Abstract

This paper describes a new method for turnout design developed by VAE Aktiengesellschaft of Zeltweg, Austria and work done by BWG Butzbacher Weichenbau Ges.m.b.H., a company of the VAE Group.

The traditional turnout design methods assume the vehicle to be a mass point travelling on a curve.

Recognizing the shortcomings of this method VAE initiated a research and development effort to examine new methods for the design and evaluation of turnout geometries using the Association of American Railroads’ NUCARS vehicle dynamics model. The goal was to find out what sequence of diverging route curves and spirals would lead to optimal vehicle performance in a turnout.

The results show that: Tangential geometries are superior to other types of entry geometries, turnouts incorporating clothoids are clearly superior to constant radius geometries and geometries with clothoids for the entry and the exit to the turnout are better than single clothoid geometries. With this method it is possible to reduce the forces created between wheel and rail by up to 30%.

BWG has developed a method to further reduce the forces that are created when a car makes the transition from stockrail to switch blade. The method is called “Kinematic Gauge Optimization = KGO”. Making better use of the rolling radius difference it allows to further reduce the forces in a turnout by up to 50%.

Calculated results will be given.
1 Introduction

This paper describes a new method for turnout design developed by VAE Aktiengesellschaft of Zeltweg, Austria. With over 130 years of experience in the design and manufacture of turnouts, VAE is the world’s leading supplier of special trackwork. This includes turnouts for such diverse applications as the Italian State Railway’s Direttissima high-speed line in Europe and Union Pacific’s heavy-haul coal lines in North America. Specialty products include rail joints for Hong Kong’s Tsing Ma suspension bridge, an electronic monitoring and diagnostic system for special trackwork, and a state-of-the-art hot box detector.

Traditional turnout design methods assume vehicle response is determined by kinematics, rather than dynamics [1,2]. Turnout centerline geometry is defined by a series of spiral (clothoid) or constant radius curve segments. The resulting geometry is usually represented graphically by plotting curvature versus track position. An example is shown in Figure 1.

![Figure 1. Turnout Geometry as Curvature versus Position](image1)

For a given vehicle speed and assuming the vehicle to be a point mass, the uncompensated lateral acceleration through the turnout can be calculated. Turnouts or crossovers are generally designed based on three parameters derived from the kinematic acceleration. These are:

- Maximum uncompensated lateral acceleration (m/s²)
- Maximum rate of acceleration change (m/s³)
- Maximum entry and exit jerk (m/s⁴)*

*Jerk is calculated using an assumed vehicle length, usually the truck center distance.

The task of the designer is to develop a geometry meeting limiting values specified by the customer. Clearly the simplest geometry is a constant radius curve. This also provides the lowest uncompensated lateral acceleration. The penalty, however, is an unacceptable entry and exit jerk due to step changes in track curvature at the turnout start and end. Increasing the entry and exit radii will force a decrease in the mid-point radius. This will lower the entry and exit jerk while increasing the maximum lateral acceleration. To further complicate the designer’s task, overall geometry is often fixed. For example, when considering a crossover, track center distance is not a variable. Crossover length and turnout angle may also be fixed.

A failing of the traditional design method is that vehicle response is clearly dynamic. At its simplest, a vehicle and its suspension system might be considered a single degree of freedom mass-spring-damper system. The changes in track curvature created by a turnout are equivalent to a set of step inputs. As shown in Figure 2, simple kinematic considerations will underestimate actual response. Field measurements confirm that lateral accelerations in turnouts are up to twice the kinematic values [3].

![Figure 2. Kinematic versus Dynamic Response](image2)

Recognizing the shortcomings of the existing design approach, VAE initiated a research and development effort to examine a new method for the design and evaluation of turnout geometries. This considers turnout design as a vehicle/track interaction problem. The chosen method is to use a vehicle dynamics simulation to predict forces and accelerations through the turnout.

2 The Vehicle Dynamics Model

For this project, VAE used the Association of American Railroads’ NUCARS vehicle dynamics model [4]. First released in 1987, NUCARS is a generalized multi-body simulation code with specialized features particular to rail vehicle applications.

NUCARS models the vehicle/track system as a set of masses and connections. These represent the car body, bogies, wheel sets, and the links created by suspension components. Provision is made to represent the various non-linearities inherent in a rail vehicle. One of particular importance is wheel/rail interaction. NUCARS includes a state-of-the-art non-linear wheel/rail interaction model. The two components of this model are non-linear calculation of wheel/rail contact geometry and contact force calculation based on the theories of Hertz and Kalker. The contact geometry model represents the geometric constraints created by contact between wheel and rail. This includes the effect of rail cross-section changes through the switch point and frog. Contact patch size and ellipticity are calculated using the theory of Hertz. The forces generated by rolling contact and sliding or creep between wheel and rail are obtained from Kalker’s non-linear theory [5].
3 Optimization Methodology

3.1 Problem Definition

As mentioned, the goal of the VAE development effort was a design method to determine optimal turnout geometries. Plainly stated, what sequence of diverging route curves and spirals would lead to optimal vehicle performance in a turnout or crossover?

The first task was to define the optimization problem in terms of a limited set of design variables. One requirement is thus the selection of specific form for the turnout geometry. The form to be discussed here is a vertex clothoid as illustrated earlier in Figure 1. Note that this is by no means the only geometry this method has been applied to. It is the simplest. The vertex clothoid defines the turnout diverging route as a pair of back-to-back spirals. The design problem becomes one of choosing the initial radius, the radius at the begin of the second spiral, the final radius, and the lengths of the two spirals.

The next step in the problem definition is to create a non-dimensional set of design parameters. Radius values are non-dimensionalized with respect to the minimum radius of curvature, while the vertex position is non-dimensionalized with respect to the total turnout length. For a single vertex clothoid turnout, this results in three non-dimensional parameters, each ranging from 0 to 1. These describe the geometry in a generalized form:

- Initial radius parameter: $\alpha_1 = \frac{R_{\text{min}}}{R_1}$
- Final radius parameter: $\alpha_2 = \frac{R_{\text{min}}}{R_2}$
- Vertex location: $\nu = \frac{L_{\text{vertex}}}{L}$

A fourth parameter is the location of the minimum radius. Figure 3 illustrates the three possibilities. Most optimal solutions correspond to Case 2 with the vertex in the body of the turnout.

![Figure 3. Potential Turnout Geometries](image)

3.2 Response Variables

Having defined the design problem, the next question is how to evaluate turnout performance in terms of simulation output variables. VAE has chosen to examine ride quality, wheel/rail forces, and predicted rail wear rates.

For ride quality, the response values of interest are lateral acceleration and jerk (the acceleration first derivative). Based on ISO and CEN standards, acceleration and jerk values are filtered to remove the high-frequency components which do not influence ride quality [6,7].

Turnout component life is most strongly influenced by wheel/rail lateral forces and predicted rail wear rates. Lateral forces are determined by wheel, by truck side, and by truck total. The single wheel force determines local stresses on turnout components. Rail in a turnout, particularly at the switch point, does not have the strength of a full rail section. The truck side lateral force is an indicator of the potential for rail rollover or fastener loads. Total truck force determines the likelihood of track panel shift. Rail wear rates predict the rate of loss of cross-section, of particular importance at such critical areas as the switch point.

3.3 Optimization in Practice

The use of simulation as an integral component of the design process has required the development of an optimization program to steer the vehicle dynamics code. Software created by The Arc Group Incorporated, VAE’s partner in this project, automatically generates NUCARS input files for an array of parameter values. This includes generating turnout geometry data and wheel/rail cross-sections. NUCARS is then used to produce simulation outputs. These are analyzed by further purpose-written software to determine the optimal solution.

The task of the designer is essentially to define a solution space. The current optimization code uses a simple grid search within the parameter space. More sophisticated search methods are anticipated in the future. The optimal solution is defined through an objective function weighting various response values. Considerable effort has been involved in evaluating the influence of the chosen weighting factors.

While the resulting optimal geometries are often vehicle specific, some generalizations can be made. First, turnouts incorporating clothoids are clearly superior to constant radius geometries. A gradual increase in diverging route curvature leads to reduced initial accelerations. The maximum curvature or tightest radius generally occurs after a point mid-way through the turnout. The final radius is generally smaller than the initial radius. This creates an asymmetric geometry considerably different from current designs.

Before presenting some sample results, several practical observations should be made. First, the optimal design may not always be practical in terms of manufacturing cost. One feature of the optimization program is the ability to examine design parameter sensitivity. This allows the influence of deviations from the optimal design to be evaluated. Next, the best turnout will perform poorly if improperly installed. The design simulations assume perfect geometry. Repeated simulations made with varying random track defects indicated that the average response was virtually identical to the perfect geometry response. This implies that design calculations can predict net or average improvements. If desired, design robustness can then be verified through stochastic calculations.
4 Kinematic Gauge Optimization KGO

To further reduce the forces created by a car entering the diverging route of a turnout the Butzbacher Weichenbau GesmbH BWG, a company of the VAE Group, has developed a method of optimizing the transition geometry in the switch area. The method is called “Kinematic Gauge Optimization = KGO”.

The steering of railway wheels is achieved through the rolling radius difference between the left and the right wheel on an axle. In a standard turnout when a wheel makes the transition from the stock rail to the switch point the contact point between wheel and rail moves outward to a smaller rolling radius on the wheel. This has a negative steering effect, the axle starts to turn towards the switch point and the flange of the wheel rides against the gauge face of the switch point. This results in high lateral forces and wear on the switch points.

A KGO turnout makes better use of this rolling radius difference by an asymmetric widening of the gauge in the transition area in the switch. The gauge of the stock rails is widened in such a way that the wheels steer in the right direction at the right time. This avoids hard flange contact of the wheels and the switch points, reduces the lateral forces and so also reduces the wear of the components.

In these turnouts the switch points become thicker much quicker which makes the points more stable and at the same time gives more wear allowance.

5 Sample Results

This section will present several sample results. First are example predictions of a simulation for a standard AREMA #20 geometry turnout, a coal hopper car and a running speed of 40 mph. These are followed by predictions for a turnout with optimized geometry and the same lead length and turnout angle. The final results show the benefit of using an optimized transition geometry according the KGO method. The example given is for a high speed turnout for 190 mph on the tangent line and 140 mph in the diverging line. The calculation is for an ICE train with ORE 1002 wheel and compares the predicted results for a geometry without and with KGO.

5.1 AREMA #20 Turnout Response

The base line for the comparison of different geometry variations is the standard AREMA #20 turnout. Figure 4 shows lateral forces through the turnout for a loaded coal hopper car at a running speed of 40 mph for the left and right wheel of the first axle.

5.2 Optimized #20 Turnout Response

To illustrate the influence of the optimization process this section gives an example of a turnout with the same lead length and turnout angle as a standard AREMA #20 turnout. The turnout curve consists of two back to back clothoids (spirals) with the bigger radius of 4000’ at the entry of the turnout, a smaller radius of 2100’ in the body of the turnout and a bigger radius of 4200’ at the heel end of the turnout. Figure 5 shows again the lateral forces through the turnout for a loaded coal hopper car at a running speed of 40 mph for the left and right wheel of the first axle.
5.3 Influence of KGO Optimization

This section presents the results for a high speed turnout for 140 mph turnout speed. Again the car type, the speed, the axle load and the general dimensions of the turnout remain the same for both examples. The only thing that changes is the transition geometry in the switch area with the first turnout having no KGO transition and the second is with KGO.

![Graph showing lateral wheel/rail forces for the first axle in the turnout without KGO optimized transition.](image1)

**Figure 6.** Leading Axle Wheel/Rail Forces in a High Speed Turnout without KGO

Figure 6 shows the lateral wheel/rail forces for the first axle in the turnout without KGO optimized transition.

![Graph showing lateral forces for the first axle in the turnout with KGO optimized transition.](image2)

**Figure 7.** Leading Axle Wheel/Rail Forces in a High Speed Turnout with KGO

Figure 7 shows the lateral forces for the first axle in the turnout with KGO optimized transition. This example demonstrates that by only changing the transition geometry in the switch area it is possible to reduce the maximum forces in this area by approximately 40%.

6 Implementation

As a first test of this design method, VAE has developed a turnout for the Italian Railway’s High Speed Line. The turnout is installed and has passed its first running tests very favorably.

Currently VAE and VAE NORTRAK are working with the two biggest railroads in the USA to develop a new optimized turnout geometry for the Heavy Haul territories.

We hope to report in the future on the improved ride comfort and reduced maintenance requirements provided by VAE’s new optimized high-speed and Heavy Haul crossover designs.

Turnouts with optimized geometry according to the KGO method are installed on DB German Railway’s high speed lines and on RENFE Spanish Railway’s high speed lines AVE since the late 1980s with big success.

7 Conclusions

In virtually every area of engineering, the use of increasingly sophisticated tools has led to improved designs. New methods allow the design engineer to evaluate more alternatives and have greater confidence in the suitability of the chosen solution. The use of vehicle dynamics software brings this trend to turnout design.

The optimization methods presented here result in turnout and crossover designs which:

♦ Reduce passenger compartment accelerations and thus improve passenger ride quality
♦ Reduce wheel/rail forces and thus reduce turnout maintenance requirements

Both of these advantages are of considerable potential importance. For example, many rail carriers have begun to experience capacity problems as traffic increases. Maximum allowable speed through existing turnouts often determines capacity at critical junctions or terminals. An improved turnout geometry offers the potential to increase operating speed while not exceeding the peak acceleration values obtained in current geometries. A reduction in turnout forces in turn reduces turnout maintenance requirements. This reduces the demand for line closures or rerouting due to maintenance work. Both factors increase available line capacity.
8 References


