A GIS-Assisted Rail Construction Econometric Model that Incorporates LIDAR Data

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Abstract
Identifying the optimum route for new railroad lead-tracks using traditional field methods is often time-consuming, is costly, and does not allow for easy investigation of alternative routes. The NASA sponsored Affiliated Research Center (ARC) at the University of South Carolina worked with Norfolk Southern Corporation to develop a remote sensing and GIS-assisted lead-track route selection model. The objective was to compare the traditionally surveyed routes to those derived using the output from the remote sensing and GIS-assisted modeling. The critical element in the design of the model was the calculation of a cost surface. The cost variables for the model were developed based on expert advice from Norfolk Southern employees. The solution employed a raster GIS econometric routing model for the exploration of potential routes using construction cost factors such as grade (cut and fill cost), road crossings, stream crossings, and track cost. The use of remotely sensed data was a key element of the research. The digital elevation model used in the grid-based econometric model was obtained from Light Detection and Ranging (LIDAR) data with accuracy 0.3- by 0.3-m (1- by 1-ft) elevation postings. The route selected using the remote sensing and GIS-assisted modeling was similar to the traditionally surveyed route. The GIS-based optimal path lead-track model can be used to identify rapidly a variety of potential routes based on the most important cost factors.

Introduction
Resurgence in the importance of railroads as industrial infrastructure in the past two decades has resulted in the need for many new lead-tracks to traverse the distance between new industrial sites and existing railroad mainlines. Locating and evaluating potential lead-track railroad routes has traditionally relied on visual map inspection and extensive in situ field measurements. Conventional methods can be inefficient and usually do not facilitate convenient investigation of alternative routes and “what-if” scenarios. As a consequence, Norfolk Southern Corporation teamed with the NASA Affiliated Research Center (ARC) at the University of South Carolina to investigate the use of remote sensing and GIS technology for lead-track route selection modeling (Macchiaverna et al., 1996). Norfolk Southern Corporation is a Virginia-based holding company that owns 25,253 miles of rail and 14,400 miles of road in 20 states, primarily in the southeast and midwest, and in Ontario, Canada. It is a major U.S. company with more than 25,800 employees and 1997 revenues of $4.2 billion.

The principal objective of the project was to develop a spatial, GIS-assisted, lead-track econometric model that incorporated most of the heuristic “rules-of-thumb” used in the conventional lead-track route selection process. Accurate elevation and slope information derived from a digital elevation model (DEM) was essential to the lead-track modeling process because of the expense of (1) earth removal (cut) that must take place through hills to maintain a relatively level grade, and/or (2) earth fill or trestle construction that might be required to traverse a river valley. Therefore, an additional objective of the study was to determine the feasibility of creating an accurate DEM as an input to the lead-track econometric model without conducting extensive ground investigation. Light Detection and Ranging (LIDAR) remote sensing was selected for this project because it has the potential to obtain a dense network of elevation values (e.g., 0.3- by 0.3-m postings with an elevation accuracy of ±15 cm), the digital elevation model (DEM) can be extracted rapidly, and the data may be collected during either leaf-on or leaf-off conditions if the canopy is not completely closed (Nilsson, 1996; Vaughn et al., 1996; Ridgway et al., 1997; Ackermann, 1999). Norfolk Southern needs the flexibility for determining the location of lead-tracks throughout the year, not just during the leaf-off season.

Traditional photogrammetric derivation of the digital elevation model is certainly an alternative during the leaf-off period (Flood and Gutelius, 1997; Jensen, 2000). However, Huisings and Vaessen (1997) found LIDAR to be more cost-efficient than tachymetry, GPS, and analytical and digital photogrammetry. Potzold et al. (1999) suggested that the LIDAR data collection of digital elevation data required only 25 percent to 33 percent of the budget needed for a typical photogrammetric project. Pereira et al. (1999) constructed a digital elevation model from laser data in an effort to replace the traditional photogrammetric method of the Survey Department of Rijkswaterstaat. They found that the system provided the necessary accuracy, and the time required to generate the DEM using the laser data was much shorter than using photogrammetric methods. Thus, Norfolk Southern Corporation was interested in determining if LIDAR technology was an acceptable alternative to more traditional survey methods for obtaining elevation data, especially during leaf-on conditions.

Study Area
A new Bridgestone/Firestone tire plant was recently built near Aiken, South Carolina. The facility required the construction of a new railroad lead-track between the main railroad line and the tire plant. The lead-track was to be located somewhere...
within a tract of land approximately 2,100 m wide and 6,750 m long. An aerial photography mosaic showing the location of the tire plant and the existing rail line is shown in Figure 1a. The area is dominated by plantation Loblolly Pine (Pinus taeda) owned by a timber company. Several utility easements and paved and unpaved roads are also present.

The terrain varies from 96 to 168 m (315 to 550 ft) above mean sea level (msl). A U.S. Geological Survey (USGS) 7.5-minute DEM of the area is shown in Figure 1b. Several of the stream ravines are relatively steep in which dense stands of deciduous oak and hickory forest thrive.

Methodology

GIS Modeling Logic and Inputs

Norfolk Southern Corporation engineers traditionally use visual inspection of USGS 7.5-minute topographic quadrangles and field surveys to identify and evaluate the locations of potential lead-track lines. A proprietary manual titled Guidelines for Design and Construction of Privately Owned Industry Tracks is used to estimate the costs associated with lead-track road crossings, culverts, track, trestles, and cut and fill material. While the methods do produce valuable results, engineers sometimes find them generally inefficient over long distances where many maps need to be edge-matched and examined.

USC-ARC personnel were allowed to use the criteria and cost estimates found in the manual to develop a spatial, optimal-path econometric model that identified potential routes. Experts at Norfolk Southern Corporation identified the following railway construction cost factors as being most important:

- grade construction (cut and fill cost)
- road crossings
- stream crossings
- track cost

A flow diagram of the lead-track remote sensing and GIS-assisted econometric model is shown in Figure 2. Information on the major input parameters used to generate a cost surface are summarized in Table 1. The conceptual problem is to determine a least-cost path through a cost surface. Cost surface modeling is a well-defined function of grid-cell-based cartographic modeling. Tomlin (1990) describes it in terms of spreading from a source cell to adjacent cells through a cost surface with the objective function of minimizing the total cumulative cost to the destination cell. For this research, the cost surface function was implemented using the Spatial Analyst Extension of ESRI's (1999) ArcView™ following a procedure described by Mitchell (1999). The most important aspect of the research was the calculation of a cost surface that closely approximated the cost of constructing a unit length of rail across the physical terrain and man-made features. Once that surface was constructed, any number of models could be generated using different origins and destinations. The objective was to determine a proposed route using the same origin and destination selected by the company. To reduce the time necessary to run the model and to minimize storage requirements, all spatial data were resampled (nearest neighbor) to a 3- by 3-m (10- by 10-ft) grid cell.

USGS 7.5-minute 1:24,000-scale Digital Line Graphs provided information on transportation, hydrography, existing

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**Figure 1.** (a) A new railroad lead-track must be constructed between the existing railroad line and the new Bridgestone/Firestone tire plant near Aiken, South Carolina. This aerial photography was acquired on 19 July 1998 at a scale of 1:10,000 and depicts the location of the existing railroad line and the tire plant. The outlined area is referred to in Figure 6. (b) The corresponding 30- by 30-m digital elevation model is from the Trenton and Graniteville, South Carolina 7.5-minute usgs quadrangles with hydrology shown in gray. The terrain varies from 96 to 168 m (315 to 550 ft) above mean sea level.
railroad lines, power transmission lines, wetlands, hypsography, and soils. Rail lines should not exceed a grade of 2 percent (2 m for every 100 m horizontally) according to Norfolk Southern guidelines. Therefore, an accurate digital elevation model was essential. The 30- by 30-m 7.5-minute USGS DEM shown in Figure 1b did not contain elevation information in x, y, or z of sufficient detail for cost surface modeling.

LIDAR Data Collection

Aerotec, Inc (Bessemer, Alabama) acquired the LIDAR data on 19 July 1998 using an AS350BA helicopter and a Saab TopEye™ airborne topographic survey system (Figure 3). The sensor system consisted of a scanning laser rangefinder, inertial navigation unit, onboard Global Positioning System (GPS) receiver, pilot guidance system, ground reference base station, and mission planning and data post-processing software. The laser rangefinder operated in the near-infrared region of the spectrum at 1064 nm. As expected, water bodies and new blacktop pavement absorbed the incident laser energy, resulting in less laser return from these surfaces.

The laser rangefinder emitted 7,000 pulses per second and scanned the terrain ±20° off-nadir across-track as the aircraft flew at approximately 228 m (750 ft) above ground level (AGL) with a forward air speed of 25 m/sec (48 knots). This resulted in a swath width of approximately 76 m (250 ft) and individual pulse footprints of approximately 0.24 m (9.5 in) in diameter. The LIDAR overflights obtained approximately 138 × 10⁶ laser returns from ground surface objects. The electronics recorded the first and last return from each incident laser pulse which were recorded in separate files. These files were used to identify the returns associated with (1) the vegetation canopy (first return), and (2) the ground (last return). The DEM used in the econometric lead-track model was created using returns obtained primarily from the ground after a vegetation removal algorithm was applied.

A land surveyor obtained accurate X, Y, Z data for the length of a traditionally proposed Norfolk Southern lead-track line. This survey was performed before the LIDAR data acquisition. A substantial field effort was conducted by the USC ARC.

**Table 1. Input Parameters Used to Generate a Model Cost Surface**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Grade</td>
<td>The digital elevation model constructed from the LIDAR data was essential to create the cost grid for grade construction. The amount of cut and fill necessary for each grid cell was computed as the difference between the existing elevation and the desired elevation. The desired elevation was assumed to be an evenly sloped surface between the starting and ending points of the proposed railway. The volume of material needed multiplied by the cost was assigned to each grid cell. This resulted in cut and fill material cost grids.</td>
</tr>
<tr>
<td>Road Crossings</td>
<td>The USGS DLG transportation layer was used to locate existing roads. The roads were assigned to a category based on the type of crossing required. The vectors were converted to a grid and reclassified to the total cost of crossing them. This cost included crossing material used, crossing length (i.e., road width), and crossing protection required. This resulted in road cost grid.</td>
</tr>
<tr>
<td>Stream Crossings</td>
<td>The USGS DLG hydrography was used to identify stream location. The only cost of crossing streams is the cost to place culverts under the railway fill. To create the stream crossing cost grid, cells containing a stream were assigned a crossing value.</td>
</tr>
<tr>
<td>Rail Cost</td>
<td>In addition to the special construction costs to modify the grade and to cross roads or water bodies, there is also the cost for the materials and labor to build a railroad. The rail cost grid represents the cost per track foot multiplied by the diagonal distance across the cell. Any cost above the rail cost represents the cost of impediment.</td>
</tr>
<tr>
<td>Miscellaneous Factors</td>
<td>To ensure that the model calculated only feasible alternatives, it was not allowed to cross certain features. In addition to eliminating ponds, the existing railway and the existing buildings in the area (the Bridgestone/Firestone plant and a nearby industrial site) were deleted. The actual procedure involved assigning &quot;no data&quot; to the cost surface.</td>
</tr>
<tr>
<td>Optimal Path Model</td>
<td>Six cost surface grids were summed to produce a total cost grid. This grid, the start point grid, and the end point grid were input to ArcView's Cost Distance function, which output an optimal path grid. The linear path depicted in this grid was converted to a vector line feature. This line was then generalized.</td>
</tr>
</tbody>
</table>

**Figure 2.** The flow diagram used to generate the least-cost route for a new lead-track based on a remote sensing and GIS-assisted econometric model and Norfolk Southern's knowledge base. Variables used to generate the cost surfaces are summarized in Table 1.

**Figure 3.** LIDAR data were acquired on 19 July 1998 by Aerotec, Inc. using an AS350BA helicopter and a Saab TopEye™ airborne topographic survey system. The system acquired the data using a scanning laser rangefinder operating at 1.064 nm and 7,000 pulses/second. The terrain was scanned at ±20° off-nadir across-track as the aircraft flew at approximately 228 m (750 ft) AGL.
Figure 4. Based on a comparison of in situ percent canopy closure estimates at 17 locations and the percent of LIDAR last return pulses actually hitting the ground at these same locations, approximately 80 to 90 percent of the LIDAR pulses reached the ground when the terrain consisted of vegetation with a canopy closure of 30 to 40 percent ($r^2 = 0.791$). When the canopy was 80 to 90 percent closed, only 10 to 40 percent of the pulses hit the ground.

Figure 5. (a) LIDAR last returns over a relatively level power line utility corridor. The density of the pulses reveal the existence of the power line. More dense tree canopy at the edge of the corridor will cause the digital elevation model in this area to be less accurate. (b) LIDAR last returns in the vicinity of a ravine. The elevation data are more accurate on the right where there was no canopy to obscure the laser pulses.

Results

LIDAR Derived Digital Elevation Model

Norfolk Southern Corporation was interested in the effects of canopy closure on LIDAR signal penetration at the selected in situ measurement sites. As expected, the greater the canopy closure, the lower the LIDAR pulse penetration through the canopy (Jensen et al., 1987; Jensen, 2000). For example, Figure 4 reveals that approximately 80 to 90 percent of the LIDAR pulses reached the ground when the terrain consisted of vegetation with a canopy closure of 30 to 40 percent ($r^2 = 0.791$). Conversely, when the canopy was 80 to 90 percent closed, only about 10 to 40 percent of the pulses reached the ground.

LIDAR-derived DEMs extracted over level terrain and in the vicinity of a ravine are shown in Figures 5a and 5b, respectively. In both cases, the DEM is most accurate where there was minimal canopy to obscure the ground return. The DEM was less accurate in the vicinity of the ravine because the deciduous forest canopy did not allow as many pulses to penetrate to the ground. Unfortunately, this is where the most accurate elevation information must be obtained because it is here that a substantial amount of cut and fill might be required or a trestle might have to be constructed. This problem is not resolved at this time. What is needed are improved canopy removal algo-
rithms that extract the digital elevation information from only those laser hits that actually interact with the ground surface.

The several LIDAR flightlines of data were processed to yield a digital elevation model consisting of a raster of a 3- by 3-m (10- by 10-ft) pixels. These data were within ±0.50 m (±1.65 ft) of the registered land surveyor data along the traditionally proposed lead-track route.

A comparison of a 30- by 30-m USGS 7.5-minute DEM and 3- by 3-m LIDAR-derived DEM for a small portion of the study area is shown in Figure 6. The corresponding area is outlined in Figure 1a. Note the significant detail present in the LIDAR-derived data. Buildings, roads, and utility corridors are visible in the LIDAR data. A generalized, color-coded planimetric view of the DEM of the study area derived using LIDAR data is shown in Plate 1a.

Plate 1. (a) A generalized planimetric view of the digital elevation model of the study area derived using LIDAR data and a comparison of the modeled and surveyed routes. (b) A modeled cumulative cost surface. Where the cost of laying track is low, the cumulative cost surface is relatively flat. Where the cost of laying track across a road or stream is high, the modeled cost surface appears as bright peaks. (c) A three-dimensional view of the terrain comparing the traditional proposed surveyed route and the GIS-assisted model route.
tive cost surface is relatively flat. When the cost of laying track
across a road or stream is high, the modeled cost surface
appears as a bright peak. Norfolk Southern Corporation com-
pared several modeled routes with the traditionally proposed
route and came to the conclusion that it is beneficial to be able
to test numerous alternative routes analytically before deciding
on the final lead-track. A three-dimensional view of the land-
scape with the traditional proposed route and the modeled route
is shown in Plate 1c. Such modeling and simulation can save
time and money.

Conclusions
An optimal path, least-cost econometric model was con-
structed using off-the-shelf software and available collateral
USGS data. The primary limitation was the detail and accuracy
of available elevation data. Although the grid-based optimal
path model cannot take into account all factors considered in
developing a lead track, it can identify potential routes based on
the most costly factors, including grade construction, road
crossings, stream crossings, and rail cost. Other factors such as
land cost, zoning, and land availability could also be integrated
in the model.

LIDAR appears to be a useful method for obtaining accurate
X, Y, Z data even during the growing season unless the canopy
is completely closed. Generally, the greater the canopy closure,
the less accurate the LIDAR-derived DEM that is used in the lead-
track location model. However, it is important to point out that,
even in relatively dense canopies, some of the laser energy pas-
ses through holes in the canopy, reaches the ground, and then
makes its way back through the canopy once more to be
recorded by the LIDAR sensor. Improved canopy removal algo-
rithms are needed that extract the digital elevation information
from only those laser hits that actually interact with the ground
surface.

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Figure 6. (a) A 30- by 30-m digital elevation model derived
from the USGS 7.5-minute Trenton, South Carolina quadran-
gle. (b) A 3- by 3-m digital elevation model derived using
LIDAR data. Note the detail of the buildings, roads, and utility
corridors present. However, there is some error in ravines in
the LIDAR-derived digital elevation model due to dense
canopy.