

Predictive Modeling of Roadway Costs in Northeastern Nigeria

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Road investments often exceed 20 percent of the development budget in most developing countries, such as Nigeria. Fast-growing population and economic development require an expanded road network. Application of probabilistic analysis methods during the early planning, or pre-engineering, phases allows for the prediction of probable construction and maintenance costs. Satellite remote sensor imagery can supply quantified descriptions of terrain conditions. When this information is digitized and stored in a Geographic Information System, a data base is created that can be queried to produce appropriate predictive models for roadway construction and maintenance costs. Those can, in turn, create a series of predictive economic roadway development models that reflect alternative design scenarios. Definition of the most economical routes that satisfy the constraints can be automatically produced by optimization algorithms based on linear programming techniques. The results are summarized of a study conducted over the past 3 years at the International Institute for Aerospace Survey and Earth Sciences (ITC), in Enschede, The Netherlands, which developed and tested those methods for road planning in northeastern Nigeria.

Investment on roads accounts for a substantial proportion, often in excess of 20 percent, of the development budget in most developing countries, such as Nigeria. Fast-growing population and economic development require an expanded road network. Previously, the identification of routes with the lowest construction and maintenance costs had been based mainly on scanty information from small-scale geological maps and from often inadequate topographic data. As a consequence, unforeseen geotechnical problems frequently were encountered at the time of detailed final ground surveys or during construction and, because the problems could affect a considerable length of road, led to greatly increased construction or maintenance costs.

A number of researchers in the 1970s began to quantify road construction and maintenance costs. The MIT Highway Cost Model (1) and the subsequent Road Transport Investment Model developed by the British Transport and Road Research Laboratory (2) were used to study the design and operation of specified roadway links in developing countries. Those models required a detailed specification of the alignment and were suitable for engineering design support, the evaluation of alternatives, and similar activities in the pre-construction phase. Those models do not address the selection of the general transportation corridor or route.

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Application of similar, but more generalized, probabilistic analysis methods during the earlier planning, or pre-engineering, phase should allow the prediction of probable construction and maintenance costs. The use of satellite remote sensor imagery, supplemented by aerial photography when available, can supply quantified descriptions of terrain conditions. Those data sources greatly improve the information available to the road system planners. When this information is digitized and stored in a Geographic Information System (GIS), a data base is created that can be queried to produce appropriate predictive models for roadway construction and maintenance costs and can, in turn, create a series of predictive economic roadway development models that reflect alternative design scenarios. Definition of the most economical routes that satisfy the constraints can be automatically produced by optimization algorithms based on linear programming techniques. The feasibility of those techniques has been studied by Akinyede (3) during the past 3 years at the International Institute for Aerospace Survey and Earth Sciences (ITC), in Enschede, The Netherlands.

DEVELOPMENT OF THE TERRAIN DATA BASE

An initial test area, covering about 25,000 km² in northeastern Nigeria, was selected for study in cooperation with the Nigerian Federal Ministry of Works. Following extensive regional terrain analysis by using a variety of satellite remote sensor systems, two smaller test areas, 4500 and 600 km², were selected for detailed study.

Description of the Test Area

Northeastern Nigeria includes a geological rift zone, the Benue Trough, created when South America separated from Africa. As a consequence the area is variable both topographically and geologically. The terrain is characterized by rugged hilly regions underlain by granite and sandstone, sedimentary and volcanic plateaux, isolated steep volcanic plugs, and low swampy plains. These features combine to form some of the most variable and attractive scenery in Nigeria.

A Precambrian basement complex, dominated by granites and gneisses, underlies considerable areas. The rocks are overlain by Cretaceous sedimentary rocks, predominantly sandstones and shales of both marine and continental origin. The older sedimentary rocks are complexly folded and create long ridges. The younger rocks are more gently folded. All are faulted. Younger Quaternary sediments are found in the

northern portions of the area and to the south are volcanic flows and vents. The geology has been mapped and described in detail (4, 5).

This variety of conditions creates potential problems and opportunities for road construction. Some regions have abundant high quality sources of aggregates and others have few or none. Highly plastic "black cotton" clay soils are found in areas of basalt flows. Laterite soils are common in many areas and are especially persistent in the north.

Definition of the Land Systems Mapping Units

Terrain information was developed by applying techniques of land systems classification. The terrain is assessed on the basis of certain geologic, geomorphic, and geotechnical characteristics spatially related to the ground by defining areas (land systems and land facets), each of which is characterized by essentially uniform characteristics.

The method is hierarchical. Over broad regions, and at small scales of mapping, major land systems are defined on the basis of similar landforms, rocks, and soils. At a more detailed level, land facets may be defined that have uniform slopes, soils, and hydrologic conditions. The land systems classification has gained wide acceptance as a highway planning methodology in many developing countries, including Nigeria (6–8).

Initial land systems were defined in this project by applying standard visual photointerpretation methods to Landsat Thematic Mapper (TM) satellite imagery and to Side Looking Airborne Radar (SLAR) imagery. Subsequently, two more detailed test areas (the Ngamdu and Gongola areas) were selected and further evaluated by using SPOT satellite images and some aerial photography. Those studies developed 8 major land system units, 19 major sub-units, and 30 detailed Land System Mapping Units (LSMUs) within the two test areas.

Geographic Information System

The outlines of those LSMUs were digitized and stored, along with their attributes, in a GIS relational data base. An IBM-PC-based software system was used. The system, called ILWIS, was developed at the ITC for use in developing countries (9). Figure 1 presents the basic system.

ILWIS includes a spatially oriented image data base and an associated nonspatial attribute data base as is shown by Figure 2. The image data base contains a digital representation of the study area map, defined as a series of lines (arcs) and points (nodes), that combine to form a sequence of map units (polygons). Each LSMU (the ILWIS developers prefer the term Terrain Mapping Unit or TMU) is defined by one or several polygons in the image data base.

The associated attribute data for each LSMU use a commercial relational data base product called ORACLE. A series of numerical models can be created, according to specified algebraic and logical rules defined by the ILWIS user. The composition and structures of those data bases are described by Akinyede (3). The following sections describe the concepts underlying the predictive roadway cost models developed by using ILWIS capabilities.



FIGURE 1 Typical ILWIS hardware installation.

DEVELOPMENT OF PREDICTIVE COST MODELS

A series of predictive cost models was developed that use the available terrain data elements to estimate probable roadway construction or maintenance costs. Construction costs are estimated in terms of grading costs, pavement costs, and drainage structure costs.

Grading Cost Prediction Model

Grading costs are calculated by using estimates of cut and fill operations developed from data defining the terrain roughness and material excavation characteristics. Typical grading costs for a specified length of roadway may be predicted by multiplying the volumes of cut and fill required by the unit costs of excavation, handling, and placement of those materials.

Determining Cut or Fill Volumes

A roadway, of width L , crossing a typical symmetrical V-shaped valley, may be supported by a fill volume having a maximum fill height of h , a side slope gradient of g , and a length of fill D (see Figure 3). After examining Figure 3 it is obvious that such a fill volume can be subdivided into two identical wedges (A and B) and four identical triangular side pyramids (1, 2, 3, and 4). The volume of each wedge is $D \times h \times L/4$. The volume of a right pyramid can be computed as (base-area \times height)/3 so that the volume of each side pyramid is $D \times g \times h \times h/12$.

The volume of a cut through a hill can be approximated in an identical fashion, although the side-slope gradients in a rock cut will be much steeper than in a fill. The volumes of benched rock cuts can be satisfactorily estimated by using an average side-slope gradient for purposes of predictive cost modeling. Thus,

$$\text{total volume of a fill (or cut)} = \left(\frac{hL}{2} + \frac{100h^2}{3g} \right) D$$

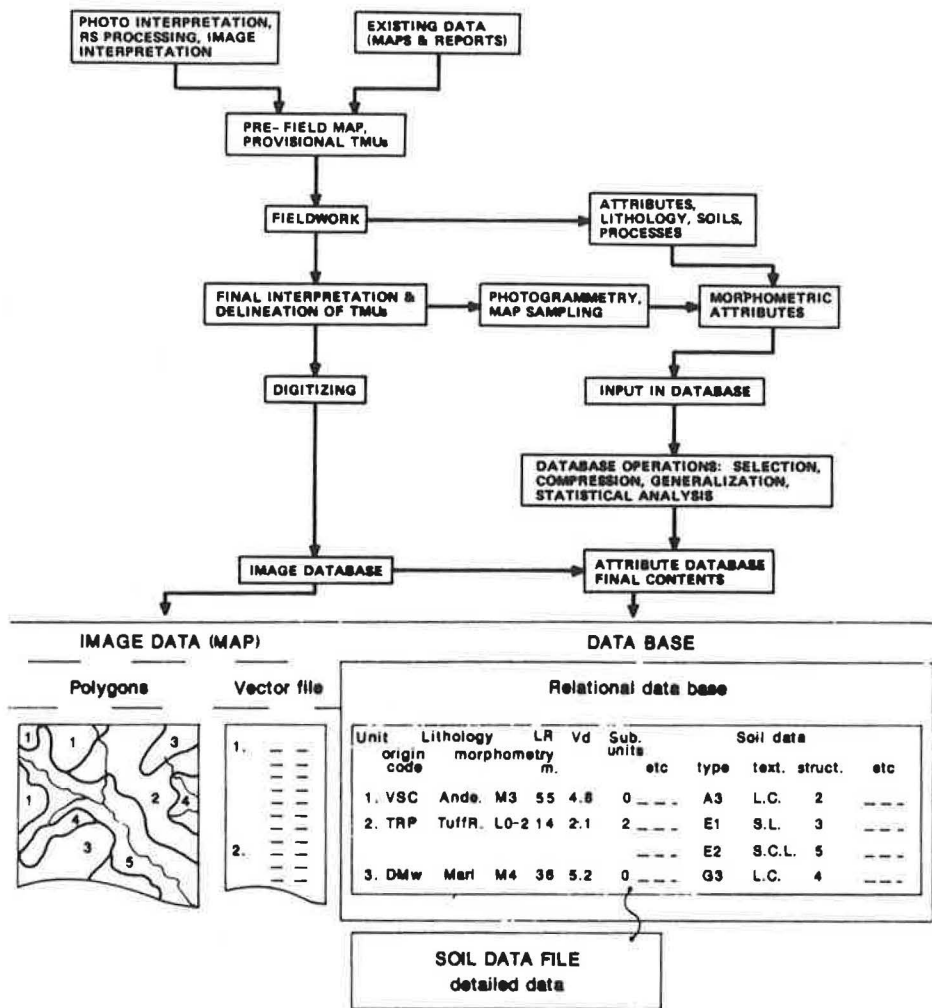


FIGURE 2 Procedures for creating the GIS data base.

where

- D = typical length of fill (or cut),
- h = typical maximum height of fill (or cut),
- L = roadway width, and
- g = side slope gradient in percent (for either fill or cut).

The values of roadway width (L) and fill side-slope gradients are defined by Nigerian road design standards for all road classes. The values for g in cuts are related to the local soil or rock conditions and thus can be defined for each LSMU. The values of D and h can be related to terrain roughness conditions, for each LSMU, by the methods and assumptions defined in the following four steps.

1. Defining characteristic terrain roughness: The terrain roughness was defined for each LSMU by the frequency of valley crossings along four directions (north-south, east-west, northeast-southwest, and northwest-southeast) and by the local relief and were estimated by placing a circular template, with a diameter of 8.3 cm, on 1 : 25000 scale aerial photographs or topographic maps or both and estimating the frequencies of valley crossings and the local relief. The valley frequency

count was estimated in terms of fractional valleys per circle diameter. From such frequency counts it is possible to compute a typical valley width W (in meters) according to the formula

typical valley width = W (meters)

$$= \frac{\text{circle diameter (cm)} \times \text{map scale denominator}}{100 \times \text{frequency count}}$$

At least eight different sampling locations were chosen within each LSMU so that means and standard deviations of the typical valley widths for each of the four directions, and the minimum and maximum local relief values, a total of 10 descriptors, were computed for each LSMU.

2. Estimating typical cut/fill lengths (D): In a regularly undulating terrain, with a typical valley width W , the desire to balance cuts and fills will cause the road grade to move from cut to fill and back against at approximately the midpoint of each slope, regardless of the chosen ruling gradient. Under these circumstances the typical cut or fill length (D) will be about one-half the typical valley width (W). Admittedly, such

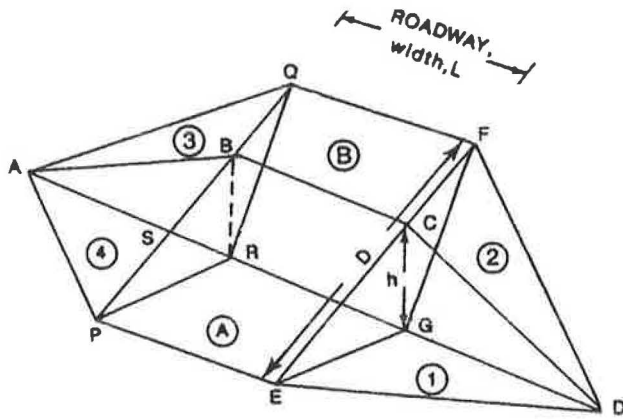


FIGURE 3 Geometrical representation of an idealized roadway fill.

a relationship includes a number of simplifying assumptions that include (a) roughly equal side-slope gradients in cuts and fills, (b) local mass-balance equalities can be readily achieved, (c) material bulking and shrinkage ratios are either very small or offsetting and can be neglected, and (d) the amount of excavated material unsuitable for placement in fills, and thus must be wasted, is small and can be neglected. A correction factor is used to account for the necessary "wastage" of material excavated in a cut but unsuitable for a fill. Each LSMU is supplied with an estimate of the fraction of such unsuitable material that is likely to be encountered, and the total volume of material is increased by this amount. Adjustments can also correct for volume imbalances owing to other reasons, including differences in cut and fill side-slopes (3).

3. Estimating the maximum cut/fill height (h): The final value required by the volume formula is the estimated maximum height (h) of the cut and fill. This value is related to the terrain roughness estimates. For any desired principal direction a valley side-slope gradient (VSG) can be computed from the typical valley width and local relief data (see Figure 4). The VSG value can be compared to the maximum allowable longitudinal roadway gradient (rg), which is defined by Nigerian authorities. As is indicated by Figure 4 the maximum cut/fill height (h) can vary between a maximum value h_{max} and a minimum value h_{min} , where

$$h_{max} = (\text{local relief})/2 = z/2$$

$$h_{min} = h_{max} - \Delta h$$

$$\Delta h = \frac{(rg) \times (W/4)}{100} = \frac{(rg) \times W}{400}$$

$$\begin{aligned} \text{average typical } h &= h_{max} - \Delta h/2 \\ &= \frac{z}{2} - \frac{(rg) \times W}{800} \end{aligned}$$

where

- z = local relief,
- h = typical maximum height of fill (or cut),
- h_{max} = largest maximum height of fill (or cut),
- h_{min} = smallest maximum height of fill (or cut),
- rg = ruling longitudinal roadway gradient, and
- W = typical valley width.

4. Estimated grading volumes for smooth terrain: That formula will not give satisfactory values when the VSG is less than the allowable longitudinal roadway gradient (rg). Under such condition, the road profile can follow the terrain without any cutting or filling. Such terrain can be considered "smooth." However, road construction will require some minimum volume of fill to raise it above the general terrain and allow for drainage. In the areas studied, Nigerian practice includes the construction of subgrades between 1 and 3 m high, depending on local soil conditions. Accordingly, the volume estimation step includes an initial comparison of the VSG and rg values. When "smooth" terrain is thus defined, a minimum subgrade height, defined for the LSMU, is used to calculate default values of grading volumes.

Defining Unit Costs for Materials Excavation, Handling, and Placement

All unit cost values for grading costs were obtained by examining bills of quantity from recent road construction contracts in this area or in nearby areas (see Table 1). Insufficient information exists within the recent road construction bills of quantities to establish relationships between excavation costs and anticipated rock strengths and jointing patterns. The current Nigerian road costing practice is to classify all rippable rocks, including most of the sedimentary rocks in this area, as soils. All hard rocks, including most basalts and granites in this area, that require blasting are classed as rock for excavation.

The haul distance was assumed equal to the typical length of the cut or fill (D) and was compared to the 500 m haul distance criteria in Table 1 and the appropriate cost, for either soil or rock, was selected. Those include the entire costs for excavation, handling, and placement of the materials.

Creation of the Grading (Earthwork) Cost Model

A series of four different grading cost models, one for each of the primary geographic orientations (north-south, east-west, northwest-southeast, and northeast-southwest), were developed for the test areas. Those four cost models are most similar in regions that are relatively smooth. In those regions the grading costs are related to the requirement of raising the roadbed above the surrounding terrain to ensure adequate drainage and are little affected by ridge or valley orientations. Some directional differences can be seen in regions with more pronounced relief. Higher grading costs are associated with roadway directions that traverse frequent ridges or valleys. Figure 5 presents a simplified map example of the earthwork cost model for the Gongola test area, which was computed for east-west oriented routes.

Pavement Construction Cost Prediction Model

The cost of constructing the pavement for a given length of road can be computed by multiplying the required volumes of different pavement materials by their unit costs when delivered to the construction site.

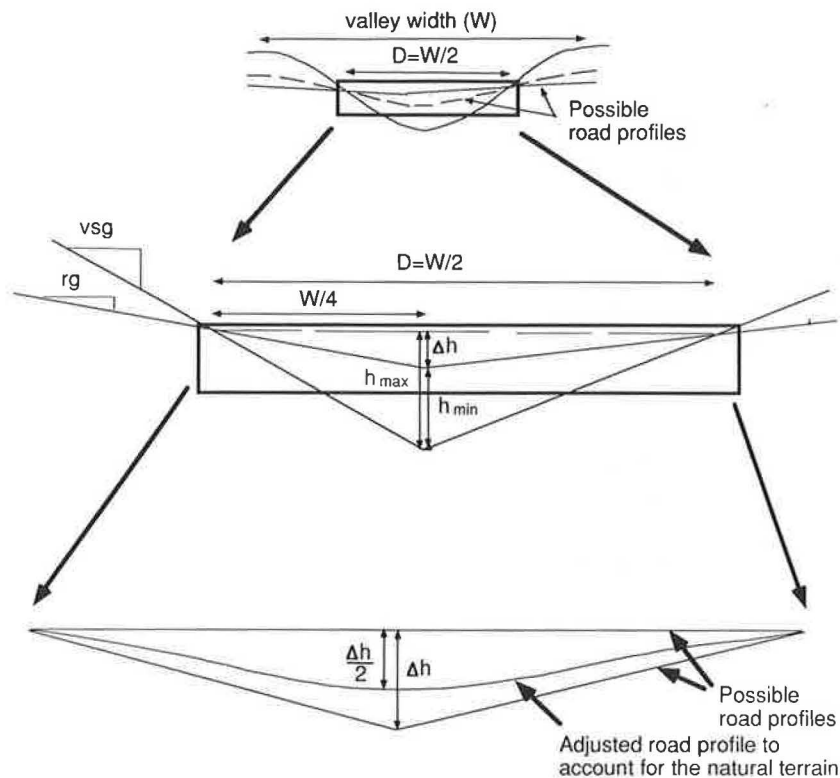


FIGURE 4 Sketches indicating idealized geometrical relationships between valley side gradient (vsg), allowable longitudinal road gradient (rg), and typical fill parameters length of fill ($D = W/2$) and fill height (h).

TABLE 1 COST OF HAULAGE AND EARTHWORK OPERATIONS DETERMINED FROM BILLS OF QUANTITIES FOR RECENT NIGERIAN ROAD CONTRACT AWARDS

Item Number	Item Evaluated	Distance Involved	Unit Cost N/m ³	Source of Information
1a	Haulage cost for fills, including spreading & compaction	less than, equal to 500m	2.65	Cedaconsult 1978 (6)
1b	ditto	over 500m	3.50	
2a	Haulage cost for granular base material from borrow pit, including laying and compaction	less than, equal to 500m	4.00	Aggarwal & Jafri 1985 (16)
2b	Extra haul cost	over 500m	0.38/km	
3a	Excavation or ripping in soil or soft rock to any depth in cutting & ditches & hauling suitable material to fill site, including laying, compaction and disposal of unsuitable material.	less than, equal to 500m	2.30	Cedaconsult 1978 (6)
3b	ditto	over 500m	3.40	
4a	Excavation in rock, including secondary crushing	less than, equal to 500m	10.75	Cedaconsult 1978 (6)
4b	ditto	over 500m	11.85	

NOTE: Costs of materials are expressed in the Nigerian currency, Naira per cubic meter.

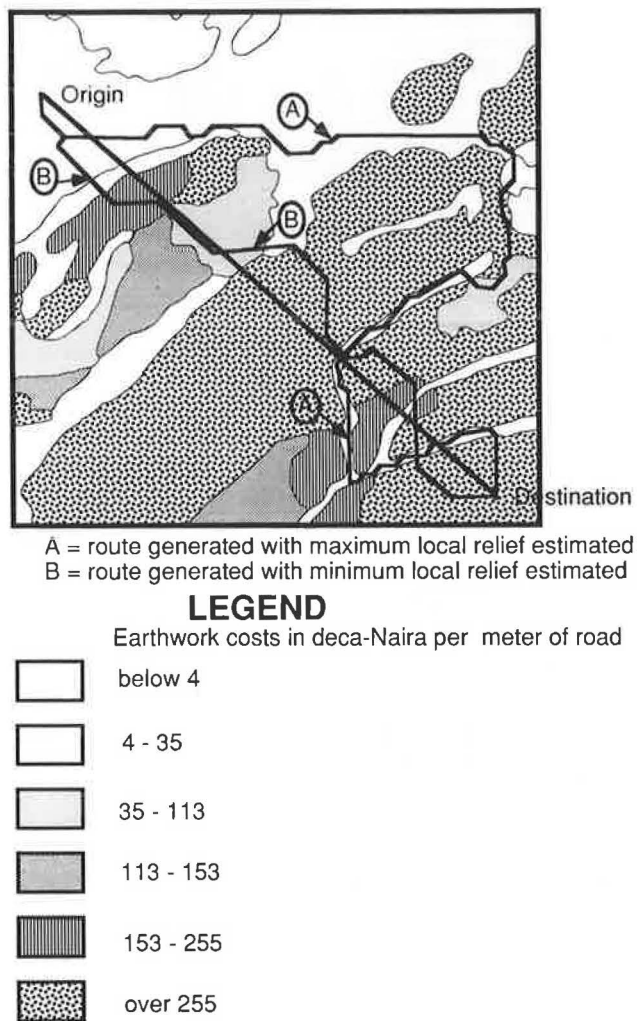


FIGURE 5 Example of earthwork cost map and generated routes.

Computation of Required Volumes

Standard Nigerian bituminous pavement road design includes a 5-cm-thick bituminous surface, a base course 15-cm thick, and a variable thickness of sub-base according to different subgrade strengths as measured by CBR values. Pavement and base course widths are specified according to road type and local terrain conditions, with higher classes of road and smoother terrains given wider dimensions. The volumes of bituminous pavement, base course, and sub-base materials required for a given length of roadway (in this case a roadway length of 40 m was used for estimation purposes) can be computed from those specifications and from a knowledge of local terrain characteristics and subgrade CBR values. This information was readily available within the ILWIS attribute data base.

Computation of Delivered Unit Costs

The unit costs for materials, delivered to a given location, can be estimated by summing the unit costs of production at the

source and the haul costs. The estimation of those values involves five steps.

1. Estimation of unit haul costs: Haul costs for moving materials from pit or quarry sources to the construction site are computed according to general relationships. For short distances a fixed unit charge has to be made to cover equipment and materials handling costs. Beyond this distance costs increase linearly with distance. Finally, at some larger distance the haulage costs become prohibitively large, and a region of "marginal haul" can be identified.

2. Identification of "source-sheds": At many construction locations a number of competing sources, each with different materials quality and haul distance, may be found closer than the marginal haul distance and are potential sources. Source areas are defined by examining the LSMU attributes to identify those containing adequate quantities of suitable materials. The selection of the most economical source involves the concept of "source-sheds." Just as the surface of the earth is divided into a series of watersheds, the region of interest can be conceived as being covered with a "cost-surface" containing a series of hollows that correspond to the materials sources. The elevation of each hollow is related to the unit cost of producing the material. The surrounding areas are covered by sloping surfaces with gradients corresponding to the haul costs that will intersect to form "divides," which define a series of polygonal source-sheds. A source-shed is thus defined as a region where it is cheapest to obtain material from a single source. Figure 6 defines this basic concept. This basic concept needs to be modified to allow for more realistic simulations in many actual situations.

3. Adjustment for local trafficability and terrain conditions: Straight-line or cross-country haulage routes may be feasible in areas characterized by relatively flat terrain and surficial materials with good trafficability characteristics. The source-sheds can be computed with radial distances from the limits of source areas defining the haul costs. The source-sheds then approximate a series of intersecting-conics. Such conditions were true in the northern Ngamdu test area, which has relatively smooth lateritic terrain covered by shallow eolian sands. The definition of source-sheds must take into account the distribution of existing roads and the trafficability of all other regions in areas where soils and topography potentially interfere with cross-country travel. Rugged areas, or areas underlain by weak soils, for example, must be treated as barriers. The southern Gongola test area is characterized by those conditions. Consequently, the source-sheds in this region are much more complex and the resulting cost maps are much less regular.

4. Incorporation of materials quality considerations: A strict selection of materials sources based only on delivered price to the construction site may not always be the preferred solution. For example, a source having a higher quality may perform much better in service than an alternate lower-quality source. Its higher quality may bring a premium price at the source, however, owing either to higher production costs or to perceived market values. Under the basic procedure defined, such higher-priced premium-quality sources will not develop very extensive source-sheds in competition with lower quality materials. An extra step must be added to the development of the delivered unit cost model to allow for the higher-quality

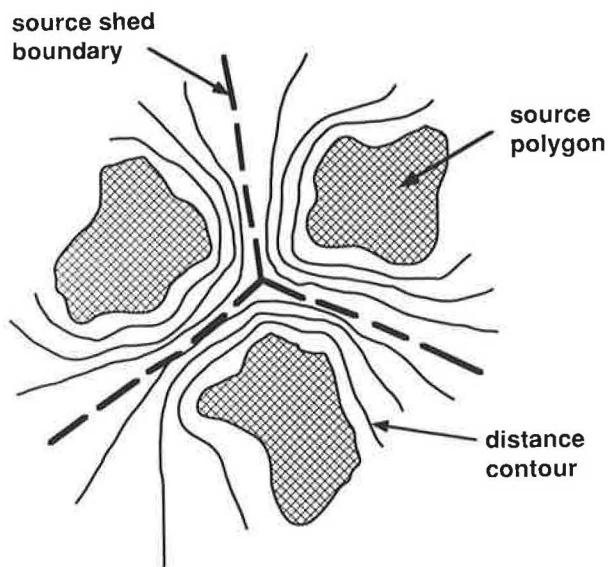


FIGURE 6 Definition of source sheds.

sources to be more frequently identified and selected. If the production prices of the higher-quality materials are artificially reduced, or those of the lower-quality materials are raised, then the source-sheds of the higher-quality materials will expand relative to those of lower quality. Essentially, the solution involves the use of "shadow prices," which incorporate not just economic factors but also judgment values.

5. Computation of delivered materials costs: Once the source-sheds are identified according to this modified pricing procedure, the true unit production costs are combined with the defined source-sheds and contain the unit haul costs to compute the delivered materials unit costs.

Computation of Overall Pavement Cost Model

The procedures outlined permit the development of cost models for each element of the pavement (bituminous surface, base course, and sub-base). Again, recent road construction experience data (Table 1) were reviewed to supply appropriate cost factors. The individual cost models were then summed to create a pavement construction cost model.

Prediction of Drainage Structure Costs

Drainage structure costs may be estimated from terrain and watershed hydrology data by using simple hydrologic estimation techniques to determine peak flows. A separate study of drainage crossing prediction was conducted over part of the Gongola test area, in a region characterized by rugged terrain and a fairly dense drainage network.

The selected test area included 58 watersheds, which were digitized and stored within ILWIS. The Rational method for small watersheds (less than 25 km²) and the Talbott formula for larger watersheds, relationships between peak discharge and catchment area, were developed for each major terrain type by using standard hydrologic estimation procedures. Existing roadway engineering reports for northeastern Nigeria

yielded relationships between peak discharge and culvert size for small drainages and between catchment area and length of bridge. It is possible to estimate approximate drainage structure costs along previously defined routes with this information. For example, routes selected to minimize grading and pavement costs can then be subjected to drainage structure cost analysis.

Integration of drainage structure costs into the selection of routes requires the development of a directionally related drainage structure cost predictive model, analogous to the predictive grading cost model described previously. The characteristic terrain roughness data, according to directional orientation, do supply valley frequency information. However, additional data concerning the size of the tributary being crossed, catchment area, or peak runoff value cannot be obtained from those data. Accordingly, additional analyses were undertaken to develop predictive relationships between stream order (a measure of size) and anticipated peak runoff for major LSMUs. With such data it may be possible to relate some relevant drainage structure design parameters, and therefore costs, to the various LSMUs. Some limitations can be foreseen. For example, many site-specific concerns exist at any crossing site that involve factors such as scour and bridge footing conditions. Work is continuing on this model.

Maintenance Cost Prediction Model

Maintenance costs may be developed on the basis of pavement maintenance and other right-of-way maintenance costs and can be estimated by using basic terrain and local materials durability factors and assumed baseline traffic volumes. A common rule-of-thumb suggests that 60 to 70 percent of the maintenance costs are related to pavement repairs.

General right-of-way maintenance activities include the clearing of vegetation, removal of debris from ditches and culverts, and the repair of side-slopes (either in cut or fill) subjected to erosion. In addition there may be occasional catastrophic failures, such as landslides or "washouts" at drainage crossings. All of those conditions can be related to local terrain and soil or rock erodability characteristics within a relatively uniform climate. Some factors, concerning the erosion of side-slopes, also will be affected by the amount of cut and fill related to topographic roughness.

Similarly, it should be expected that pavement deterioration will be related to subgrade conditions under specified traffic loadings. With such relationships it is possible to estimate annual pavement maintenance expenditures, useful pavement life, and similar factors to mapped data elements within each LSMU.

Accordingly, a maintenance cost model can be constructed that relates the terrain roughness and materials characteristics for each LSMU to an expected annual maintenance level. However, this requires some empirical relationships, based on experience in the region, that can predict anticipated annual maintenance efforts, or costs, according to such terrain characteristics. Unfortunately, such data are lacking for this part of Nigeria at present. The development of empirical relationships will allow the further application of the LSMU concept by including maintenance cost predictions to road planning and management in Nigeria.

ROUTE SELECTION METHODS BASED ON MINIMUM TOTAL COST CRITERIA

Those predictive cost models can be analyzed further to generate possible routes that best satisfy selected design criteria. Linear programming techniques have been applied to combinations of predictive cost models to identify routes (10–13). More recently, Linden (14) applied those methods to investigate the framework for planning support during highway location studies in Holland.

A new algorithm, GROUTES, was implemented for this study (15). Like its predecessors the algorithm determines the route, between any desired pair of termini, having the lowest total cost and takes into account both the distance traveled and the cost of movement per unit of distance. Those costs can be compared with the cost of the shortest (straight-line) alternative.

The GIS capabilities and the predictive cost models described earlier supplied the necessary cost matrices to the GROUTES algorithm. A number of analyses was made by using combinations of earthwork cost, pavement cost, and drainage crossing cost models. Figure 5 shows a typical result.

Generally, the generated routes were much cheaper than the straight-line routes, although they were longer. Costs for the cheapest routes ranged from 6 to 15 percent of the direct route costs. Lengths ranged up to double the straight-line distance.

Earthwork and drainage crossing costs dominated in determining the routes. Pavement costs were rather insignificant. The route selection and cost estimates appear most sensitive to the accurate determination of local topographic relief values, a parameter only indirectly estimated from most satellite imagery.

CONCLUSIONS

A series of procedures has been developed that allow the creation of predictive cost models that can support roadway planning in regions with limited terrain data. The use of remote sensing image interpretation techniques, in conjunction with GIS computer techniques, allows for the creation of a suitable data base. The predictive modeling techniques create numerical models that define roadway cost factors by accessing such a data base. Display of those factors as maps can be helpful in regional planning.

The cost models were analyzed further to generate possible routes that best satisfy Nigerian road design criteria. The cost of the cheapest route was found to be much less than that of the most direct route. Thus, the combination of predictive cost models and route identification may stimulate the development of more roads, even in areas with rugged terrain conditions.

Field visits in Nigeria and existing road construction reports were used to check several of the parameters used in the predictive models, but it has not yet been possible to compare the estimated route costs with those actually experienced. The concepts have been developed with examples from north-eastern Nigeria, but similar procedures can be applied to other areas in Nigeria and in many other developing countries.

The route selection model is relatively simple to use, and its application and data requirements are well within the capabilities of potential users. The model is a decision making tool for transport planners and a cost-saving method that will be effective for the management of the economy in the road sector.

REFERENCES

1. F. Moavenzadeh. *Investment Strategies for Developing Areas: Analytic Model for Choice of Strategies in Highway Transportation*. Research Report 72-62, MIT Department of Civil Engineering, Cambridge, Mass., 1972.
2. R. Robinson, H. Hide, J. W. Hodges, J. Rolt, and S. W. Abay-nayaka. *A Road Transport Investment Model for Developing Countries*. Transport and Road Research Laboratory Report 674, Department of the Environment, Crowthorne, Berkshire, England, 1975.
3. J. O. Akinyede. *Highway Cost Modelling and Route Selection Using a Geotechnical Information System*. PhD thesis. Faculty of Mining and Petroleum Engineering, Technical University, Delft, The Netherlands, 1990.
4. J. D. Carter, W. Barber, and E. A. Tait. The Geology of Parts of Adamana, Bauchi, and Bornu Provinces in Northeastern Nigeria. *Geological Survey of Nigeria Bulletin*, No. 30, 1963.
5. C. A. Kogbe. Attempt to Correlate the Stratigraphic Sequence in the Middle Benue with those of Anambra and Upper Benue. *Earth Evolution Science*, 1981. pp. 144–148.
6. Cedaconsult Nigeria Ltd. *Soils, Materials, and Pavement Design for Kwanga-Kusari-Shani Road*. Preliminary Road Engineering Report, Vols. 1 and 2, Borno State Ministry of Works, Nigeria, 1978.
7. J. W. P. Dowling. The Classification of Terrain for Road Engineering Purposes. *Proc., Conference on Civil Engineering Problems Overseas*, Institute Civil Engineers, London, 1968, pp. 209–236.
8. J. N. Bulman and C. J. Lawrence. The Use of Satellite Imagery in Highway Engineering in Africa. Presented at IRF IVth African Highway Conference, Nairobi, Kenya, 1980.
9. A. M. J. Meijerink, C. R. Valenzuela, and A. Stewart. *The Integrated Land and Watershed Management Information System: ILWIS*. ITC Publication 7, International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands, 1988.
10. A. K. Turner and R. D. Miles. The GCARS System: A Computer-Assisted Method of Regional Route Location. In *Highway Research Record 348*, HRB, National Research Council, Washington, D.C., 1971, pp. 1–15.
11. A. K. Turner and I. Hausmanis. *Special Report 138: Computer-Aided Transportation Corridor Selection in the Guelph-Dundas Area of Ontario*. HRB, National Research Council, Washington, D.C., 1973, pp. 55–70.
12. A. K. Turner. A Decade of Experience in Computer Aided Route Selection. *Photogrammetric Engineering*, Vol 44, No. 12, 1978, pp. 1561–1576.
13. A. K. Turner. Interactive and Graphic Techniques for Computer-Aided Route Selection. In *Transportation Research Record 729*, TRB, National Research Council, Washington, D.C., 1979.
14. G. Linden. *Highway Location: Towards a Framework for Planning Support*. Geo Pers, Groningen, The Netherlands, 1989.
15. M. C. Ellis. *General Route Selection Program Documentation*, ITC Internal Publication, ITC, Enschede, The Netherlands, 1989.
16. H. R. Aggarwal and R. H. Jafri. A Preliminary Study to Modify Material Specifications for Base Laterites for Secondary Roads. In *Geotechnical Practice in Nigeria*. (A. O. Madedor and J. O. Jackson, eds.), R.O.C., Surulere, Lagos, Nigeria, 1985, pp. 109–131.