5 rad and a midpoint obstacle.

On short transition curves, passenger discomfort is caused mainly by high lateral jerk and high roll velocity, while on very long transition curves, the discomfort is caused by high lateral accelerations (since the radius is reduced). A lower effective roll factor results in lower $P_{CT}$ values, but also in longer optimal transition curves, since the negative effects of small curve radii are reduced. For the same reason, a higher limit than 150 mm for cant will result in longer optimum transition curves.

Figure 4 shows $P_{CT}$ values according to the dynamic analysis, for tilting trains running at 250 km/h on curves with an angle of 0.1 and 0.5 rad respectively and with an obstacle placed either in the middle of the curve or at the end. Again, all alignment alternatives are evaluated with the optimal cant. It is found that larger angles between the straight lines and obstacles near the middle of the curve (rather than near the end) favour longer transitions.
In the calculations, the limits for wheel forces and climbing ratio were not exceeded unless the transition curves were far longer than optimum and the cant deficiencies were larger than 415 mm. However, no track irregularities were used in the simulations. Hence, further investigations, including different levels of track irregularities, are necessary.

Figure 4. $P_{CT}$ for a tilting coach passing curves at 250 km/h. Dynamic analysis.

Conclusions

It has been found that
- large angles between the adjacent straight lines
- obstacles in the middle of the curves (rather than near the ends), and
- low roll coefficients of the vehicles

favour longer transition curves, even though the radii must be reduced.

In particular, tilting trains favour longer transitions since the comfort in these trains is less affected by reductions of radii. Generally, train speeds have a low influence on the optimal lengths of the transition curves.

References
Statens väg- och transportforskningsinstitut (VTI) har kompetens och laboratorier för kvalificerade forskningsuppdrag inom transport- och samhällsekonomi, trafiksäkerhet, fordon, miljö samt för byggnad, 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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