ALIGNMENT ANALYSIS AND COMPARISON TECHNIQUES FOR SMALL RAILROAD PROJECTS IN THE 21ST CENTURY

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ABSTRACT

The current guidance provided for alignment studies stems largely from Wellington's "Economic Theory of The Location of Railways" which discusses the problem of minimizing grades and curves on a transcontinental scale. However, modern engineers often find themselves working on a less grand scale with shorter projects such as industrial spur build-ins and urban by-passes, and needing to consider a host of engineering and environmental factors other than railroad geometry to complete a modern railroad alignment study. This paper describes alignment analysis and comparison techniques that have been used successfully in the development of preferred railroad geometry for such projects ranging from five to 50 miles in length. Two main techniques are highlighted: indexes for comparing grades and curves on short alignments, and the matrix approach to alignment analysis and comparison. The matrix approach allows a particular alignment to be evaluated on the basis of multiple criteria, each considering several factors. To avoid bias in the creation of the matrix, each evaluation area is given a weight in advance of the study by the owner. Once alignments are established, the evaluation is made in the form of a score, including those criteria and factors where the observed data is qualitative and not quantitative in nature. The individual alignment scores are then multiplied by the weights to form an overall alignment score. This overall score can be directly compared to that of other alignments to make decisions regarding a preferred alignment and a final recommendation to the owner.

INTRODUCTION

In the current environment of railroad capacity expansion, an increasingly common task assigned to a railway engineer is the comparison of several alternative alignments for a new rail line. The basic criteria for railroad alignment comparison and route selection stem largely from the classic text by A.M. Wellington titled "Economic Theory of the Location of Railways" that describes the ideal railroad as that taking the flattest, straightest and shortest route between two points. While Wellington discusses the problem of minimizing grades and curves on a transcontinental scale, modern engineers often find themselves working on a less grand scale with shorter projects such as industrial spur build-ins and urban bypasses, and needing to consider a host of engineering and environmental factors other than railroad geometry to complete a railroad alignment study. In addition, remote sensing and computer design programs allow multiple alignment alternatives to be generated in a fraction of the time it took Wellington to develop a single route in 1887.

The need to simultaneously evaluate a number of routes or alignment alternatives with respect to multiple engineering, environmental and social factors led to the development of a matrix analysis approach for railroad alignment studies. The process was adapted from practices which are more commonly used in general transportation planning and has been refined over the course of several railroad alignment studies. This paper will outline the matrix analysis approach, including descriptions of the various evaluation categories and methods of weighting and scoring. An important component of the matrix analysis approach is the calculation of indexes that allow quick and efficient comparisons between the grades and curves on multiple short alignments. These indexes will be described in more detail following the description of the matrix analysis approach.

MATRIX ANALYSIS APPROACH

The matrix analysis approach is used to compare multiple alignment alternatives under consideration for a railroad project. The alignment alternatives are selected such that they represent distinct routes with differing horizontal layouts. However, it is possible for alignment alternatives to have common segments, particularly near start and end points. The analysis does not require that the alignment alternatives have common start or end points. This is useful when studying a line into a new industrial plant where there are several possible locations to tie the line to an existing mainline.

In the matrix analysis approach, each alignment alternative is judged relative to several evaluation categories. These evaluation categories are subdivided into multiple decision criteria against which the alignments are scored. The individual scores for each criteria are weighted and summed to produce a category score. These category scores are then weighted again and summed to produce a total score for the alternative. The total score derived through this "double weighting" system provides a means to directly compare the overall performance of each alternative relative to the various decision factors deemed important by the client.

To make an effective comparison, each alignment alternative must be developed to the point where preliminary horizontal and vertical geometry has been established. If a more detailed survey of the study area has not been conducted, preliminary alignments can typically be developed using digital elevation data or topographic map contours available from the United States Geographic Service to model the existing ground. A more detailed comparison can be made if a very preliminary earthwork model is developed for each alignment. This model, made by a first pass of a generic subgrade slope template in a rail design program, not only provides quantity information for cost estimation but also provides a footprint for the evaluation of environmental impacts and can illuminate potential constructibility issues.

EVALUATION CATEGORIES

In this railroad application of the matrix analysis approach, five evaluation categories are used to evaluate the engineering, financial, societal, environmental and political aspects of a railroad project. The five evaluations categories are:

- Operational efficiency, mobility and safety effects
- Cost effectiveness
- Social and economic effects
- Environmental effects
- Public and agency support

As mentioned above, each of these evaluation categories are further broken down into multiple criteria for which scores are determined, typically on a scale of zero to five, with zero being the least optimal and five being the most optimal.

The criteria include quantitative factors that can be measured through field investigation (such as acres of wetland impact), examination of design features and geometry (such as ruling grade), and preparation of preliminary cost estimates. The criteria also include qualitative factors such as ease of implementation, social and economic effects, and public and agency support that cannot be measured directly but, with the aid of various sources of information regarding the alignment alternatives, engineering judgment can provide reasonable scores. In the following sections, the criteria for each evaluation category are described in more detail.

Operational Efficiency, Mobility and Safety Effects

The criteria for the operational efficiency, mobility and safety effects are selected to provide a measure of how optimal an alignment alternative is from a traditional engineering perspective. That is, they attempt to measure how well the alignment minimizes length, curves and grades to produce a railroad that operates efficiently and safely. The decision criteria are:

- Operational efficiency
- Public safety
- Railroad operational safety
- Number of grade crossings added (or eliminated)
- Level of service at grade crossings

These criteria illustrate how both qualitative and quantitative factors are combined to produce a score for a particular evaluation category. They also illustrate how many of the criteria are both quantitative and qualitative in nature. While the number of grade crossings added can easily be quantified, public safety and railroad operational safety are more qualitative assessments based on a combination of alignment geometry, proposed operations and proximity to population areas. Operational efficiency falls somewhere between quantitative and qualitative as, although individual route characteristics such as total length, ruling grade, rise and fall, and total curvature can easily be measured, interpreting this data results in an overall assessment of the operational efficiency of the route that is somewhat qualitative. Some of specific techniques developed for comparing operational efficiency will be discussed later in this paper.

This variation in criteria also illustrates that the matrix analysis approach does not consider the railroad design in a vacuum, as it includes items such as the level of service at grade crossings that do not impact the owners or operators of the railroad but do have an impact on the railroad's surrounding transportation systems and population.

Cost Effectiveness

The criteria for the cost effectiveness category are selected to provide a measure of the overall cost of the projects both in terms of construction capital and ongoing operations. The decision criteria are:

- Total cost
- Railroad operational and maintenance cost
- Roadway maintenance costs
- Ease of implementation

The matrix analysis allows the alignments to be evaluated not just on the basis of initial construction cost, but also on the basis of continual operating and maintenance expenses. Maintenance expenses are estimated with the aid of "Equated Mileage Parameters" outlined in Chapter 16, Part 11 of the American Railway Engineering and Maintenance-of-Way Association "Manual for Railway Engineering". The equated mileage parameters use the length and geometric characteristics of each alignment alternative to calculate maintenance costs in terms of an equivalent length of tangent track. This equivalent length can then be compared between alignments to determine the relative score for this decision criterion. Note that the roadway maintenance costs created by the addition of grade crossings or grade separations that may or may not be borne by the owner of the proposed railroad under study are included in the matrix analysis. The inclusion of ease of implementation, or constructibility, as a decision criterion further illustrates that the matrix analysis approach does not seek to solely identify the alignment with the ideal geometry or lowest initial cost but to identify the alternative that will be the best overall solution. Commonly encountered situations that lead to a low ease of implementation score include multiple bridges or grade separations, deep cuts, high fills, water and wetland issues, poor construction access and availability of right of way.

Social and Economic Effects

The criteria for the social and economic effects category are selected to provide a measure of the impact of the project on the population and economy of the surrounding region. The decision criteria are:

- Number of properties impacted
- Change in property values
- Compatibility with regional plans and planned/existing development

The number of properties impacted gives consideration to both the number of landowners impacted by the project and the total acres of right of way required. It is important that both factors are considered as a relatively large number of landowners will require more time and effort to negotiate purchase of the required land. This can impact schedule and be a source of delay for the project. Change in property values accounts for potential impacts to landowners whose property is not required for the right of way but are adjacent to the project. Compatibility with regional and planned development considers the impact of the railroad project on land use. Constructing a railroad through a planned or existing industrial or warehouse area may be a positive impact as the additional mode of transport could encourage development and bring additional economic activity to the region. However, location of a railroad near residential areas may discourage development or create an artificial barrier that impedes growth in a certain direction or make roadway movement between adjacent areas more difficult. A proposed rail line that cuts a residential area off from a nearby school would be a good example to prompt a poor score for this decision criterion.

Environmental Effects

The criteria for the environmental effects category are selected to provide a measure of the impact of the railroad project on the environment. Besides creating a railroad solution that is most in harmony with the surrounding landscape and ecosystem, minimizing environmental impact can speed the review and permitting process during the detailed design phase of the project. The environmental effects decision criteria are:

- Number of potential noise and vibration-sensitive receptors affected
- Concentrations of minority and low-income populations within corridor
- Number of parklands, historical, cultural, and archaeological resources affected
- Presence of regulated material sites, mines, brownfields and landfills
- Effects on waters of the United States, including wetland areas
- Proximity to floodplain
- Effects to prime farmlands
- Effects to endangered species and wildlife habitat

The environmental effects criteria are typically evaluated using a combination of field reconnaissance and geographic information system research conducted by an environmental scientist. If a preliminary earthwork footprint or right of way requirement for an alignment alternative is not available, environmental effects are typically estimated using a 200' wide corridor for direct impacts and a 1000' wide corridor for items such as noise receptors and minority or low-income populations. During the alignment study phase of a project, it is often the case that right of entry has not been obtained for landowners along the various alignment alternatives. In this case, the environmental scientist must make their best effort at estimating environmental effects from a combination of field data collected from vantage points on public property or land otherwise accessible, aerial images and topographic maps.

Public and Agency Support

The criteria for the public and agency support category are selected to provide a measure of the political impact of a railroad project. The public and agency support decision criteria are:

- Level of public support
- Level of agency support
- Schedule

Unless there is an uneven population distribution across the study area or a glaring reason for the public to support a particular alignment, level of public support is often treated as being equal for the various alignment alternatives. The reason for this being that there are typically nearly equal numbers of residents along each of the alignment alternatives who are equally opposed to the selection of that particular alignment. Depending on the stakeholders and jurisdictions involved, agency support tends to vary more widely between alignment alternatives. For obvious reasons, both public and agency support are more of a consideration for publicly funded projects. The schedule decision criterion is an important consideration for projects that must meet a certain in-service date such as a line serving a newly constructed power plant. Under these conditions, alignment alternatives with shorter schedules or less risk of falling behind schedule are scored more favorably than those with longer construction schedules or higher risk of delays. This is similar to but slightly different from the “ease of implementation” criteria described earlier. Although potential implementation difficulties often increase risk of falling behind schedule, it is possible that an alignment alternative that is more difficult to construct may actually be completed on a shorter overall schedule, earning it a higher score for the schedule decision criteria.

WEIGHTING AND FLEXIBILITY

One of the strongest attributes of the matrix analysis approach is that specific client needs or objectives can be met by adjusting the weights in the matrix prior to conducting the alignment analysis. At the start of an alignment study, the rail design team will provide the client (future railroad owner) with a description of the evaluation criteria and a blank matrix without any weights. The client then has the opportunity to recommend, or work with the design team to develop, a weighting scheme that exactly reflects the relative importance of the various criteria to their organization. For example, an industrial client seeking to build a lengthy spur to a second railroad to gain access for competitive purposes may place a greater importance than average on construction cost and operational efficiency of the spur to meet the needs of their business case. At the same time, a public agency seeking to reroute a railroad around an urban area may place a greater importance on overall regional mobility, levels of service at grade crossings, social effects such as compatibility with proposed regional development, and public support. Both of these perspectives can easily be accommodated within the matrix analysis framework by adjusting the weights accordingly at the onset of the process.

Adjusting the weights at the start of the process before any alignment alternatives are developed also helps to eliminate bias which may otherwise be introduced by weighting the various evaluation categories and decision criterion later in the study process. This also has the added benefit of giving the design engineer a better idea of the optimal design for the client. With a weighted evaluation matrix in place prior to developing alignment alternatives, the design engineer can seek to develop alignments that are optimized toward the particular evaluation criteria that are weighted most heavily and will provide the best railroad solution for the client.

SCORING

For each alignment alternative, the scores for each decision criteria are entered into a table or evaluation matrix. An example of an evaluation matrix is shown in Figure 1. The evaluation matrix also shows the relative weights of each decision criteria and of the evaluation categories. This double weighting system is used to convert the individual decision criteria scores (ranging between zero and five) into a total alignment alternative score (ranging between zero and 500).

The final result of the scoring procedure is a summary matrix of scores with evaluation categories (and the total score) as rows and each alternative as a column. An example of a summary matrix is shown in Figure 2. In this example, alignment alternative C has the highest total score and is selected as the preferred alignment for further study and detailed design. In addition to comparing the total scores for competing alignments, displaying the data in this matrix format and grouping various decision criteria into broad evaluation categories via the double weighting system permits evaluation category scores to be readily compared between categories and between alignments. This allows the design engineer to determine which of the evaluation categories are driving the decision between alignments and examine the sensitivity of the total scores to changes in scoring in specific categories. It also aids the design engineer in identifying potential trade-offs between the various evaluation categories. For example, if Alignment A had a higher score than Alignment B due to scoring poorly in the environmental effects category but was an attractive option otherwise, the design engineer could go back and possibly adjust the design of Alignment A to eliminate some of the environmental impact. This may come at the expense of a lower score elsewhere but ideally the change could be made such that these decreases would be isolated to lightly weighted categories, resulting in an increased overall score and making the alternative more attractive.

NODAL ANALYSIS

When a large number of alignment alternatives are being studied and the alternatives cross over each other multiple times and have many different common segments, a slightly different form of the matrix analysis approach can be considered. This approach is called nodal analysis. In a nodal analysis, instead of examining alignment alternatives that run from the start point to the end point, the alignments are broken at locations where alignments cross and where common segments begin and end. These locations become nodes and the remaining alignments segments between them become links in a study network. Once the nodes and links are defined, the matrix analysis approach is used to evaluate each link independently and calculate a total score for each link. A search algorithm can then be used to determine the series of links that provides the path through the study network with the highest average score per link. This path then becomes the preferred alignment for further study and detailed design. Nodal analysis is commonly used in roadway alignment modeling, particularly in the routing of rural local roads where a high number of possible options exist.

When a nodal analysis is attempted for a railroad project, problems are usually encountered. Unlike roadways that can meet at intersections or make sharp curves and rapid changes in gradient, railroads, particularly those operating at mainline speeds above 30 mph require broad horizontal curves and lengthy vertical curves. This creates issues at nodes where the direction and grade of incoming links do not always match the possible options for outgoing directions and grades. Essentially each possible connection at a particular node requires its own unique geometric treatment that, due to railroad design criteria, can extend for hundreds of feet outside of that node and change the curvature and grade characteristics of the approaching links. Thus, under railroad design conditions a different incoming link must be designed to match each possible outgoing link at a particular node, eliminating the efficiencies of the nodal analysis. After attempting a nodal analysis on a railroad project, it was determined that instead of attempting to account for every possible combination, it was more expedient to select fewer but more likely alignments through the study network and then analyze them in their entirety using the original matrix analysis approach.

ESTIMATES OF OPERATIONAL EFFICIENCY

One of the more highly weighted decision criteria is the operational efficiency of the proposed railroad. For a major railroad project, train performance calculators or other simulation software are often used to model alignment alternatives and compare running times and fuel consumption. However, for a smaller railroad project, often such detailed analysis is too time consuming for the desired schedule or is outside the scope and budget of the study. In these instances, a simplified method of estimating which alignment alternative best minimizes length, grades and curves is needed. While measures of alignment length are straightforward, two indexes have been developed to meet the need for curves and grades.

Curve Index

The simplest measure of how severe the curvature is on a particular alignment is to identify the highest degree (or tightest) curve on the alignment alternative and compare between alternatives. This measure, however, does not provide any information regarding the length of this tightest curve nor does it provide any information regarding the number, length or degree of the other curves on the alignment alternative.

A commonly used measure of total curvature is the total degrees of central angle of curvature for the entire alignment alternative. This value is calculated by summing the defection angle (or central sweep angle delta) for every curve along the alignment alternative. In this manner, the total degrees of central angle provides a measure of how much curvature each alignment contains. By dividing by 360 degrees, the number of complete circles of curvature can be compared between alignment alternatives. However, the total degrees of central angle does not provide a measure of the tightness of these curves and it is the tightness of these curves that determines allowable train speed, train resistance and impacts rail wear and required maintenance activity.

To improve upon total degrees of central angle, a value of curve index is calculated for each alignment alternative. Curve index is the sum of the product of the deflection angle (or central angle) and degree of curvature for each curve along the alignment alternative:

$$I_C = \sum \Delta D \qquad (1)$$

Where I_C = curve index

Δ = deflection angle or central angle

D = degree of curvature

With this form, tighter curves (higher degree of curvature curves) are weighted more heavily in the curve index calculation. The heaviest curve index penalty is assigned to those curves which have both a large central angle and a tight degree of curve.

Figure 3 illustrates a hypothetical situation where curve index can distinguish between horizontal alignment alternatives that have equal values for tightest curve and total degrees central angle of curvature. In this case, the alignment with the broad larger radius (smaller degree) curves has a lower curve index value and, on the basis of curvature, is a more attractive alternative in terms of operating efficiency.

Grade Index

The simplest measure of gradient on a particular alignment alternative is the ruling grade or the segment with the steepest uphill gradient. Although the ruling grade has operational implications in determining maximum train length for a given locomotive, it does not give any indication regarding the number or severity of other grades on the alignment alternative.

Ruling grade is often supplemented by measures of rise and fall. For the purposes or this discussion, rise and fall is defined as the sum of the absolute value of the total vertical elevation change over each segment of constant grade:

$$Z = \sum | GL | \qquad (2)$$

Where Z = rise and fall

G = percent grade

L = length of constant grade segment

The calculated value of rise and fall provides a good measure of the amount of undulation on a particular alignment alternative. This helps to give the engineer an idea of the fuel consumption, running time and train handling requirements of the alignment alternative. However, rise and fall does not give an indication of how steep the grades are that result from the undulation. It is the combination of the steepness of the grades and the total rise and fall that provides the engineer with the best picture of the efficiency of the vertical alignment.

To measure the combination of these effects, the value of grade index is calculated for each alignment alternative as follows:

$$I_G = \sum G^2 L \qquad (3)$$

Where I_G = grade index

G = percent grade

L = length of constant grade segment

The calculated value of grade index provides a measure of undulation with segments on steeper grades weighted more heavily than those on less severe grades. The resulting high grade index value for alignment alternatives with rapidly undulating steep grades reflects the difficulties encountered in handling trains over such territory.

Figure 4 illustrates a situation where two alignment alternatives have different profiles but have equal ruling grades and rise and fall. The grade index, however, can distinguish between the two alternatives with the alternative featuring longer but less severe grades being the more attractive option in terms of vertical alignment.

Once length, curve index and grade index are determined for a particular alignment alternative, they can be compared against other alignments to allow the engineer to gauge the relative efficiency of each alignment alternative and score them appropriately.

CONCLUSION

The matrix analysis approach for railroad projects has been successfully implemented and refined during the course of several industrial spur build-in and urban bypass railroad alignment studies, ranging in length from 5 to 50 miles. For each project, the matrix analysis approach, including measures of curve index and grade index to help determine operational efficiency, was used to compare various alternatives relative to multiple decision criteria and then recommend a preferred alternative for further study and detailed design. These experiences proved that the broad scope and flexibility of the matrix analysis approach to railroad alignment studies greatly aids rail designers in meeting the specific needs of their clients.

LIST OF TABLES AND FIGURES

FIGURE 1: Example of Evaluation Matrix

Category	Weight	Alternative		
		A	B	C
Operational Efficiency, Mobility and Safety Effects (25% of total)				
Operational Efficiency of the Railroad	50%	4	4	3
Number of At-Grade Railroad/Roadway Crossings Added	10%	2	2	2
Levels of Service at Grade Crossings	10%	4	4	4
Railroad Freight Safety	15%	3	3	3
Public Safety	15%	3	3	3
Cost-Effectiveness (30% of total)				
Total Project Cost	50%	3	3	4
Railroad Operating and Maintenance Cost	25%	4	4	3
Roadway Operating and Maintenance Cost	10%	3	3	3
Ease of Implementation	15%	3	3	4
Social and Economic Effects (20% of total)				
Number of Properties Affected	35%	2	2	5
Change in Property Values	50%	3	3	4
Compatibility with Regional Plans and Planned/Existing Development	15%	4	4	5
Environmental Effects (15% of total)				
Number of Potential Noise and Vibration-Sensitive Receptors Affected	15%	5	5	5
Concentrations of Minority and Low-Income Populations within Corridor	10%	4	4	4
Number of Parklands, Historical, Cultural, and Archaeological Resources Affected	10%	3	4	3
Presence of Regulated Material Sites, Mines, Brownfields, and Landfills	10%	5	5	5
Effect on Waters of the US, Including Wetlands Areas	15%	3	4	4
Proximity to Floodplain	10%	4	4	4
Effects to Prime Farmlands	15%	1	2	1
Effects to Endangered Species and Wildlife Habitats	15%	2	3	2
Public and Agency Support (10% of total)				
Level of Public Support	35%	2	2	4
Level of Agency Support	35%	3	3	3
Schedule	30%	3	3	4

FIGURE 2: Example of Summary Matrix

Category	Alternative		
	A	B	C
Operational Efficiency, Mobility and Safety Effects			
Category Score	3.5	3.5	3.0
Weight	25	25	25
Weighted Category Score	**88**	**88**	75
Cost-Effectiveness			
Category Score	3.3	3.3	3.7
Weight	30	30	30
Weighted Category Score	98	98	**110**
Social and Economic Effects			
Category Score	2.8	2.8	4.5
Weight	20	20	20
Weighted Category Score	56	56	**90**
Environmental Effects			
Category Score	3.3	3.8	3.4
Weight	15	15	15
Weighted Category Score	49	**57**	51
Public and Agency Support			
Category Score	2.7	2.7	3.7
Weight	10	10	10
Weighted Category Score	27	27	**37**
Total Scores			
Total Score	316	325	**362**

FIGURE 3: Curve Index Comparison

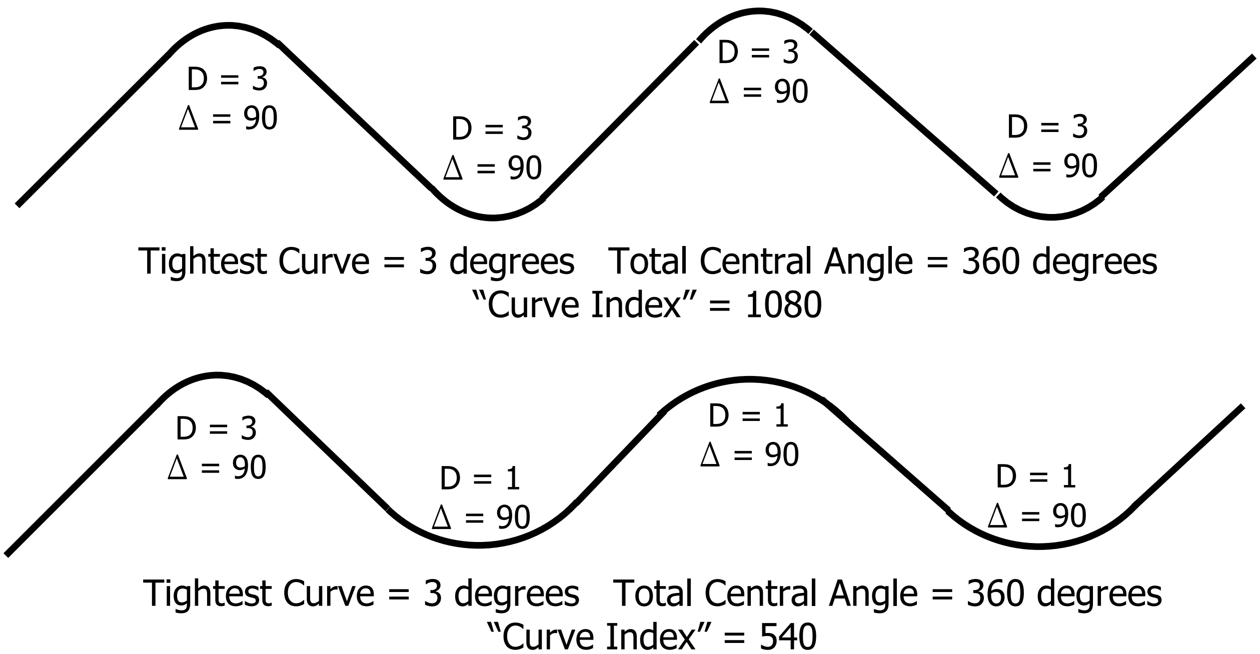

FIGURE 4: Grade Index Comparison