Preliminary Roadway Alignment Design: A Spatial-Data Optimization Approach

Y. Abdelrazig, R. Moses

Abstract—Roadway planning and design is a very complex process involving five key phases before a project is completed; planning, project development, final design, right-of-way, and construction. The planning phase for a new roadway transportation project is a very critical phase as it greatly affects all latter phases of the project. A location study is usually performed during the preliminary planning phase in a new roadway project. The objective of the location study is to develop alignment alternatives that are cost efficient considering land acquisition and construction costs. This paper describes a methodology to develop optimal preliminary roadway alignments utilizing spatial-data. Four optimization criteria are taken into consideration; roadway length, land cost, land slope, and environmental impacts. The basic concept of the methodology is to convert the proposed project area into a grid, which represents the search space for an optimal alignment. The aforementioned optimization criteria are represented in each of the grid's cells. A spatial-data optimization technique is utilized to find the optimal alignment in the search space based on the four optimization criteria. Two case studies for new roadway projects in Duval County in the State of Florida are presented to illustrate the methodology. The optimization output alignments are compared to the proposed Florida Department of Transportation (FDOT) alignments. The comparison is based on right-of-way costs for the alignments. For both case studies, the right-of-way costs for the developed optimal alignments were found to be significantly lower than the FDOT alignments.

Keywords—Optimization, planning, roadway alignment, FDOT.

I. INTRODUCTION

ROADWAY planning and design is a very complex process involving five key phases before project is completed; planning, project development, final design, right-of-way, and construction [1]. In designing a highway, engineers gather information about the topography of the area, ground conditions, and possible adverse environmental impacts [2]. In the early planning stages of a highway, it is very important to take the right decisions as far as selecting alternative alignments and screening them as this proves to save time and money as the project proceeds into detailed design where less flexibility is attained [3]. Historically, poor planning has resulted in unnecessary delays in project completion. A delay in project completion often results in additional costs [4].

A set of initial possible alignments is usually developed either manually or using special software packages which have been widely used recently. Developing a preliminary

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alignment for a new road is mainly a trial and error process involving defining the trial alignment, then checking to see if it complies with the horizontal and vertical controls, then modifying it in successive iterations until all the controls are complied with. After refining the alignments, a preliminary design is then conducted on possible alignments in order to come up with a cost estimate. The final decision for selecting an alignment will depend upon right-of-way and land acquisition costs, environmental impacts, construction costs, maintenance costs, and user costs.

This research attempts to streamline and computerize the development of preliminary alignment alternatives. The main objectives of this research are:

1. Develop a methodology to optimize preliminary roadway alignment based on certain criteria utilizing Geographic Information Systems (GIS) spatial data as an implementation platform. The optimization is based on four major criteria:
- Roadway Length: minimizing the overall length of the alignment.
- Land Slope: minimizing the slope variation traversed, which corresponds to fewer construction costs.
- Land Cost: minimizing land acquisition costs.
- Environmental constrains: minimizing environmental features disturbance such as lakes, wetlands, floodplains, etc.
2. Use case studies from the State of Florida to apply and implement the methodology developed and benchmark the results.

II. HIGHWAY ALIGNMENT OPTIMIZATION

Traditional highway design requires experienced engineers to repetitively evaluate various alternatives in order to determine the most promising alternative which satisfies the functional needs, is optimal in its location minimizing the construction costs, and minimizing environmental impacts. Since the number of alternatives joining two highway end points is unlimited, a manual design may arrive at a merely satisfactory solution rather than a near-optimal design. Highway design optimization models tend to identify the best possible highway alignment while satisfying a set of design constraints such as minimum curvature, sight distance and gradient. Highway construction projects highly depend on geographical information obtained from field surveys such as topographical features, property parcels, and environmental features such as floodplains and wetlands. Since several costs of highway alignments are sensitive to geography, using GIS as a tool to calculate these costs is very efficient and time

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saving.

In the field of highway design, various optimization techniques have been applied to locate an alignment between two known locations. Jong [3] successfully applied Genetic Algorithms (GAs) for optimizing highway alignments. His representation of the area was in a matrix format. The decision variables were considered as the intersection points located on the vertical cuts on a horizontal plane connecting the start and end points of the alignments. GIS was not used in this method and this created a problem of inefficiency as it is time consuming to manually populate the cost and elevation matrices used in the input file required for running the model. Jha and Schonfeld [5] developed a model to optimize highway alignments by integrating GAs, the cost functions developed by Jong [3], and GIS.

Jha [6] modified the model developed earlier by Jha and Schonfeld [7] taking into consideration dynamic decision-making capabilities during optimal search such as; bridge cost when rivers are encountered and intersection costs when roads are encountered. Jha and Schonfeld [7] developed a GIS-based model to optimize the right-of-way cost for highways. The model tries to overcome some weaknesses in the similar earlier model created which were: not considering the value of damage to a property due to the partial taking by the proposed alignment, not considering other geographic entities such as lakes and rivers, and unrealistic and incomprehensive formulation for geographically sensitive costs. The model developed is a two-dimensional optimization model using GAs, so vertical alignment and earthwork costs are not considered in the algorithms' objective function.

Jong and Schonfeld [8] developed an evolutionary model, modified from classic GAs, for solving three-dimensional alignment optimization problems considering horizontal and vertical alignments simultaneously. The region of project area is considered a continuous space in which important spatial information is stored by employing a matrix format. Kalamaras et al. [4] applied multi-criteria analysis to solve the problem of selecting the optimal highway alignment in a quantitative manner.

This research aims to streamline the development of preliminary alignment alternatives. The grid matrix concept is utilized to represent the project area and a horizontal and vertical optimal alignment is developed based on four criteria. A GIS platform is used for implementation to streamline the process by having seamless integration of all the steps, which is lacking in previous research. Two case studies from the State of Florida are applied to benchmark the results.

III. RESEARCH METHODOLOGY

For the problem under study, the geographic space is represented as a grid and spatial data are developed as tiles of a given dimension for display and analysis. The raster (grid) data structure provides the richest modeling environment and operators for spatial analysis. In a raster, the area is partitioned into equal-dimension cells within which the properties such as land acquisition cost and the internal variation of elevations are relatively small to that between different cells. This

produces a finite set of spots generated to be utilized in the process of the determination of the optimum road alignment.

Special tools are available to merge grid data for overlay analysis as they can be merged on a cell-by-cell basis to produce a resulting data set. The functions and processes used to merge grid data are referred to as map algebra, because the grid data sets are merged using arithmetic and Boolean operators called spatial operators.

The following are the steps developed in this research for developing an optimal highway alignment. The steps are straightforward and can be applied to any roadway project. However, due to the fact that each area has its own specific characteristics, and each data set for different locations might be obtained from different agencies, data preparation and preprocessing may slightly differ from one location to another. The methodology steps described are all executed in ArcMap software. It is the working environment where all the analysis, visualization, maps creation, and results presentation takes place.

A. Input Data Preparation and Preprocessing

For accuracy of geographic location and analysis, the data sets that are added need to be correctly positioned with respect to each other. To achieve that, the coordinate system of the layers added to a data frame needs to be the same. For the analysis to be exact, the coordinate system of the data sets is checked using ArcCatalog software. ArcToolbox software projection wizard is used to make a permanent projection for all layers into a unified coordinate system if there are data sets that have varying coordinate systems. Data sets needed for this analysis are:

1. Parcel Data: The attribute table of this layer has to contain information about the total land value for each parcel.
2. Contours: A contour data set is needed which has elevation information.
3. Water bodies: This includes all the water features for the area, such as lakes, rivers, wetlands, ponds etc.
4. Major and minor roads: This contains information about the existing road network for the area.
5. Flood Zones: This is a data set showing where floodplain areas are located based on data collected for a number of years.
6. Environmental protected areas: This shows location of any environmental areas that are protected or preserved.

Usually, different data sets are compiled from different agencies, and so some of them might have different coordinate systems. The metadata is checked for each data set to see if any projections need to be performed on any layer to unify the coordinate system.

B. Creating a Study Area

A study area is created by drawing a boundary, specifying the start and end points of the alignment, and then using the clipping function in order to clip all of the layers into the boundary created. Consequently, the search space for the new optimal location is created. To create a study area, a new polygon shape-file is created to represent the boundaries of the

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study area. A defined coordinate system is needed to enable the shape-file analysis. A coordinate system is assigned for the area boundary which matches that for the rest of the data sets. Furthermore, each of the layers needs to be cut so that it is narrowed down to the study area's boundary. For this purpose, the geo-processing function "clip" is used. In this function, the attributes of the features in the output layer are the same as those of the features in the layer being clipped. Finally, a starting and destination points of the proposed road are drawn on the map.

C. Creating a Slope Raster

The slope raster is created based on a contour layer that represents the study area and extends beyond its boundary to get an accurate slope raster. The selection of the contours is made so as to ensure that the resulting slope raster has proper values on the edges of the study area because the slope is calculated in a relative manner from one plane to another. To generate a slope raster, the contours layer needs to be converted into a Triangulated Irregular Network (TIN). A TIN is built from a series of irregularly spaced points with values that describe the surface at that point (e.g., an elevation). From these points, a network of linked triangles is constructed. Adjacent triangles, sharing two nodes and an edge, connect to form the surface. A height can be calculated for any point on the surface by interpolating a value from the nodes of nearby triangles.

From the TIN raster created, a slope raster is created by calculating the maximum rate of change between each cell and its neighbors, and so the slope of a cell in a raster is the steepest downhill slope of a plane defined by the cell and its eight surrounding neighbors. The output slope dataset can be calculated as percent slope or degree of slope.

D. Creating a Parcel Raster

Creating a parcels raster includes selecting parcels that can be used for right-of-way and converting this vector layer into a raster that represents the cost per square foot data field. However, water bodies, such as lakes and ponds, and environmental constrains such as floodplains and any protected areas are considered in the search space. The impacts of these environmental features are taken into consideration by assigning them a very high unit cost so that they will be avoided during the search for the optimal alignment. The parcels (Use Code) are examined to see what property types are in the study area, and to decide what can be used for the search space. These codes are assigned by the state's Department of Revenue Land Use Code(s) Classifications. Finally, after the parcels layer has been modified and environmental features accounted for, it is converted into a raster layer.

E. Creating a Cost Raster

For analysis purposes, two optimum alignments are obtained and then compared to the alignment suggested by the planning organization. One is obtained using only the effect of land cost where the Parcels Raster is used as the Cost Raster in the analysis. For the second alignment, the effect of slope is factored in and the Cost Raster represents the combined effect of land cost and land slope. To combine the Slope Raster and the Parcels Raster, both need to be reclassified to a common scale and then added using the "Raster Calculator" function to produce the output Cost Raster.

F. Creating a Cost-weighted Distance Raster and a Direction Raster

The Cost-Weighted raster is created using the "Cost Weighted Distance" function which uses the starting point of the proposed alignment created earlier and the Cost Raster and produces an output raster called Cost-Weighted Distance Raster. In the Cost-Weighted Distance Raster, a value is calculated and assigned to each cell; this value is the least accumulative cost of getting back from that cell to the starting point along the least cost path. The direction raster provides a road map, identifying the route to take from any cell, along the least-cost path, back to the nearest source. The algorithm for computing the direction raster assigns a code to each cell that identifies which one of its neighboring cells is on the least-cost path back to the nearest source. Each cell is assigned a value representing the direction of the nearest, cheapest cell on the route of the least cost path to the nearest source. This process is done for all cells in the Cost-Weighted Distance Raster, producing the Direction Raster, specifying the direction to travel from every cell in the Cost-Weighted Distance Raster back to the starting point.

G. Obtaining the Optimal Alignment

All the steps described so far, end up in the formulation of a study area in which an optimal alignment connecting a two points is to be located based on three factors: 1) Land cost which is represented in the Parcels Raster, for which environmental factors were taken into consideration by giving them high unit cost, 2) Distance which is represented by the Direction Raster, and 3) Topography which is represented by the slope raster where the aim is to avoid traversing steep slopes as it constitutes to higher construction costs. And as mentioned earlier, two alignments are to be found, one based on the land cost only, and another based on the combined effects of land cost and land slope. The tool used here is the "Shortest Path" function which is used to find the shortest path from a point, or a set of points to a destination or a set of destinations. By creating the Cost-Weighted Raster and the Direction Raster based on unit costs defined by the Cost Raster, the function identifies the optimal path (road alignment) between two specified points. The output is a line shape-file showing the optimal road alignment.

H. Comparing Land Acquisition Costs

In this research, it is assumed that only the fraction of the parcels taken by the right-of-way of an alignment is acquired. Based on this assumption land acquisition costs, of the resulting two optimum alignments, are compared to the alignment suggested by the planning organization. The total cost for the right-of-way of each alignment is calculated and compared to the proposed alignment. For each alignment, a buffer is created at a distance which represents half the right-

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of-way width of the road on each side of the alignment. A polygon layer is created which represents the right-of-way area for the alignment. Then parcels that are in the right-of-way area are clipped and their area is calculated to calculate the land acquisition cost. A flowchart summarizing the research methodology is presented in Fig. 1.
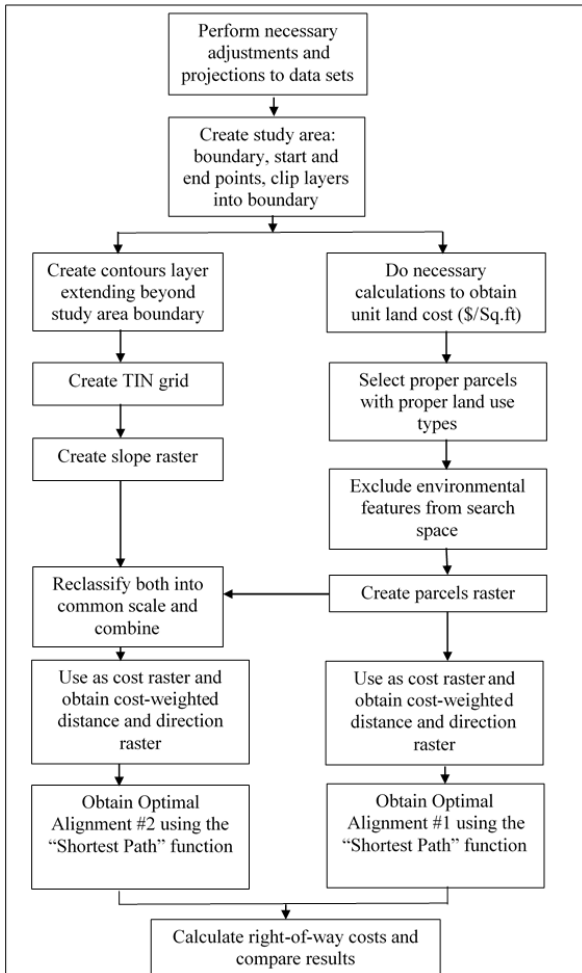

Fig. 1 Research Methodology Flowchart

IV. CASE STUDY: PECAN ROAD

This project is located in the northern part of the city of Jacksonville in Duval County, Florida. The planning organization is the FDOT, District 2. This project consists of a new two lane roadway connecting Lem Turner Road/Braddock Road to Pecan Park Road. Since this is a new roadway, there is no existing Annual Average Daily Traffic (AADT). The year 2030 AADT for the proposed two-lane facility is 1,214, with a forecasted Level of Service (LOS) of B. There is one alternative being proposed by the FDOT. The main concern here is the needed right of way width so that the analysis can be carried out. The right-of-way should be wide enough to accommodate all of the cross-sectional elements throughout the project [9]. The functional classification is assumed as an arterial with a design speed of 40 mph. Based on these two assumptions and the projected AADT of 1,214,

the following can be obtained from the American Association of State Highway and Transportation Officials (AASHTO) [9] design guide; the minimum width of traveled way is 22 ft, the minimum width of usable shoulders is 6 ft, and the minimum horizontal clearance is 10 ft.

The aforementioned methodology was used to obtain two optimal alignments. A third heuristic alignment was developed to smooth the two optimal alignments. The right-of-way costs were calculated for the two optimal alignments, the heuristic alignment, and the FDOT alignment. Table I illustrates the right-of-way costs obtained for the all alignments. Optimal Alignment 1 has the lowest cost because the only factor involved in the search was land cost. Both Optimal Alignments 1 and 2 has significantly lower right-of-way cost than the FDOT Alternative. The reduction is about 36% for Optimal Alignment 1, and 18% for Optimal Alignment 2. However, the two optimal alignments are rather jagged. Consequently, utilizing Optimal Alignments 1 and 2, a heuristic alignment is generated to develop a smoother alignment, shown as Trial Alignment in Fig. 2. The Trial alignment is considered the end product of this methodology. The total right-of-way cost for the Trial Alignment is calculated and presents an approximately 31% cost reduction from the proposed FDOT Alignment.

All the alternative alignments, as well as the FDOT alignment, are presented in Fig. 2.

TABLE I
SUMMARY OUTPUT FOR RIGHT-OF-WAY COSTS

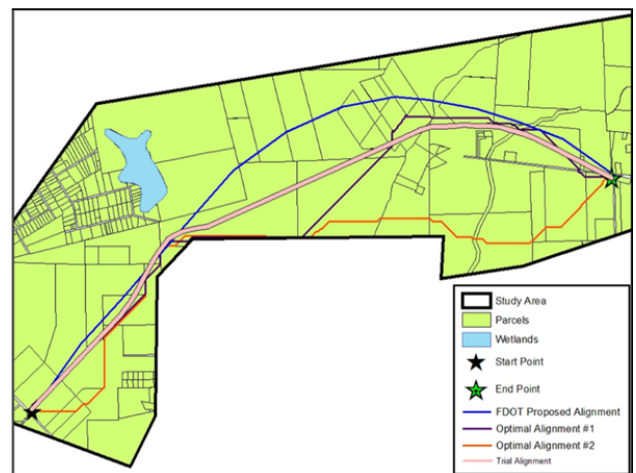| Alternative	Right-Of-Way Cost ($)	Length (miles)
FDOT Proposed Alignment	1,806,103	6.75
Optimal Alignment #1	1,156,738	6.08
Optimal Alignment #2	1,477,578	5.97
Trial Alignment	1,245,210	5.56

Fig. 2 Case Study Alignment Alternatives

V. CONCLUSIONS

The objective of this research is to develop a methodology for optimizing a new road alignment using a GIS environment. This approach is employed in the preliminary planning phase of a roadway design project, where the optimum location is

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obtained based on factors such as cost, land slope, and environmental impacts. The principle of the methodology is to convert the study area into a grid or raster which represents the search space for an optimal location.

A case study for new alignments planned by FDOT is used to illustrate the developed methodology and to test its ability to produce an optimal alignment. For each case study, two different optimal alignments are found. Optimal Alignment 1 is found based on the land cost, and Optimal Alignment 2 is found based on land cost with the land slope factored in, while avoiding environmental features. Both optimal alignments are compared to the FDOT proposed alignments. The basis for comparison is the right-of-way cost for each alignment. The right-of-way cost calculation is carried out in GIS. For both case studies, the computed optimal alignments right-of-way costs are found to be significantly lower than the FDOT proposed alignment. For case study one, the reductions in right-of-way costs are 36% and 18% for optimal Alignments 1 and 2, respectively. For the second case study, the reduction is about 36% for both optimal alignments. Even though the resulting alignments have significantly lower right-way costs than the FDOT proposed alignment, they are rather jagged, and therefore cannot be suggested as viable alternatives to the FDOT alignment proposal. Consequently, for each case study, a smoother trial alignment is generated utilizing the direction indications given by the two optimal alignments. The trial alignments' right-of-way cost reductions from the FDOT alignment are %31 and %32 for the two case studies respectively.

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