Abstract

Railway alignment design is a very complex process. In this process, the engineers often face a wide variety of factors and a huge number of alternatives. They should select an economical path based on topography, soil condition, environmental impact such as air pollution and noise, socioeconomic factors, as well as expected level of service of the railway in terms of fright or passenger transportation.

Traditional alignment design usually consists of a series of phases starting from a broad area, then narrowing down to several possible transportation corridors, and finally focusing on the detailed alignment designs in the selected corridor. This procedure requires professional judgment in various fields including transportation, economics, geology, civil, mechanics, environment and politics.

In this research, it is tried to formulate railway alignment design as an optimization problem. Due to the huge amount of variables (alternative alignments) and several complex constraints, it is known that this problem potentially is a very large problem. The steps, which are, consider in the research are:

- Identifying the major and sensitive cost components and important constraints in the railway design.
- Developing a model for optimizing railway alignment
- Designing an algorithm for solving the proposed model
- Computerizing the model and building prototype user-friendly software for easy use in applications.

Key words: Optimization, Railway, Alignment, Design, Software
1. Introduction

Railway design is the problem of selecting an economical alignment based on topography, soil conditions, socioeconomic factors, and environmental impacts such as air pollution and noise as well as expected level of service of the railway in terms of fright or passenger transportation, and other factors. The best route from the standpoint of user benefit and economy together with the socioeconomic and environmental impacts likely to be encountered are all taken into consideration.

These factors with several design constraints make the problem to be very complex, and so, the railway alignment designs to be a very time consuming process. In this process, the engineers face a wide variety of factors and huge number of alternatives.

Manual traditional alignment design, usually consist of a series of steps starting from a broad area, then narrowing down to several possible transportation corridors, and finally focusing on the detailed alignment designs in the selected corridor. This procedure requires experienced engineers to interactively evaluate different alternatives and select the most promising alignment. This procedure also requires professional judgment in various fields including transportation, economics, geology, civil, mechanics, environmental and politics. Since this is a problem with an infinite solution set, a manual design is very time-consuming and may result not necessarily a near-optimal alignment.

Formulating the railway alignment as an optimization problem and finding an algorithm to solve the problem and find optimum alignment with minimum total cost between each given two points have been our goals in this research. Developing such model is much difficult because of several reasons such as:

1. The problem has infinite solution set with many alternative alignments,
2. Due to the complex cost structure associated with each alignment, and
3. Since each alignment has the very high sensitivity to the different alternatives and any small change in the alignment, will result in a significant change in the total cost.

In this way, we should consider several assumptions to make the problem applicable. This paper is organized as follows. In chapter 2, railway costs are introduced. An overall review of major and sensitive cost components also is found in this chapter. Chapter 3 presents a model for optimizing railway alignment. This chapter contains a discussion about relation between railway cost and alignment configurations. Important constraints in railway design and assumptions in modeling railway alignment also are presented in this chapter. Attempting for designing an efficient algorithm for solving the proposed model is discussed in the chapter 5. Finally, Chapter 6 presents a prototype computer program, which has been developed to input various data and information, build desirable data structure, and fined optimum railway alignment automatically.
2. Railway costs

The cost components of a railway like other transportation project can be classified to:

- Supplier costs
- User costs
- Out of system costs

The supplier costs are the costs, which are paid by a government or a railway agency to build and operate the railway. The user costs are costs, which are, associated with the people who use the proposed railway such as value of time that each user spends in the railway system. Finally, Out of system costs are costs that are associated with the people who may not be suppliers or users of the railway such as air pollution and noise cost. For a railroad project each of the above category can be classified by itself to the following items:

The supplier costs can be contained of:
- Planning, Design, and administrative costs
- Right of way cost
- Construction cost
- Operating cost
- Maintenance cost

The user cost is contained of:
- Access time cost
- Waiting time cost
- Travel time in the train cost
- Accident costs
- (Un)Comfortable costs

The out of system costs can be included:
- Environmental costs
- Social costs

Among the above cost only some of them are significantly sensitive to the alignment characteristics and are more important to this research. With this point of view, each category is briefly discussed below:

2.1 Major and sensitive cost components for railways

A railway project includes some steps, started with a feasibility study, then followed by planning, design, construction, and finally operation and maintenance steps. The planning and design costs, which normally occur at the first stage of a railway project, are almost similar for different railway alignment alternatives. Administrative costs, which occur during the life of the project, are also relatively similar for various
railway alignment alternatives. So these three types of cost can be not considered in the railway economic analysis.

Right of way and land acquisition costs that vary with distance and local land uses and values (rural versus urban location, for example) are one of the most sensitive costs and should be considered in railway alignment design.

Railway construction includes many detailed items. The major railway cost items can be classified by subgrade cost and upgrade cost. Subgrade cost includes earthwork, drainage, bridges, tunnels, and miscellaneous items. Upgrade cost includes, ballast, ties, rails, fastening and other track material, signal and communication cost and even sometime stations cost. Each of these items is also sensitive to railway alignment. In the other words, the percentages of each above construction cost components are not fixed and depend on the railway location. For example a railway through a flat area may have a higher percentage of upgrade cost, where a railway over a mountainous area will have a higher percentage of earthworks and so subgrade costs.

Operating and maintenance costs of a railway project are very expensive tasks. These costs are funding throughout the lifetime of a railway. Because the geometry characteristics of a railway such as gradient and curvature may affect the operating and maintenance cost, these costs should be considered from the planning phases of a railway project. Recently, several softwares such as 'ECOTRACK' have been developed which help railway agencies make economical decision based on railway characteristics and maintenance data. These tools are very useful but this research needs a function to relate the maintenance costs to railway design characteristics such as relation between degree of a curve or slop to maintainability. In this way, the existing estimation of maintenance costs from the existing source such as UIC codes (codes 414 and 715) are used to estimate some part of the maintenance cost. We accept some engineering and professional judgments to estimate those parts of maintenance cost, which are not be presented in previous research and leave better estimation for future researches. It is also desirable to consider the sensitivity of operating cost upon the characteristics of railway alignments.

The major components of user costs are the travel time cost (includes access time to the station, waiting time in station and travel time in the train), accident cost, and (un)convenience cost. All of these costs depend on trip distance and railway geometric design characteristics. For example, the high gradients can cause to increase trip time and the little radius curvatures, may cause to increase the accident costs and (un)convenience cost. The travel time cost can be computed by multiplying total passenger (and/or goods) hours by unit time value of passengers (or goods). This cost is a grate item in railway costs. The accident costs, which are usually estimated by multiplying accident rate and the average cost per accident, also represent a great economic loss and should be regarded as a cost of railway projects. In this research it is tried to find or develop a relation between accident costs and curvature radius. It is also desirable to find an applicable measure of convenience and also relation between this measure and railway geometry characteristic.
The construction of the railway systems influences the land use patterns in the adjacent area, and cause environmental impacts such as noise pollution. In some situations, environmental issues may become the most critical factors in railway design. Although, this is difficult to incorporate all social and environmental costs to the total cost of a railway directly, but it should be tried to quantify and consider to this cost as much as possible in evaluation of different alternatives.

3. Model for optimizing railway alignment

As mentioned before one of the goals in this research is modeling railway alignment as an optimization problem. Normally, the decision variables in this model are alignment configurations. The presentation of the decision variables will be discussed in the next sections. The objective function of the model is the total cost function with respect to alignment configurations, which is, discuss in the following section. Finally, the constraints are capacity constraints and geometry constraints.

3.1 Relation between railway costs and alignment configurations

As mention before in the process of modeling the railway alignment optimization problem, after identifying the major and sensitive cost components we should capture some logic relations between railway costs and alignment configurations. Because all costs must be suitably quantified in terms of railway design features so that the total cost functions can be minimized with respect to the alignment features. Railway costs can be also classified into Location-dependent, length-dependent, volume-dependent, time-dependent, traffic-dependent, and railway geometry-dependent costs.

Location-dependent cost includes the land acquisition; environmental cost and railway base construction cost, which is influenced by the location and the covered area of the alignment and soil condition. Length dependent cost is influenced by alignment length. This cost includes the rail and its equipment such as ties, fastenings, and communication costs. The volume dependent costs include excavation, embankment, ballast and sub ballast costs. In several cases, when the volume of ballast and sub ballast stays unchanged along the alignment, it is possible to convert this cost into length-dependent cost.

The operating cost, maintenance cost, user cost and some portion of environmental costs are examples of traffic-dependent. The user costs also can be known as an example of the time-dependent cost. Finally, some part of maintenance that is depending to slope, curvature or other geometry features of a railway can be an example of geometry-dependent costs. With these classifications, the formulation of railway cost function in terms of design characteristics of the alignments is easier.

In an optimization alignment problem, different categories of costs will cause different alignment configurations. For example length-dependent costs tend to choose a straight alignment, while location-dependent costs may tend to choose an indirect
alignment. The optimum alignment feature will balance between different types of costs. Another important aspect of railway costs is whether a cost is major or sensitive. If a cost item assigns itself a high percentage of the total cost, it is known as a major cost. The sensitive cost is one that is sensitive to the changes of the design characteristics of the alignment. A major cost is not necessarily a sensitive cost and if a cost was minor or insensitive, it may be excluded from the optimization model.

3.2 Important constraints in a railway design

Railway alignments have many geometric specifications. Alignments must be designed in such a way that trains can move along the railway safely, smoothly and comfortably. The designed railway also must satisfy the proposed demand constraints of the passenger and goods. So some constraints and operational requirements must be regarded in railway design. The important constraints can be classified as follows:

3.2.1 Capacity and traffic considerations

Capacity or the maximum allowable cars (passenger or goods), which can move along a segment of a railway, is depended on the communication equipment, distance between stations, the length of the stations, the length of the trains, available power and technology of the locomotives and several other factors.

3.2.2 Horizontal alignment

The horizontal alignment that is the centerline of a railway on the horizontal plan usually consists of tangents, circular curves as well as smooth transition curves between a tangent section and circular curve. The constraints on some other properties such as super elevation on the circular or transition curves also are considered as horizontal alignment constraints.

3.2.3 Vertical alignment

The vertical alignment, which is obtained from the vertical plan along the corresponding horizontal alignment, usually consists of a series of grades jointed to each other by parabolic curves. It is noticeable that the maximum gradient is an essential constraint in a railway project.

3.3 Assumptions in modeling railway alignment

As mentioned before, the railway alignment design problem is a very large and complex problem due to huge number of variables, which come from a continuous solution set and several complex constraints. The following assumptions are made to make this problem solvable.

In the first step, it is assumed that there is a rectangular region, which contains the start and end points of the alignments. This is the interest region and we would search for best alignment just in this region.
It is impossible to store all information at all points in the region of interest. That is due to lack of available information at all points and also constraint of available memory. So, a data format is required to minimize the needed memory and carry important information for the entire region. A grid format which is compatible with a GIS (geographic information system) is employed in this research and assumed that all location dependent costs such as land acquisition cost, land-use pattern, and soil conditions of each cell is uniform. It is also assumed that the internal variation of elevations is relatively small. If \((x_0, y_0)\) and \((x_{\text{max}}, y_{\text{max}})\) are minimum and maximum coordinate of the study region and the dimension of each cell is \(D\), we have \([\frac{x_{\text{max}} - x_0}{D}], [\frac{y_{\text{max}} - y_0}{D}]\) cells in the study region.

The alignment is modeled by setting intersection points in 3-Dimensional space. Then connecting the start and end points of the alignment through the set of intersection points will yield a piecewise linear trajectory in 3-Dimensional space. The horizontal alignment is obtained from the orthogonal projection of this 3-Dimensional alignment on the horizontal plan. For obtaining a continuous and smooth alignment, the circular and transition curves are fitting at each intersection point on the horizontal plan. To do these jobs, an iterative procedure was used. The vertical alignment is obtained from vertical plans along the corresponding horizontal alignment. Then another iterative procedure is also used to assign the parabolic curves to each intersection point on the vertical alignment and generate a smooth and continuous alignment.

As we know, an alignment is consisting of horizontal and vertical alignment. For horizontal alignment, the main considerations may be land acquisition and other costs dependent on the location of the alignment. For the vertical alignment, the most important factor is probably earthwork costs. However the horizontal and vertical alignments are interdependent and most cost components are highly correlated to both the horizontal and vertical alignment. But the complexity of geometric requirements of 3-Dimension alignments makes the problem to be split into two steps. In the first step the horizontal alignment is design and then the corresponding vertical alignment is design.

### 3.4 Formulation of railway alignment

Considering above assumptions, the decision variables in this model are the coordinates of intersection points while each intersection point is a unique sell of our grade-formatted region. So cost function must be able to reflect the features of the alignment, described by these decision variables. It is assumed that location-dependent cost of each cell consists of various items such as land acquisition, soil stabilization, environmental impact and several more cost items, which are added to each other with their properly weighted according to their relative importance. To compute the location-dependent cost of an alignment, we first locate the cells that alignment passes through them. Then with calculating the length of alignment at each cell and multiplying it by alignment width and unit cell cost for each item the location-dependent cost of each cell is calculated. The total location-dependent cost is obtained by summation of each cell location costs. The computation of length-dependent cost for a railway alignment is obtained from multiplication of the railway length and unit length-dependent cost. The
unit length-dependent cost includes unit construction cost (ballast, rail, ties, fastening and…), unit railway maintenance cost and unit environmental cost (for some portion of environmental cost).

For estimating the earthwork costs that includes excavation, embankment and transportation cost for moving soil to a landfill or from a borrow pit, “average-end-area” method [10] is used. To apply this method, the alignment is divided to some sections with some station points. The distance between station points is depended to region type, resolution rate and engineering judgment. Then the cut or fill cross-section area at each station along the horizontal alignment is calculated. For calculation the cross-section area the railway and ground elevation is required. The road elevation can be computed from the parabolic equation for vertical curves. The ground elevation is equal to the elevation of the cell where the station point is located on it.

The operating and maintenance cost as well as accident and (un) convenient cost would be generally increases non-linearly with increasing the alignment slope or decrease the radius of curves. On the other hand, the initial cost will tend to decrease with increasing a slope or decreasing radius of curves due to shorter railway alignment. So some relations must be designed to allow selection of optimized value of decision variables to jointly minimize initial cost and maintenance cost. The Operating and Maintenance cost of a railway project can be classified to these items:

- Maintenance, control and replacement of railway components and structures
- Cost of ordering locomotives, freight and passenger cars, and replacing them after depreciation
- Maintenance cost of transportation equipment

There is not any approved function for estimating all of these items. So in the first step, and before obtaining better functions and methods, we are going to use engineering judgment together with some standard relation such as Davis equations and suggested factor from resources such as UIC codes to calculate the above cost.

The number of cars in each train can be calculated based on some factors such as locomotive power, maximum slop of the alignment, designed velocity, and weight of the cars. For calculating the car number, some empirical formulas that define some relations between the train resistance and its specifications such as weight, velocity and air resistance can be used. At this study the Davis equation [1 and 2] is used. In this calculation always some constraints such as station length should also be considered.

After calculation of the number of cars in each train, the train speed at each section of alignment can be approximated with regard to section geometry characteristics. So the travel time between start and end point is obtained. Then if we have an approximation of annual gross tonnage and annual passenger, the daily freight and passenger trains demand can be calculated. With regard to station stopping time at each station and travel time between origin and destination, the required locomotives and cars for the corresponding alignment are calculated without neglecting the alignment capacity.
With regard to this information the operational cost, maintenance cost of the railway, vehicles and other equipment can be calculated.

Having travel time between start and end points, an approximation of yearly passenger and freight traffic and the money value of the passenger and goods time, we can calculate total travel time cost by multiplying travel time by traffic volume by value of time for passenger and goods separately and then sum them together to obtain travel time cost for users.

The estimation of accident costs is relatively difficult due to the multiple complex causes of an accident may happen any where along an alignment, however, it is likely that accident costs and rates are higher on sharper curves due to changes in speed and inconsistency geometric design standards. Before obtaining a good function for accident rate with respect to curve radius, we can neglect this item or accept some relation, which offered for roadway [5] with a correction factor.

4. Designing an efficient algorithm for solving the proposed model

By summation of all above discussed cost components, the total cost of an alignment alternative is calculated. For railway design optimization model, minimizing total railway costs can optimize the corresponding alignment, because the total cost is a criterion reflecting the goodness of an alignment. For computation of each cost component, the alignment information must be available, so we need an algorithm to generate alignments and compute the total cost related with decision variables (i.e. the intersection points). For solving the optimization problems we need a search algorithm. Since not all costs considered have linear forms or can explicitly represent the decision variables and due to the huge size of a problem, the linear programming cannot use to solve the problem. Dynamic programming is well and requires less computation, but has great difficulties in generating a realistic alignment due to its assumption of independence between sub problems. So, it is sense that the numerical search method’s offers more flexibility in model formulations, but requires far more computations to find a near globally optimal solution for a real problem. In this study, it is tried to use some heuristic search methods like simulated annealing (SA) or Genetic Algorithm (GA) for this purpose.

5. Computerizing the optimum railway alignment model

It has been tried to develop a computer program to do all above activities in a visual and user-friendly manner. Recently, the prototype version of this program is finished. This program has been coded in Visual C++ 6. A good interface environment is provided that asks users to inter (or introduce as a file) all required data and information for designing a railway alignment. This information includes following data.

- The X and Y coordinates range of the study area,
- Coordinates of the start and end points,
• A minimum acceptable curve radius and maximum acceptable slope together with the penalty for violating these constraints,
• Characteristics and unit costs of components of up grade material such as ballast, ties, rails, fastening, and so on,
• Unit cost of different earth works activity such as excavation, embankment, and unit transportation cost for moving soil to a landfill or from a borrow pit,
• Unit tunnel and bridge cost, and
• A unit cost of locomotives, cars and other equipment as well as some information such as weight of cars and locomotives, power, number of axle, axle load, load factors and so on.

The program can show all information not only in a data base system but also in graphical forms. For example, clicking on a point in the study region, one can see all location costs, which are associated to the point. The program also can show costs, elevations, horizontal and vertical alignments as 2 or 3-D maps.

6. Summary and Conclusion

In this research the railway design problem, was considered as an optimization problem. The objective function is to minimize the total cost, which is obtained by summation of supplier cost, user cost and out of system costs. The constraints of this optimization problem are the various constraints of a railway alignment such as capacity and traffic constraints as well as horizontal and vertical alignment constraints.

Our goal was developing a model to formulate and solve optimum railway alignment design problem. Regarding mentioned aspects and for simplification, we classified the costs into different groups: Location-dependent, length-dependent, volume-dependent, time-dependent, capacity and traffic-dependent, and railway geometry-dependent costs. In spite of mentioned concepts and several other simplifications, this model is large and complex and requires some heuristic methods to be solved.

A prototype software with a visual and user-friendly interface, was developed to make a desirable database, store required information on the database and try to solve the problem for small examples by a search method.
7. References