Determination of Line and Grade for New Low-Volume Roads: Implications of a Total-Cost Approach

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The selection of general alignment and gradient for a road is posed as a unique design decision driven by the objective of minimizing total life-cycle costs of construction and vehicle operation. Inputs to the design decision process include the terrain between the origin and destination; the roadway geometry and surface type; the vehicle volume, mix, and growth rate; unit construction and vehicle operating costs; design life; and interest rate. Outputs include combinations of horizontal alignments and piecewise gradients, representing various optima based on combinations of the life-cycle cost components. These outputs provide the basis for the subsequent design decisions. The analytical procedure includes a basic cost model that reduces the terrain to a number of grade-constrained construction surfaces by using linear programming and a route selection model that computes the life-cycle costs of various alternative alignments over the surfaces and selects the ones with the least cost by using shortest path and next-best path techniques. The implications of a total-cost approach for horizontal and vertical design standards are discussed. The overall implication, however, is the potential obsolescence of predetermined geometric design standards for other than urban roads and intersections, because these standards can be uniquely determined as outputs of an analytical process.

Socioeconomic and sociocultural development in developing countries mandates the expansion of networks by the addition of low-volume links as well as the upgrading of the network by realignment and relocation of major segments of existing links. Developed countries with their underdeveloped and developing hinterlands often face the same problems, and most certainly where forestry plays a significant role in the economy, new low-volume–heavy-axle-load roads must be built when logging shifts from one area to another.

The selection of line and grade before the detailed design of the roadway geometry and pavement structure has a profound impact on the total life-cycle cost of construction, vehicle operation, and maintenance. Therefore, the total life-cycle costs should be direct inputs to an analytical selection of line and grade as output, rather than the choice of line and grade by predetermined sets of standards, which is the conventional approach.

OBJECTIVES

The overall objective of this paper is to present an analytical approach to the selection of line and grade combinations unique to the particular location situation and most likely to result in minimum total life-cycle costs. In particular the following are discussed:

1. A basic cost model, which reduces the terrain in the zone of interest between termini of a location to a number of grade-constrained construction surfaces;
2. A route selection model, which uses the basic cost model to select optimum locations as a function of construction costs and the vehicle operation costs of fuel and oil consumption;
3. The implications of a total-cost approach for horizontal and vertical design standards for new and relocated low-volume roads; and
4. Extensions of these implications to selection of line and grade for nonurban highways in general.

PROBLEM-SOLVING APPROACH

The approach adopted in the paper is methodological. A 5-km direct distance (re)location situation is presented as an example, for which the terrain is known and digitized; the average daily traffic (ADT) at the opening of the road and the classified traffic growth rates are projected; and unit costs of construction and fuel-and-oil consumption are estimated for one surface type. Quantity relationships from the Road Transport Investment Model (RTIM2), as well as relationships developed by the author for construction, are utilized in the analytical procedure. Linear programming and shortest-path techniques are employed in the basic cost model and route selection model, respectively. The combined sensitivity of line and grade to the total-cost parameters of interest is demonstrated in the process.

The model described in this paper does not yet include maintenance as an explicit input to the determination of line and grade. The computer programs are also not user interactive. These and other graphical enhancements will be added to the conceptual model.

BASIC COST MODEL

The Basic Cost Model (BCM) is a trilevel model defined on a digitized search grid between an origin and a destination representing (a) the intervening terrain at the regularized grid points, (b) cuts and fills at the grid points, and (c) a smoothed

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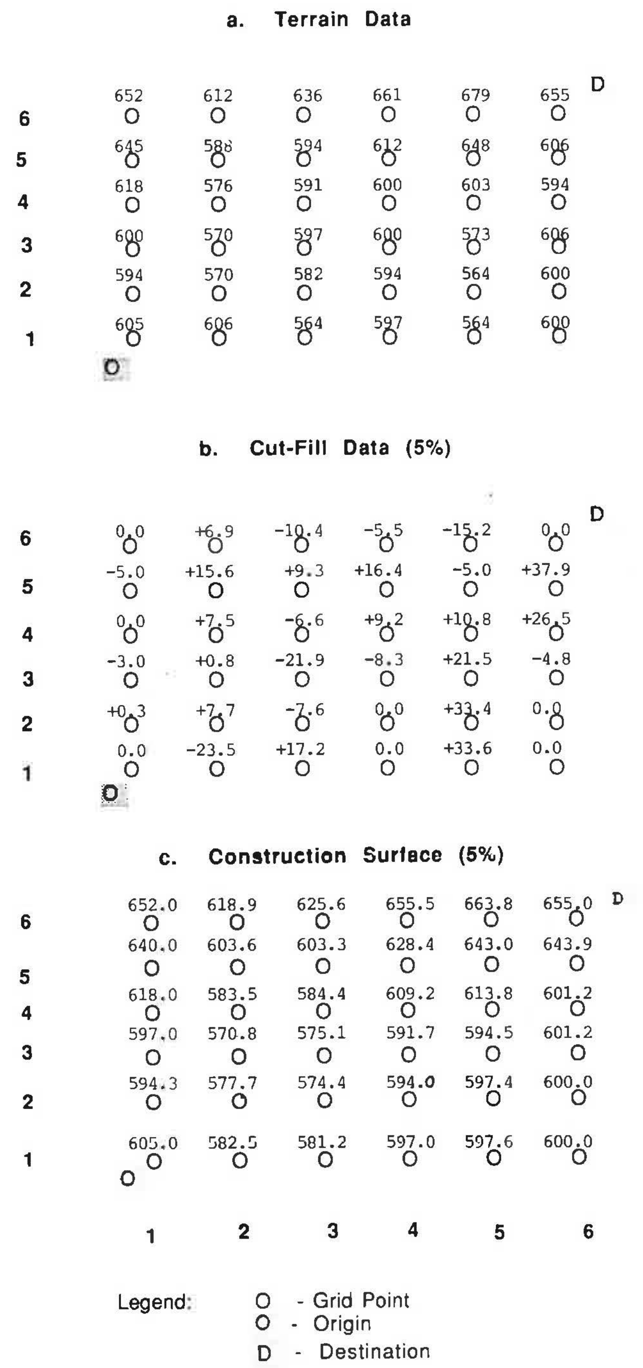
construction surface on which an infinity of horizontal alignments may be defined.

In this model the construction surface is a polynomial. For any given maximum gradient, the polynomial surface is computed such that the sum of the absolute value of the differences between it and the terrain elevations at the grid points is a minimum, subject to the constraint that the first derivative of the surface function does not exceed the absolute value of the gradient (in either of the orthogonal directions) at the grid points. The differences represent fills (+) and cuts (−), one or both of which will be zero, depending on whether the optimum polynomial surface lies above (+), below (−), or coincident with the terrain elevation at the grid point. The polynomial construction surface provides a rational basis for the estimation of the likely profiles of all possible O-D alignments through the grid points.



a. Terrain Data

	1	2	3	4	5	6
6	652	612	636	661	679	655 D
5	645	588	594	612	648	606
4	618	576	591	600	603	594
3	600	570	597	600	573	606
2	594	570	582	594	564	600
1	605	606	564	597	564	600

b. Cut-Fill Data (5%)

	1	2	3	4	5	6
6	0.0	+6.9	-10.4	-5.5	-15.2	0.0 D
5	-5.0	+15.6	+9.3	+16.4	-5.0	+37.9
4	0.0	+7.5	-6.6	+9.2	+10.8	+26.5
3	-3.0	+0.8	-21.9	-8.3	+21.5	-4.8
2	+0.3	+7.7	-7.6	0.0	+33.4	0.0
1	0.0	-23.5	+17.2	0.0	+33.6	0.0

c. Construction Surface (5%)

	1	2	3	4	5	6
6	652.0	618.9	625.6	655.5	663.8	655.0 D
5	640.0	603.6	603.3	628.4	643.0	643.9
4	618.0	583.5	584.4	609.2	613.8	601.2
3	597.0	570.8	575.1	591.7	594.5	601.2
2	594.3	577.7	574.4	594.0	597.4	600.0
1	605.0	582.5	581.2	597.0	597.6	600.0

FIGURE 1 Basic Cost Model concept.

The BCM concept is shown in Figure 1. Sample terrain data digitized on a 6 × 6 grid between the origin (1,1) and the destination (6,6) are shown in Figure 1a. The optimum polynomial construction surface, digitized for a 5 percent maximum gradient, is shown in Figure 1c. Figure 1b is the difference between Figures 1c and 1a, showing the resultant cuts and fills. For example, the suggested optimum 5 percent alignment at grid point (4,4) with a terrain elevation of 600 m (Figure 1a) would necessitate a fill of 9.2 m.

The optimum polynomial construction surface function is a byproduct of the mathematical procedure adopted. Figure 2 shows how a linear programming formulation would yield a unique BCM for every assumed maximum gradient (g). The Z_{ij} are the terrain elevations of the grid points; end-point constraints may be omitted. The outputs of interest are the C_{ij} and F_{ij}, which are the cuts and fills, respectively, on the search grid.

The BCM forms the basis for the computation of all design-related costs.

ROUTE SELECTION MODEL

The Route Selection Model (RSM) consists of a minimum path algorithm, which defines a minimum path tree; a next-best path algorithm, which uses the concept of deviations to define as many best paths as needed; and a link-evaluation submodel, which defines the alternatives linkwise in terms of gradients, speeds, fuel consumption, construction costs, and so on.

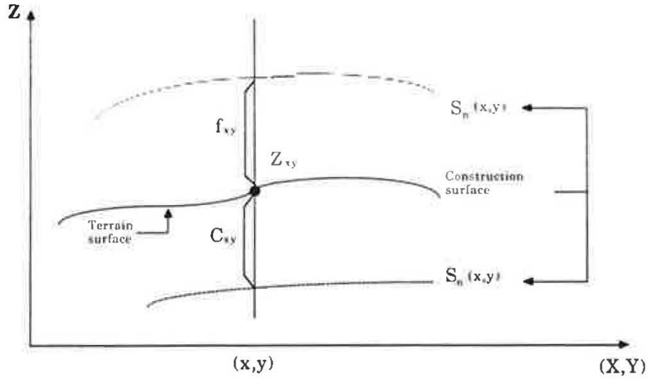
The link-evaluation submodel uses the BCM parameters along with other socioeconomic data. For example, construction quantities (to formation level) are estimated from the cuts and fills at the grid points and multiplied by unit costs to arrive at estimates of earthwork costs; from the construction surface piecewise gradients are computed and these are used, together with information about vehicle volume and mix, in the estimation of fuel and oil consumption (a major component of vehicle operation costs). Maintenance costs will also be influenced by gradients, particularly on unpaved roads in areas of heavy seasonal rainfall.

The cost estimates for vehicle operation are based on functional relationships developed by the U.K. Transport and Road Research Laboratory (TRRL) for RTIM2 (*1*). The procedure for the determination of line and grade is diagrammed in Figure 3. Conceptual and programming details may be found elsewhere (*2*).

SAMPLE PROBLEM

The grid in Figure 1 represents an area of search between an origin and destination 5 km apart. The objective is to search out, evaluate, and select economic locations in terms of both line and grade using life-cycle costs as a criterion.

Data related to construction and vehicle operation are shown in Figure 4 and Table 1. The type of surface is bituminous and the pavement width is 9.5 m. The design life is 15 years and the discount rate is 8.0 percent. The ADT on opening is given for each of five categories of vehicles, with their individual growth rates, fuel costs, and power-to-weight ratio (PW) and gross vehicle weight (GVW), where applicable.



Grid Point Function $Z_{ij} = S_n(i,j) + C_{ij} - f_{ij}$

MATHEMATICAL FORMULATION:

$$\text{MIN} \sum_i \sum_j C_{ij} + f_{ij}$$

Subject to:

general elevation constraints

$$C_{ij} - f_{ij} + S_n(i,j) = Z_{ij} \qquad \forall\, i,j$$

general grade constraints

$$\frac{\partial S_n(i,j)}{\partial x} \leq g \qquad \forall_{i,j}$$

$$\frac{\partial S_n(i,j)}{\partial x} \leq g \qquad \forall_{i,j}$$

end point elevation constraints

$$S_n(1,1) = Z_{1,1}$$

$$S_n(N,N) = Z_{n,n}$$

end point grade constraints

$$\frac{\partial S_n(1,1)}{\partial x} = \frac{\partial S_n(1,1)}{\partial x} = g_{1,1}$$

$$\frac{\partial S_n(N,N)}{\partial x} = \frac{\partial S_n(N,N)}{\partial y} = g_{N,N}$$

SURFACE FUNCTIONS :

$$S_n(x,y) = a_0(0) + a_1x + a_2y\,(1) + a_3x^2 + a_4xy^2$$

$$+ a_5y^2(2) + a_6x^2 + a_7x^2y + a_8xy^2$$

$$+ a_9y^3(3) + \text{---------}$$

FIGURE 2 Linear programming formulation of the basic cost model.

Unit costs of construction (per cubic meter) to formation level are represented by cut-to-fill (CF-COST), cut-to-waste (CW-COST), and borrow-to-fill (BF-COST) at grid coordinates. Pavement unit costs (PV-COST) (per square meter) are likewise represented.

Uniform construction unit costs are used in order to isolate the effects of the interaction of traffic, terrain, and road geometry. Neither the effects of nor the impact on maintenance is included in the example. Thus locations may be selected on the basis of construction costs only, vehicle operating costs (fuel and oil) only, or construction plus vehicle operating costs. Referring to Figure 3, the procedure is as follows:

Step 1: Compute the BCMs for a range of maximum gradients (1.5, 2, 3, 4, 5, 6, 7, and 8 percent).

Step 2: Using each of the BCMs in turn with Figure 4 and Table 1, select sets of best paths on the cost basis mentioned above. Facsimiles of the output format are shown in Figures 5–7.

What is presented to the analyst is a wide range of alternative locations with their cost implications. In this example, for each gradient, six best paths are generated for each of the three cost bases, giving a total of 144 alternative optima. This number of optima constitutes a rational and extensive basis for a comparable evaluation and recommendation.

Comparisons of the first-minimum routes chosen on the basis of construction cost, vehicle operating costs, and the sum of construction plus vehicle operating costs are shown in Figures 8, 9, and 10, respectively. Figure 11 compares second-minimum routes using vehicle operating costs. Third, fourth, sixth, or any other level of minimum, could be arranged likewise for any cost combination. Note that by doing this, it is possible to identify some global optima and in the process determine a design maximum gradient.

IMPLICATIONS OF A TOTAL-COST APPROACH

Total-Cost Criterion

The total-cost approach can set the engineer free from the restriction of design standards and instead permit the exploration of a wide range and combination of design criteria (including surface type) in the search for an optimum that is acceptable to the particular society and its decision makers in terms of construction and vehicle operation (and maintenance) costs, as well as total costs.

In the latter respect, it is suggested here that total costs should be the first-level criterion to reduce the set of alternative optima. When applied to the sample problem, total costs would reduce the set of 144 (Table 2) to a subset of 18 (Table 3), including the least total cost for the first, second, and so on, up to the sixth-minimum routes, as determined by the three cost-based search criteria of construction, vehicle operation, and construction plus vehicle operation costs.

In the sample problem eight different gradients, from 1.5 (the lowest feasible gradient) to 8 percent, are analyzed. It is clear from Table 2, however, that the optimum gradient would most likely fall within the range of 4 to 6 percent. This conclusion is arrived at by noting that the minimum of the

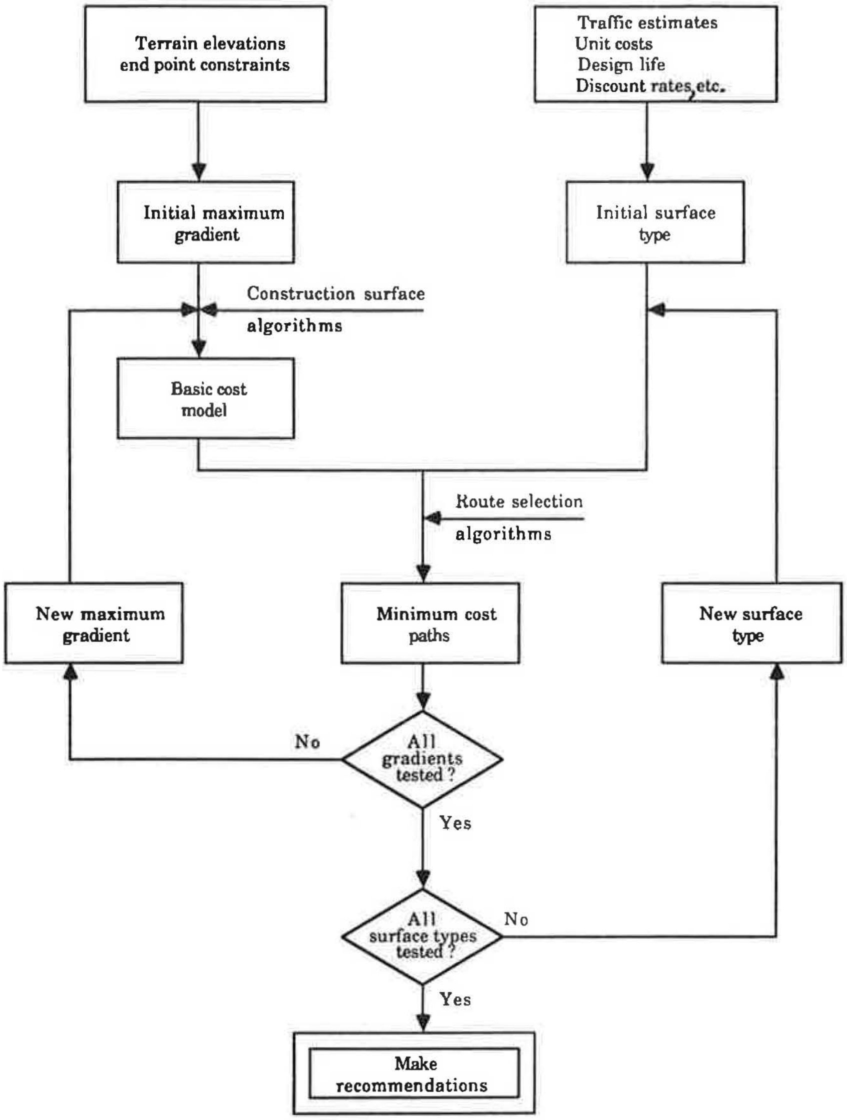


FIGURE 3 Procedure for determination of line and grade.

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STRAIGHT-DISTANCE    = DISTANCE  5.0 KM
WIDTH OF PAVEMENT    = 9.5 M
TYPE OF SURFACE :    1.BITUMINOUS
MAX. GRADIENT = 5.0%
DESIGN LIFE    = 15 YEARS

DESIRED NO. OF BEST PATHS = 6

OPTIMISE ON TRAFFIC OPERATING COSTS ONLY

TRAFFIC DATA              ADT       GR(%)     F-COST    PW        GVW

1.PASSENGER CARS          150.      3.0       9.50
2.LIGHT GOODS VEHICLES     30.      3.0       9.50
3.MEDIUM GOODS VEHICLES    81.      3.0       6.50      30.0
4.HEAVY GOODS VEHICLES    350.      5.0       6.50      13.4      10.0
5.BUSES                   170.      4.0       6.50      10.0       8.5
  TOTAL                   781.      4.1
  DISCOUNT RATE                     8.0
  LUBR. OIL : UNIT COST                       4.50
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FIGURE 4 Sample problem data.

TABLE 1 ZONE DATA AND CONSTRUCTION UNIT COSTS FOR SAMPLE PROBLEM

X	Y	ELEV.	CUT/FIL	SURFACE	CF-COST	CW-COST	BF-COST	PV-COST
1	1	605.0	0.0	605.0	22.50	22.50	27.50	500.00
2	1	606.0	-23.5	582.5	22.50	22.50	27.50	500.00
3	1	564.0	17.2	581.2	22.50	22.50	27.50	500.00
4	1	597.0	0.0	597.0	22.50	22.50	27.50	500.00
5	1	564.0	33.6	597.6	22.50	22.50	27.50	500.00
6	1	600.0	0.0	600.0	22.50	22.50	27.50	500.00
1	2	594.0	.3	594.3	22.50	22.50	27.50	500.00
2	2	570.0	7.7	577.7	22.50	22.50	27.50	500.00
3	2	582.0	-7.6	574.4	22.50	22.50	27.50	500.00
4	2	594.0	0.0	594.0	22.50	22.50	27.50	500.00
5	2	564.0	33.4	597.4	22.50	22.50	27.50	500.00
6	2	600.0	0.0	600.0	22.50	22.50	27.50	500.00
1	3	600.0	-3.0	597.0	22.50	22.50	27.50	500.00
2	3	570.0	.8	570.8	22.50	22.50	27.50	500.00
3	3	597.0	-21.9	575.1	22.50	22.50	27.50	500.00
4	3	600.0	-8.3	591.7	22.50	22.50	27.50	500.00
5	3	573.0	21.5	594.5	22.50	22.50	27.50	500.00
6	3	606.0	-4.8	601.2	22.50	22.50	27.50	500.00
1	4	618.0	0.0	618.0	22.50	22.50	27.50	500.00
2	4	676.0	7.5	583.5	22.50	22.50	27.50	500.00
3	4	591.0	-6.6	584.9	22.50	22.50	27.50	500.00
4	4	600.0	9.2	609.2	22.50	22.50	27.50	500.00
5	4	603.0	10.8	613.8	22.50	22.50	27.50	500.00
6	4	594.0	26.5	620.5	22.50	22.50	27.50	500.00
1	5	645.0	-5.0	640.0	22.50	22.50	27.50	500.00
2	5	588.0	15.6	603.6	22.50	22.50	27.50	500.00
3	5	594.0	9.3	603.3	22.50	22.50	27.50	500.00
4	5	612.0	16.4	628.4	22.50	22.50	27.50	500.00
5	5	648.0	-5.0	643.0	22.50	22.50	27.50	500.00
6	5	606.0	37.9	643.9	22.50	22.50	27.50	500.00
1	6	652.0	0.0	652.0	22.50	22.50	27.50	500.00
2	6	612.0	6.9	618.9	22.50	22.50	27.50	500.00
3	6	636.0	-10.4	625.6	22.50	22.50	27.50	500.00
4	6	661.0	-5.5	655.5	22.50	22.50	27.50	500.00
5	6	679.0	-15.2	663.8	22.50	22.50	27.50	500.00
6	6	655.0	0.0	655.0	22.50	22.50	27.50	500.00

optima in Table 2 (i.e., row-wise) fall between 4 and 6 percent. One might go even further to conclude that the 5 percent gradient is the design gradient that would be most likely to produce the minimum total cost for a wide range of options, given that it produced the minimum in two-thirds of the optima within the 4 to 6 percent range and that it completely dominates the range of gradients for the total-cost (construction plus vehicle operating costs) criteria. The 5 percent gradient is also seen to produce the global minimum among the optima.

Construction Cost Versus Vehicle Operation Cost Criterion

The total-cost criterion was used to reduce the set of 144 optima in Table 2 to the 18 optima in Table 3. Table 3 also displays additional details concerning approximate route length design, maximum and average gradients, and the breakdown of total costs into those for construction and those for vehicle operation. This subset of minima is also rank ordered from 1 to 14 (only 14 because of duplication of routes).

Construction costs would clearly dominate the engineering decision-making process in this case by the model used. The minimum-cost construction route also produces the minimum total-cost route. By contrast, the twelfth-ranked alternative produces the lowest vehicle operating cost but at the expense of almost 2.5 times the construction cost of the least-construction-cost alternative. Clearly this would be difficult for the ultimate decision maker (who would also be the ultimate financier) to accept. The long-term benefit of lower fuel consumption might not appear to justify such a substantial differential in immediate expenditure. The sixth-ranked alternative just might be acceptable in discussion, but is not likely to be adopted either. In general, however, following the narrowing down of the infinite number of alternatives to a finite subset of total-cost optima, this subset is further subjected to an analysis in terms of the trade-offs between constituent costs (in this case, construction and vehicle operation costs).

Alignment and Gradient

The design problem may be restated as the simultaneous selection of the general alignment and gradient most likely to result in the minimum life-cycle costs subject to acceptable or financially feasible levels of (initial) construction costs and

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OUTPUT FOR N-BEST PATHS

PATH NUMBER  1  FROM ORIGIN (1,1)  TO  DESTINATION : (6,6)

X    Y    FLEV    CUT/FILL    SURFACE    GRADE    COST("000)

6    6    655.       0.00      655.00      1.2     25403.758
5    5    648.     - 5.00      643.00      3.4     20528.919
4    4    600.       9.20      609.20      3.4     15218.693
3    3    597.    - 21.90      575.10    - 0.3      9897.609
2    2    570.       7.70      577.70    - 2.7      5180.740
1    1    605.       0.00      605.00      0.0         0.000

APPROX.  ROUTE LENGTH = 4.999 KM       MAX. GRADE = 3.4 %       AVG. GRADE = 2.2%

   CONSTRUCTION COST =  30763.332
   OPERATING COST      =  25403.758
                TOTAL      =  56167.090
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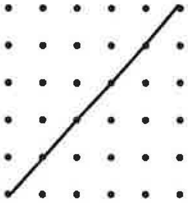

FIGURE 5 **Facsimile output for vehicle operating costs: Path No. 1.**

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PATH NUMBER  2  FROM ORIGIN (1,1)  TO  DESTINATION : (6,6)

X    Y    FLEV    CUT/FILL    SURFACE    GRADE    COST('000)

6    6    655.       0.00      655.00      1.2     26904.584
5    5    648.      -5.00      643.00      3.4     22029.744
4    4    600.       9.20      609.20      2.5     16719.519
4    3    600.      -8.30      591.70      1.7     13298.322
3    2    582.      -7.60      574.40    - 0.5      8424.784
2    2    570.       7.70      577.70    - 2.7      5180.740
1    1    605.       0.00      605.00      0.0         0.000

APPROX.  ROUTE LENGTH = 5.414 KM       MAX. GRADE = 3.4 %       AVG. GRADE = 2.1%

   CONSTRUCTION COST =  12474.325
   OPERATING COST      =  26904.584
                TOTAL      =  39328.909
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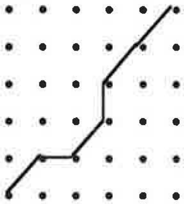

FIGURE 6 **Facsimile output for vehicle operating costs: Path No. 2.**

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PATH NUMBER 3  FROM ORIGIN (1,1)  TO  DESTINATION : (6,6)

X   Y   FLEV.   CUT/FILL    SURFACE   GRADE    COST('000)

6   6   655.      0.00      655.00     1.2     26911.263
5   5   648.     -5.00      643.00     4.1     22036.423
5   4   603.     10.80      613.80     2.2     18373.540
4   3   600.     -8.30      591.70     1.7     13298.322
3   2   582.     -7.60      574.40    -0.5      8424.784
2   2   570.      7.70      577.70    -2.7      5180.740
1   1   605.      0.00      605.00     0.0         0.000

APPROX. ROUTE LENGTH = 5.414 KM       MAX. GRADE = 4.1 %      AVG. GRADE = 2.1%

   CONSTRUCTION COST = 13288.566
   OPERATING COST    = 26911.263
               TOTAL = 40199.829
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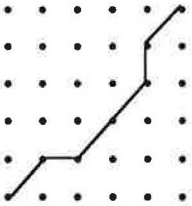
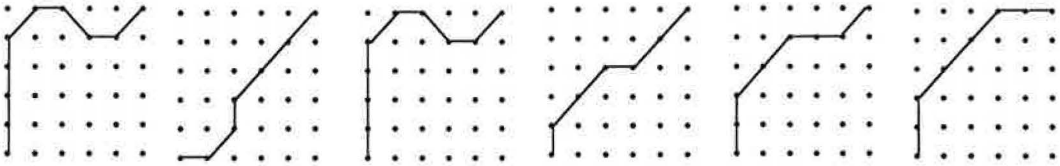


FIGURE 7 **Facsimile output for vehicle operating costs: Path No. 3.**

Surface Gradient	Best Path Length	Max. Grade	Average Grade	Construction Cost	Operating Cost	Total Cost
1.5	7.242	1.1	0.7	58 256 898	63 369 816	121 626 703
2.0	1.242	1.5	0.7	45 157 879	63 459 570	108 617 437
3.0	5.414	2.9	1.5	13 064 119	49 036 852	62 100 969
4.0	1.242	3.0	1.2	15 961 186	64 750 578	80 741 168
5.0	5.414	3.5	2.2	7 975 046	50 530 883	58 505 930
6.0	5.828	3.9	1.8	6 096 197	53 767 906	61 864 102
7.0	5.828	6.7	2.4	7 662 651	55 203 457	62 866 109
8.0	5.828	6.7	2.3	7 379 526	55 139 320	62 518 848



2 %   3 %   4 %   5 %   6 %   7 %

FIGURE 8 **First-minimum construction cost routes for sample problem.**

Surface Gradient	Best Path Length	Max. Grade	Average Grade	Construction Cost	Operating Cost	Total Cost
1.5	5.000	1.6	1.0	159 861 078	45 015 461	204 876 539
2.0	5.000	2.1	1.1	94 114 133	45 165 156	139 279 289
3.0	5.000	2.9	1.5	37 451 848	45 957 336	83 409 180
4.0	5.000	3.1	1.8	19 298 033	46 493 078	65 791 111
5.0	5.000	3.4	2.2	30 763 340	47 238 242	78 001 582
6.0	5.000	3.5	2.2	34 601 477	47 240 188	81 841 665
7.0	5.000	3.5	2.1	33 006 930	47 080 773	80 087 703
8.0	5.000	3.5	2.1	26 662 299	46 956 137	73 618 436

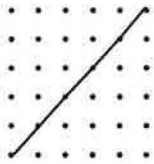
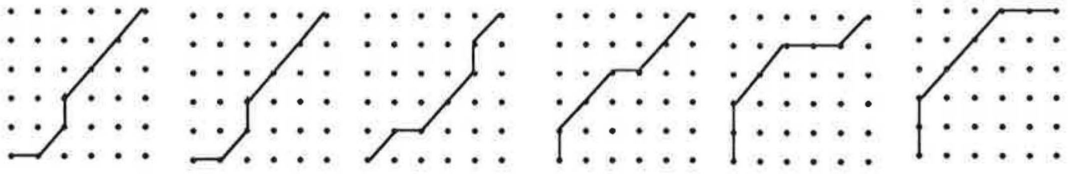

(all gradients)

FIGURE 9 First-minimum vehicle operating cost routes for sample problem.

Surface Gradient	Best Path Length	Max. Grade	Average Grade	Construction Cost	Operating Cost	Total Cost
1.5	7.242	1.1	0.7	58 256 898	63 369 816	121 626 704
2.0	5.414	2.1	1.2	48 180 902	48 532 527	96 713 429
3.0	5.414	2.9	1.5	13 064 119	49 036 852	62 100 971
4.0	5.000	3.1	1.8	19 298 033	46 493 078	65 791 111
5.0	5.414	3.5	2.2	7 975 046	50 530 883	58505 929
6.0	5.828	3.9	1.9	8 096 197	53 767 906	61 864 103
7.0	5.828	6.7	2.4	7 662 651	55 203 457	62 866 108
8.0	5.828	6.7	2.3	7 379 526	55 139 320	62 518 846


2 %

3 %

4 %

5 %

6 %

7 %

FIGURE 10 First-minimum total-cost routes for sample problem.

Surface Gradient	Best Path Length	Max. Grade	Average Grade	Construction Cost	Operating Cost	Total Cost
1.5	5.414	1.5	0.9	205 191 016	47 754 113	252 945 111
2.0	5.414	2.0	1.0	118 218 797	47 818 082	166 136 859
3.0	5.414	2.5	1.3	78 729 164	48 540 324	127 269 492
4.0	5.414	3.2	1.7	33 191 858	49 341 195	82 533 055
5.0	5.414	3.4	2.1	12 474 326	50 032 426	62 506 758
6.0	5.414	4.4	2.0	35 524 254	50 078 895	85 603 148
7.0	5.414	4.3	2.0	32 251 336	49 919 668	82 171 000
8.0	5.414	3.5	2.0	33 489 569	49 821 398	83 310 969

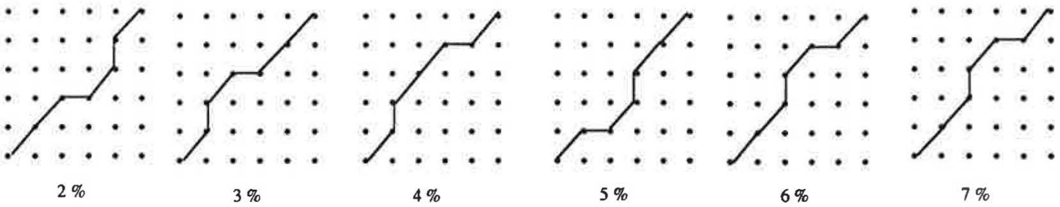


FIGURE 11 **Second-minimum vehicle operating cost routes for sample problem.**

(future) vehicle operation (and maintenance) costs. But what are the real design implications for alignment and gradient?

From Table 3, 5 percent would appear to be the most economical overall design gradient to adopt. It may be said, therefore, that one of the design outputs from the process is the overall design gradient, 5 percent. One would note, however, that the maximum gradient among the alternative optima need not necessarily equal the overall design gradient and that the average gradient over the alignment (i.e., the algebraic sum of all the rises and falls along the alignment divided by the length) is less than the maximum gradient, as is to be expected.

In the sample problem, route lengths vary from the direct distance of 5 km to approximately 6.4 km. There are three factors to note here, namely,

1. Construction cost considerations favor curvilinear alignments the extent of which is a function of overall design gradient;
2. Vehicle operating cost considerations favor direct distance alignments, regardless of gradient; and
3. Simultaneous consideration of both construction and vehicle operating costs moderates the extremes of curvilinearity and direct distance alignments.

It should also be noted with respect to the first factor that even when construction cost is the only consideration, low unit cost of construction should be traded off against length of alignment so that the total cost of construction does not exceed some maximum or concept of an optimum. One might consider, therefore, that construction cost considerations establish the maximum length, and hence curvilinearity. On the other hand, the impetus to minimize operating cost via a direct distance route should dictate that the alignment selection process be driven by a total-cost comparison of incrementally more curvilinear alignments with the direct distance route. Thus, all other locations would be viewed as "deviations" from the direct distance route to reduce construction costs to an acceptable maximum.

Finally, it should be noted that the different alignments, even for the same route lengths, influence costs through the piecewise combinations of gradient and curvature. That is to say, the design output from the process should also specify the maximum, average, and piecewise gradients (see Figures 5–7) as well as the overall design gradient for the recommended alignment if the order of magnitude of the cost implications is to be obtained. The importance of specifying all these aspects of gradients can be more readily appreciated by recalling that for any given alignment there are an infinite number of combinations of piecewise gradients, and hence an infinite set of cost implications. Thus, if a particular cost combination is deemed acceptable at a preliminary design stage (e.g., location design), it follows that the combination of alignment and gradients that produced the acceptable results must also be specified as a guide and comparator for any subsequent refinements or adjustment to the alignment and gradient.

Surface Type

The sample problem assumed a bituminous type of road surface. The analysis could be repeated for alternative surfaces to test the sensitivity of the general alignment and gradient, and to expand the range of optima, and hence the decision-making base. Essentially the model would trade off the low costs of construction for lower surface types against the higher costs of vehicle operation. Lower surface types might, how-

TABLE 2 OPTIMUM TOTAL-COST ROUTES FOR SAMPLE PROBLEM

Search criteria	**Route designation**	**Total costs of construction and vehicle operation**							
		1.5%	2.0%	3.0%	4.0%	5.0%	6.0%	7.0%	8.0%
Construction costs	1st minimum	121626703	108617437	62100969	80741766	**58505930**	61864102	62866109	62518848
	2nd minimum	130968117	118163047	62657523	78936055	**61573219**	66575727	67836789	67585047
	3rd minimum	130777414	96713438	66196961	74282125	73396805	**62100629**	66516078	65941844
	4th minimum	140019828	109187844	66094766	79686773	**62299230**	66965836	76750773	78677445
	5th minimum	140076500	102743289	74700672	82582117	67342148	**65554430**	78595312	76917102
	6th minimum	149318906	109706258	71818094	82985531	71477664	**66812258**	69162438	78033438
Vehicle operation costs	1st minimum	204876562	139279281	83409180	**65791109**	78001578	81841664	80087703	73618437
	2nd minimum	252945141	166136859	127269492	82533055	**62506758**	85603148	82171000	83310969
	3rd minimum	241681953	145293812	127106781	78724281	**63333465**	86802477	85111445	75099055
	4th minimum	231689531	215761172	111500320	80596883	86184281	**65019020**	69881344	85191828
	5th minimum	226929906	211381062	91538328	**73383766**	79755898	85651805	86773477	83505547
	6th minimum	285017437	265746469	88947773	68802453	80681812	**64798516**	80946242	77950133
Construction + vehicle operation costs	1st minimum	121626703	96713438	62100969	65791109	**58505930**	61864102	62866109	62518848
	2nd minimum	130777414	98751539	62657523	68075750	**61573219**	62100629	63541559	63074852
	3rd minimum	130869117	102743289	66094766	68345133	**61818090**	62908980	63627457	64097785
	4th minimum	138764094	102953648	66196961	68802453	**62299230**	64090934	64302906	64653789
	5th minimum	140019828	108617437	66819820	69686820	**62506758**	64798516	64932250	64686043
	6th minimum	140019828	109187844	67338086	69964609	**62843051**	65019020	65693602	65242047

TABLE 3 TOTAL-COST ARRAY FOR SAMPLE PROBLEM

Search criteria	Route designation	Route length (km)	Gradients(%)			Costs			Rank order
			design	max.	average	construction	operation	total	
Construction costs	1st minimum	5.414	5.0	3.5	2.2	**7975046**	50530883	**58505929**	1
	2nd minimum	5.828	5.0	3.5	1.7	8200056	53373160	61573216	2
	3rd minimum	5.828	6.0	3.9	2.1	8357019	53743609	62100628	4
	4th minimum	5.828	5.0	3.5	2.0	8610596	53688633	62299229	5
	5th minimum	6.242	6.0	4.1	2.0	8384327	57170102	62554429	11
	6th minimum	6.413	6.0	3.5	1.9	8391141	58421117	66812258	13
Vehicle operation costs	1st minimum	5.000	4.0	3.1	1.8	19298033	**46493078**	65791111	12
	2nd minimum	5.414	5.0	3.4	2.1	12474325	50032426	62506751	6
	3rd minimum	5.414	5.0	4.1	2.1	13288567	50044895	65333462	8
	4th minimum	5.414	6.0	3.5	2.1	14860564	50158453	65019017	10
	5th minimum	5.414	4.0	3.1	1.8	23945572	49438191	73383763	14
	6th minimum	5.414	6.0	4.5	2.1	14597288	50201223	64798511	9
Construction + vehicle operation costs	1st minimum	5.414	5.0	3.5	2.2	**7975046**	50530883	**58505929**	1
	2nd minimum	5.828	5.0	3.5	1.7	8200056	53373160	61573216	2
	3rd minimum	5.414	5.0	3.5	2.2	11497665	50320422	61818087	3
	4th minimum	5.828	5.0	3.5	2.0	8610596	53688633	62299229	5
	5th minimum	5.414	5.0	3.4	2.1	12474325	50032426	62506751	6
	6th minimum	5.828	5.0	3.7	2.1	8844034	53999016	62843050	7

ever, lead to higher costs for improved geometric alignment in order to lower operating costs.

Design Standards

Location design models can be used to establish and revise standards appropriate to any particular physical and socioeconomic environment, despite the above assertion that predetermined design standards are not a necessary requirement for the initiation of the design process. For example, the procedure may be used for a range of vehicle volumes and mix over different terrain types in a given country with its particular factor inputs, the objective being to establish threshold values as guides for the conventional highway design process. In the sample problem the likely range of gradients was narrowed down to between 4 and 6 percent. This approach could be expanded and generalized to facilitate the development and evolution of design guides.

CONCLUSIONS

The results presented in this paper suggest that

1. The economics of low-volume road design standards can be improved by sophisticated analytical methods,
2. Linkwise line and grade combinations can be uniquely determined as design output rather than standard input for a given (re)location problem, and
3. There are implications for setting highway design standards that are appropriate to specific socioeconomic environments.

Low-volume roads do not necessarily trigger low design standards, such as steep gradients, high curvature, and low riding surfaces. When the vehicle operating costs are included, these moderate the conventional response toward longer alignments with low unit construction costs to shorter alignments with higher unit construction costs but lower total construction costs. These trade-offs would be difficult to evaluate on a project-by-project basis without an analytical process that can simultaneously select line and grade on a total-cost minimization basis.

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