Intersection Construction Cost Functions for Alignment Optimization

Eungcheol Kim[1]; Manoj K. Jha, M.ASCE[2]; and Paul Schonfeld, F.ASCE[3]

Abstract: A method for precisely formulating intersection construction costs including earthwork costs, right-of-way costs, and pavement costs is introduced in this paper. Intersection design characteristics are reviewed and intersection cost components are formulated. A highway alignment is described by parametric representation in space, and vector manipulation is used to find the coordinates of intersections and other points of interest. A simplified typical fill section is studied to obtain actual ground and road elevation coordinates that are crucial for setting the boundaries and computing the costs. Because estimating right-of-way costs requires identifying affected properties and structures in the vicinity of an intersection, two examples based on geographic information system (GIS) databases from Maryland and an artificial study area are presented to show how the developed cost functions can be used in real applications. The developed intersection construction cost functions can be incorporated in previously developed highway alignment optimization models that neglected the characteristics and costs of intersections.

DOI: 10.1061/(ASCE)0733-947X(2004)130:2(194)

CE Database subject headings: Intersections; Construction costs; Earthwork; Pavements; Alignment; Optimization models.

Introduction

The performance and costs of intersections significantly affect those of the entire transportation system and the regions they serve; therefore, when developing highway alignment optimization processes, intersection cost functions should be included. However, those functions have previously been neglected, because accommodating them requires detailed cost formulations and extensive data analysis. In a previous study (Jha 2001), a highway alignment was optimized with and without considering intersection cost. The resulting alignments could differ significantly and total alignment cost could be significantly underestimated when intersection costs are neglected. In this paper a method is introduced for formulating intersection cost function that mainly focuses on construction cost components such as earthwork, right-of-way, and pavement.

Using mathematical models and computer programs, great efforts have been devoted to highway alignment optimization processes. There have been five main types of studies on highway alignment optimization: (1) Direct search using artificial intelligence techniques such as genetic algorithms (Jong 1998; Jong and Schonfeld 1999a, 2003; Jha 2000, 2003; Jong et al. 2000); (2) enumeration (Easa 1988), (3) dynamic programming (Murchland 1973; Puy Huarte 1973; Goh et al. 1988; Fwa 1989); (4) linear programming (ReVelle et al. 1997); and (5) numerical search (Hayman 1970; Pearman 1973; Goh et al. 1988). None of these studies incorporated intersection cost functions. This deficiency clearly limits the applicability of models to highways that have intersections. This paper formulates a detailed intersection construction cost function with sufficient accuracy and sensitivity for alignment optimization. This initial study is limited to intersections where two-lane rural highways cross. An example based on real geographic information system (GIS) databases from Maryland is used to demonstrate the usefulness of the developed cost function. The suitability of the functions to the highway alignment optimization processes is then assessed.

Intersection Design Characteristics

According to the American Association of State Highway and Transportation Officials (AASHTO 2001), ''the main objective of intersection design is to reduce the severity of potential conflicts between motor vehicles, buses, trucks, bicycles, pedestrians, and facilities while facilitating the convenience, ease, and comfort of people traversing the intersections.'' The AASHTO (2001) classified intersection design considerations into four basic elements: human factors, traffic considerations, physical elements, and economic factors. Of these, items sensitive to the highway alignment optimization process can be selected through specifications of cost components.

Intersection cost components (Table 1) are largely divided into four groups: (1) Construction costs; (2) operational costs; (3) environmental costs; and (4) drainage costs. Construction costs include earthwork costs, right-of-way costs, and pavement costs. Operational costs include user delay costs, accident costs, and fuel costs, while environmental costs contain many elements difficult to quantify. In this paper we only focus on construction costs that are especially sensitive to alignments, namely, pavement, earthwork, and right-of-way costs.

To describe an alignment in three-dimensional (3D) space, a parametric representation is useful (Swokowski 1979; Morten-

[1]Research Fellow, Dept. of Highway Research, The Korea Transport Institute, South Korea. E-mail: eckim@koti.re.kr

[2]Assistant Professor, Dept. of Civil Engineering, Morgan State Univ., Baltimore, MD 21251. E-mail: mkjha@eng.morgan.edu

[3]Professor, Dept. of Civil Engineering, Univ. of Maryland, College Park, MD 20742. E-mail: pschon@eng.umd.edu

Note. Discussion open until August 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 23, 2001; approved on March 24, 2003. This paper is part of the ***Journal of Transportation Engineering***, Vol. 130, No. 2, March 1, 2004. ©ASCE, ISSN 0733-947X/2004/2-194–203/$18.00.

Table 1. Intersection Cost Components Specification

Main specification	Subspecification	Elements	Sensitivity to alignment
Construction costs	Earthwork costs	Physical elements	High
	Right-of-way costs	Physical elements; economic factors	High
	Pavement costs	Physical elements	High
Operational costs	User delay costs	Traffic considerations; human factors	Medium
	Accident costs	Human factors; physical elements	Medium
	Fuel costs	Traffic considerations; physical elements	Low
Environmental costs	Noise costs	Traffic considerations; physical elements	Low
	Pollution (emission) costs	Traffic considerations; physical elements	Low
Drainage costs		Traffic considerations; physical elements; economic factors	Low

son 1997), which has been employed successfully in other studies (Jong 1998; Lovell 1999). For notational convenience, this paper adopts conventions from calculus. Boldface letters like **A** and **P** denote vectors in space. An alignment can be defined as follows and as shown in Fig. 1.

Definition: Let L_a be a set of points defined by the position vector $\mathbf{P}(u)=\langle x(u),y(u),z(u)\rangle$, where $u\in[0,1]$. If L_a is an alignment connecting the starting point (**SP**) and the ending point (**EP**), then the position vector $\mathbf{P}(u)$ must satisfy

1. $\mathbf{P}(0)=\mathbf{SP},\mathbf{P}(1)=\mathbf{EP}$;
2. $\mathbf{P}(u)$ is continuous in the interval $u\in[0,1]$; and
3. $\mathbf{P}'(u)$, tangent vector to L_a at $\mathbf{P}(u)$, is continuous in the interval $u\in[0,1]$.

Methodology

Suppose there is a set of points of intersection (PIs) defining centerlines of two intersecting roads shown in Fig. 2 as dotted lines. After applying the procedures developed and explained in Jong (1998) for filling in vertical curves, horizontal curves, and road cross-section characteristics based on design standards, the intersecting alignments are sufficiently specified to evaluate their costs. The final crossing point will most likely deviate from its original PI location.

Finding Coordinates of Intersection Point

Suppose there are two roads labeled I and II crossing at a particular point. The two-dimensional (2D) coordinates of that point should be found. We consider three different types of crossing:

1. A tangent section of one alignment intersecting a tangent section of the other alignment;
2. A tangent section of one alignment intersecting a circular section of the other alignment; and
3. A circular section of one alignment intersecting a circular section of the other alignment.

Since type 3 is the most difficult to analyze and quite likely to actually occur, this paper focuses on it. To find the coordinates of the point of intersection (PI), the equations of the circular curves should be obtained, then set equal to each other and solved for the coordinates. To do this, the coordinates of the center point of two circles, and each alignment's points of tangency (PT) and points of curvature (PC) should be obtained. Ways of finding these points are already discussed in many sources (Hickerson 1964; Wright 1996; Jong 1998; Jha 2000). Fig. 3 displays the characteristics of a typical circular section on an alignment (Jong 1998).

Using vector analysis and trigonometry, the intersection angle (Δ_i) and the coordinates of the point of curvature (C_i) and point of tangency (T_i) can be obtained as shown in Eqs. (1)–(3). Interested readers are encouraged to consult Kim (2001) for further details on the development of Eqs. (1)–(26):

$$\Delta_i=\cos^{-1}\left[\frac{(\mathbf{P}_i-\mathbf{P}_{i-1})\cdot(\mathbf{P}_{i+1}-\mathbf{P}_i)}{\|\mathbf{P}_i-\mathbf{P}_{i-1}\|\|\mathbf{P}_{i+1}-\mathbf{P}_i\|}\right] \tag{1}$$

$$\mathbf{C}_i=\begin{bmatrix}x_{C_i}\\ y_{C_i}\end{bmatrix}=\mathbf{P}_i+L_T(i)\frac{\mathbf{P}_{i-1}-\mathbf{P}_i}{\|\mathbf{P}_{i-1}-\mathbf{P}_i\|} \tag{2}$$

$$\mathbf{T}_i=\begin{bmatrix}x_{T_i}\\ y_{T_i}\end{bmatrix}=\mathbf{P}_i+L_T(i)\frac{\mathbf{P}_{i+1}-\mathbf{P}_i}{\|\mathbf{P}_{i+1}-\mathbf{P}_i\|} \tag{3}$$

To find the coordinates of a circle's center point, let M_i be the middle point of the line segment between C_i and T_i, as shown in Fig. 4 (Jong 1998). It can be shown that M_i is located on the line connecting P_i and δ_i. Therefore, by vector analysis

$$\boldsymbol{\delta}_i=\begin{bmatrix}x_{\delta_i}\\ y_{\delta_i}\end{bmatrix}=\mathbf{P}_i+R_i\sec\frac{\Delta_i}{2}\frac{\mathbf{M}_i-\mathbf{P}_i}{\|\mathbf{M}_i-\mathbf{P}_i\|} \tag{4}$$

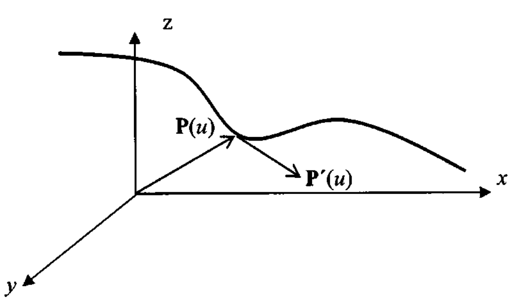

Fig. 1. Parametric interpretation of space curve

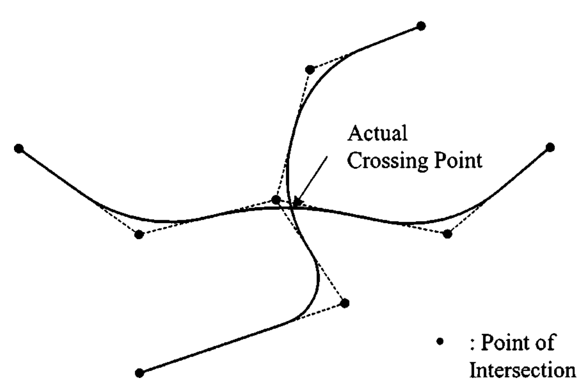

Fig. 2. Points of intersections (PIs) and final displaced crossing point

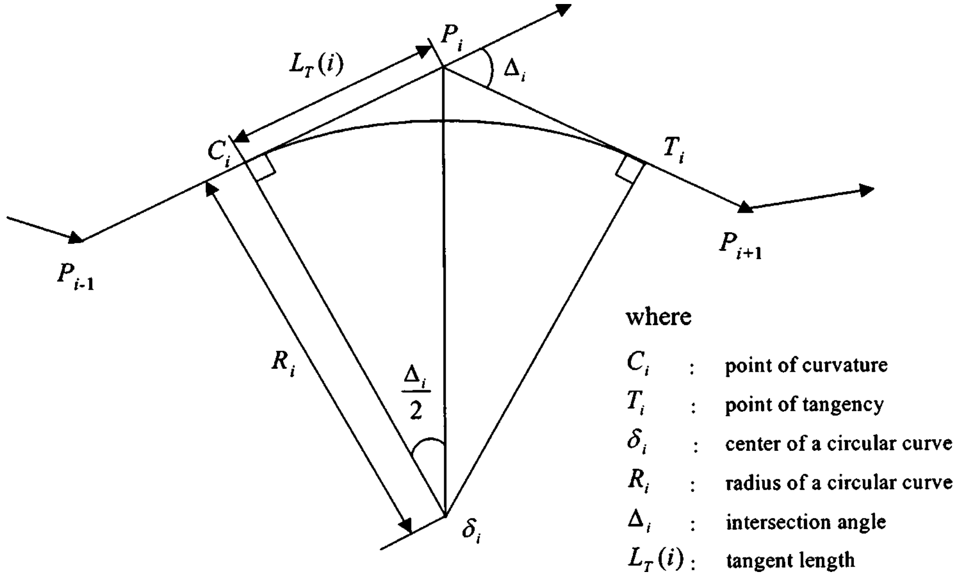

Fig. 3. Geometric specification of circular curve

The equations of two crossing circles are

$$(x^I - x^I_{\delta_i})^2 + (y^I - y^I_{\delta_i})^2 = R_i^{I2} \tag{5}$$

$$(x^{II} - x^{II}_{\delta_j})^2 + (y^{II} - y^{II}_{\delta_j})^2 = R_j^{II2} \tag{6}$$

Setting Eq. (5) equal to Eq. (6), we obtain

$$(x^I - x^I_{\delta_i})^2 + (y^I - y^I_{\delta_i})^2 - R_i^{I2} = (x^{II} - x^{II}_{\delta_j})^2 + (y^{II} - y^{II}_{\delta_j})^2 - R_j^{II2} \tag{7}$$

When solving Eq. (7), a linear equation is obtained, because the squared terms of x^2 and y^2 cancel out. By substituting that linear equation into Eqs. (5) or (6), the coordinates of the intersecting point are found. One of the two solutions is not feasible.

Pavement Costs

Estimating pavement costs is relatively simple. AASHTO (2001) design standards supply geometric specifications of additional flared areas, providing paths for turning movements. To illustrate the pavement cost calculation, a typical four-leg flared intersection is shown in Fig. 5. Although there could be numerous variations in providing traffic islands and divisional islands, all shaded areas shown in Fig. 5 should be included in estimating pavement costs. Shaded areas can generally be divided into flared areas and remaining areas.

Based on Fig. 6 and design standards for a two-lane rural highway intersection, the flared area (A_f) and remaining area (A_r) can be determined as

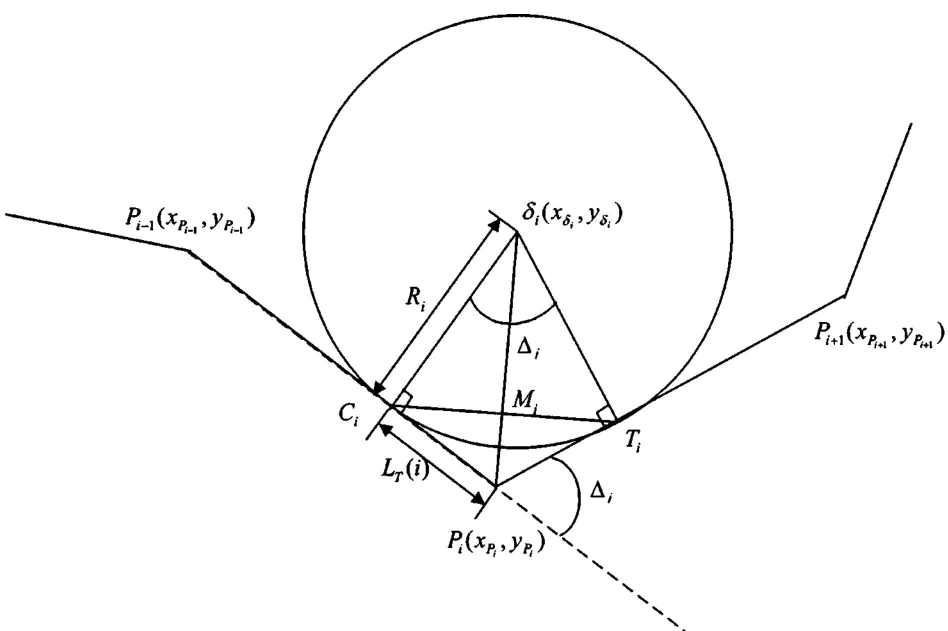

Fig. 4. Geometric relations among C_i, T_i, δ_i, and M_i

J. Transp. Eng. 2004.130:194-203.

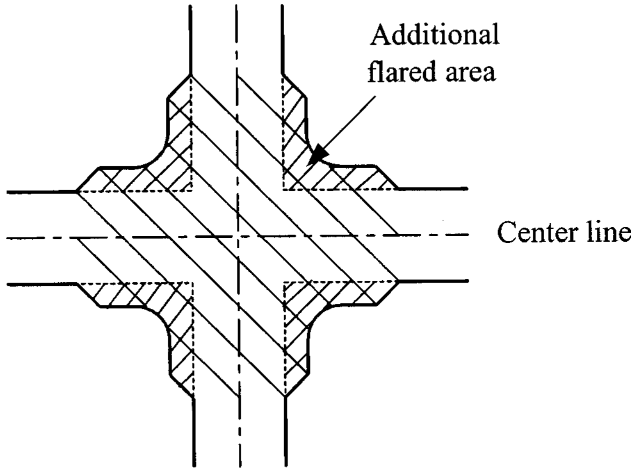

Fig. 5. Typical four-leg intersection

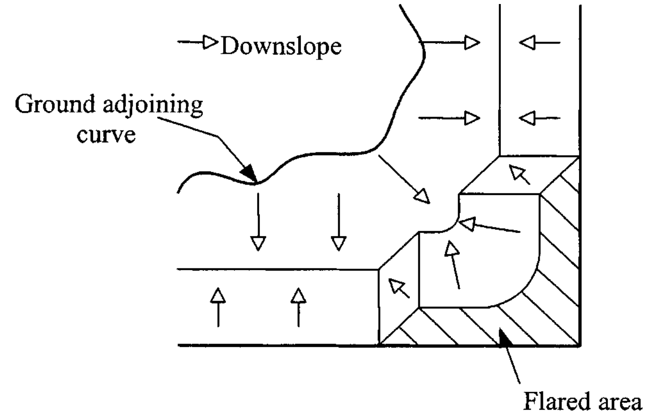

Fig. 7. Quadrant of typical fill intersection

$$A_r=\left(\frac{W}{2}\right)^2+2b\left(\frac{W}{2}\right)=\frac{W^2}{4}+bW \tag{8}$$

$$A_f=2\left(\frac{1}{2}\right)cf+2df+\left(e^2-\frac{\pi r^2}{4}\right)=f(c+2d)+e^2-\frac{\pi r^2}{4} \tag{9}$$

Thus, the total pavement area (A_p) is

$$A_p=4\left(\frac{W^2}{4}+bW\right)+4\left[f(c+2d)+e^2-\frac{\pi r^2}{4}\right]$$

$$=W^2+4bW+4f(c+2d)+4e^2-\pi r^2 \tag{10}$$

Finally, total pavement costs (C_P) can be obtained by introducing a unit cost, K_P:

$$C_P=K_P[W^2+4bW+4f(c+2d)+4e^2-\pi r^2] \tag{11}$$

in which K_P=pavement cost per unit area (dollars/m^2).

Earthwork Boundaries and Cost Estimation

Earthwork Boundaries

First, we must examine where earthwork boundaries should be placed. Boundary setting ensures that costs for approach segments and intersections are not double-counted. To describe how earthwork boundaries are set and earthwork volumes are estimated, a typical fill intersection is introduced. For explanatory convenience, only one quadrant of a fill intersection is shown in this paper. Following design standards (AASHTO 2001), a constructed fill intersection can be represented as in Fig. 7.

Although estimating earthwork volumes based on Fig. 7 is possible, just for evaluation purposes, a simplified fill intersection is redesigned as shown in Fig. 8. This simplified fill intersection may yield slightly less accuracy in estimation, but helps us develop a more understandable formulation.

Fig. 8 shows where earthwork boundaries lie. Clearly, boundaries depend on the location of the center point of the flared parts. Either the average end area method or the prismoidal method can be used for approaching segments.

Earthwork Volume Estimation

In estimating earthwork volumes and costs, the basic need is to find the coordinates of the points in Fig. 9. Afterwards, the average road elevations of each slice can be approximated using the coordinates of surrounding points.

An example shows how the coordinates of important points in Fig. 9 (A, B, D, E, F, G, H, I, J, K, and N_m) are found. If the coordinates of all these points can be found, it is easy to subdivide the area arbitrarily into many slices. Among the many points in Fig. 9, it should be mentioned that the coordinates of $I(x,y)$ are already found from the previous section, and the coordinates of

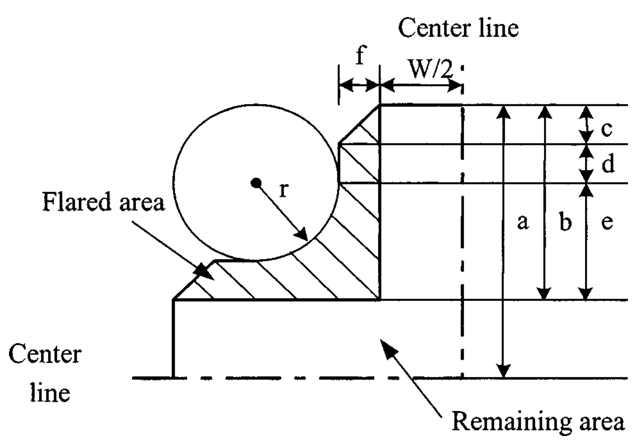

Fig. 6. Flared and remaining areas of typical four-leg intersection

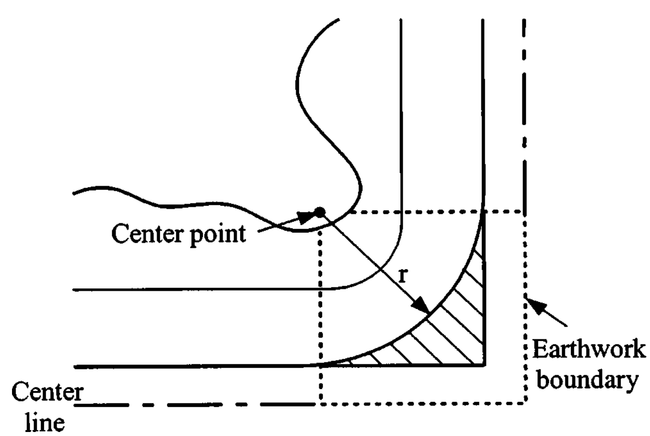

Fig. 8. Simplified quadrant of typical fill intersection

J. Transp. Eng. 2004.130:194-203.

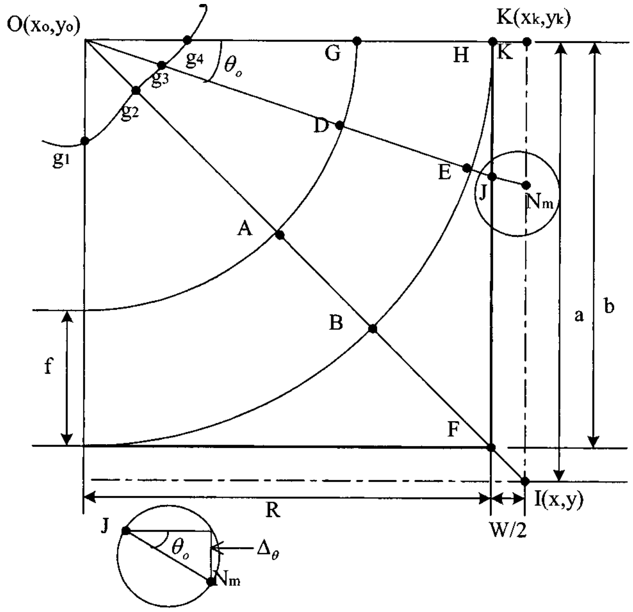

Fig. 9. Important points for determining coordinates

$O(x_o, y_o)$ and $K(x_k, y_k)$ are given by design standards. The coordinates of the remaining points can be based on this information.

The coordinates of points A, B, and F lying on the line segment between the intersecting point $[I(x,y)]$ and the center point $[O(x_o, y_o)]$ for the flared area can be found simply by using vector operations (boldface letters represent vectors):

$$\mathbf{A}=\mathbf{O}+(R-f)\frac{\mathbf{I}-\mathbf{O}}{\|\mathbf{I}-\mathbf{O}\|} \tag{12}$$

$$\mathbf{B}=\mathbf{O}+R\frac{\mathbf{I}-\mathbf{O}}{\|\mathbf{I}-\mathbf{O}\|} \tag{13}$$

$$\mathbf{F}=\mathbf{O}+\left[\|\mathbf{I}-\mathbf{O}\|-\frac{W}{\sqrt{2}}\right]\frac{(\mathbf{I}-\mathbf{O})}{\|\mathbf{I}-\mathbf{O}\|} \tag{14}$$

$$\mathbf{G}=\mathbf{O}+(R-f)\frac{\mathbf{K}-\mathbf{O}}{\|\mathbf{K}-\mathbf{O}\|} \tag{15}$$

$$\mathbf{H}=\mathbf{O}+R\frac{\mathbf{K}-\mathbf{O}}{\|\mathbf{K}-\mathbf{O}\|} \tag{16}$$

For more general cases such as points D, E, J, and N_m, we introduce a small value Δy, defined by $\Delta y=b/n$, where n is a user selected value. Next, let m be any multiple number of Δy ($\Delta y \leqslant m \leqslant b$) and N_m be the point located $m \times \Delta y$ away from $I(x,y)$. Then, the coordinates of D, E, and N_m are

$$\mathbf{D}=\mathbf{O}+(R-f)\frac{\mathbf{N}_m-\mathbf{O}}{\|\mathbf{N}_m-\mathbf{O}\|} \tag{17}$$

$$\mathbf{E}=\mathbf{O}+R\frac{\mathbf{N}_m-\mathbf{O}}{\|\mathbf{N}_m-\mathbf{O}\|} \tag{18}$$

$$\mathbf{N}_m=\mathbf{I}+m\frac{\mathbf{K}-\mathbf{I}}{\|\mathbf{K}-\mathbf{I}\|} \tag{19}$$

Now, finding J's coordinates requires finding the angle θ_o between two vectors, $\mathbf{N}_m-\mathbf{O}$ and $\mathbf{K}-\mathbf{O}$:

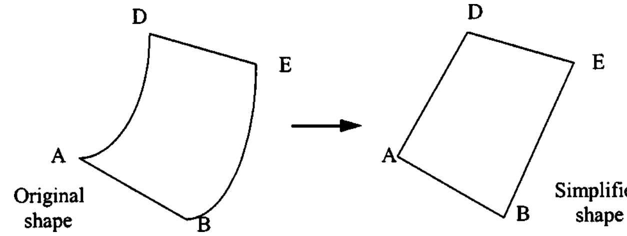

Fig. 10. Simplified shape of area $ABDE$

$$\theta_o=\cos^{-1}\left(\frac{(\mathbf{N}_m-\mathbf{O})\cdot(\mathbf{K}-\mathbf{O})}{\|\mathbf{N}_m-\mathbf{O}\|\|\mathbf{K}-\mathbf{O}\|}\right) \tag{20}$$

in which $\cdot$=inner (dot) product. Therefore

$$\Delta_\theta=\frac{W}{2}\tan\theta_o=\frac{W}{2}\tan\left[\frac{(\mathbf{N}_m-\mathbf{O})\cdot(\mathbf{K}-\mathbf{O})}{\|\mathbf{N}_m-\mathbf{O}\|\|\mathbf{K}-\mathbf{O}\|}\right] \tag{21}$$

and the size of vector $\mathbf{N}_m-\mathbf{J}$ is

$$\|\mathbf{N}_m-\mathbf{J}\|=\sqrt{\frac{W^2}{4}+\left(\frac{W}{2}\tan\theta_o\right)^2} \tag{22}$$

Finally, the coordinates of point J are

$$\mathbf{J}=\mathbf{O}+\left[\|\mathbf{N}_m-\mathbf{O}\|-\sqrt{\frac{W^2}{4}+\left(\frac{W}{2}\tan\theta_o\right)^2}\right]\frac{(\mathbf{N}_m-\mathbf{O})}{\|\mathbf{N}_m-\mathbf{O}\|} \tag{23}$$

Earthwork Cost Estimation

Given ground elevation databases, costs can be estimated by calculating the base areas of the relevant cells using previously found coordinates. For instance, to determine the base area surrounded by points A, B, D, and E in the left part of Fig. 10, that shape needs to be approximated into a simplified form, as shown in the right part of Fig. 10.

Then the base areas (A_b, m^2) are obtained as follows using a cross product:

$$A_b=\left(\frac{1}{2}\right)[\|(\mathbf{B}-\mathbf{A})\times(\mathbf{E}-\mathbf{A})\|+\|(\mathbf{E}-\mathbf{A})\times(\mathbf{D}-\mathbf{A})\|] \tag{24}$$

To find the earthwork volumes, two elevations are needed: (1) base elevation; and (2) ground elevation. This paper simply averages surrounding points' elevations (e.g., A, B, D, and E in Fig. 10) for finding the base elevation of a parcel. The corresponding ground elevation can be similarly obtained from the surrounding points' ground elevations, which are available from existing databases.

Suppose there is a total of T parcels in the intersection. Then, the total earthwork (fill) volumes (E_V) are

$$E_V=\sum_{i=1}^{T}A_i^b(Z_{b_i}^{\text{ave}}-Z_{g_i}^{\text{ave}}) \tag{25}$$

where A_i^b=base area of cell i; $Z_{g_i}^{\text{ave}}$=average ground elevation of cell i; and $Z_{b_i}^{\text{ave}}$=average base elevation of cell i. Therefore, total earthwork cost, C_E, is

$$C_E=K_F E_V \tag{26}$$

in which K_F=fill cost per cubic meter (dollars/m^3),

Right-of-Way Boundaries and Cost Estimation

By adding intersections to alignments, it is expected that the alignment right-of-way costs may increase. The coordinates of

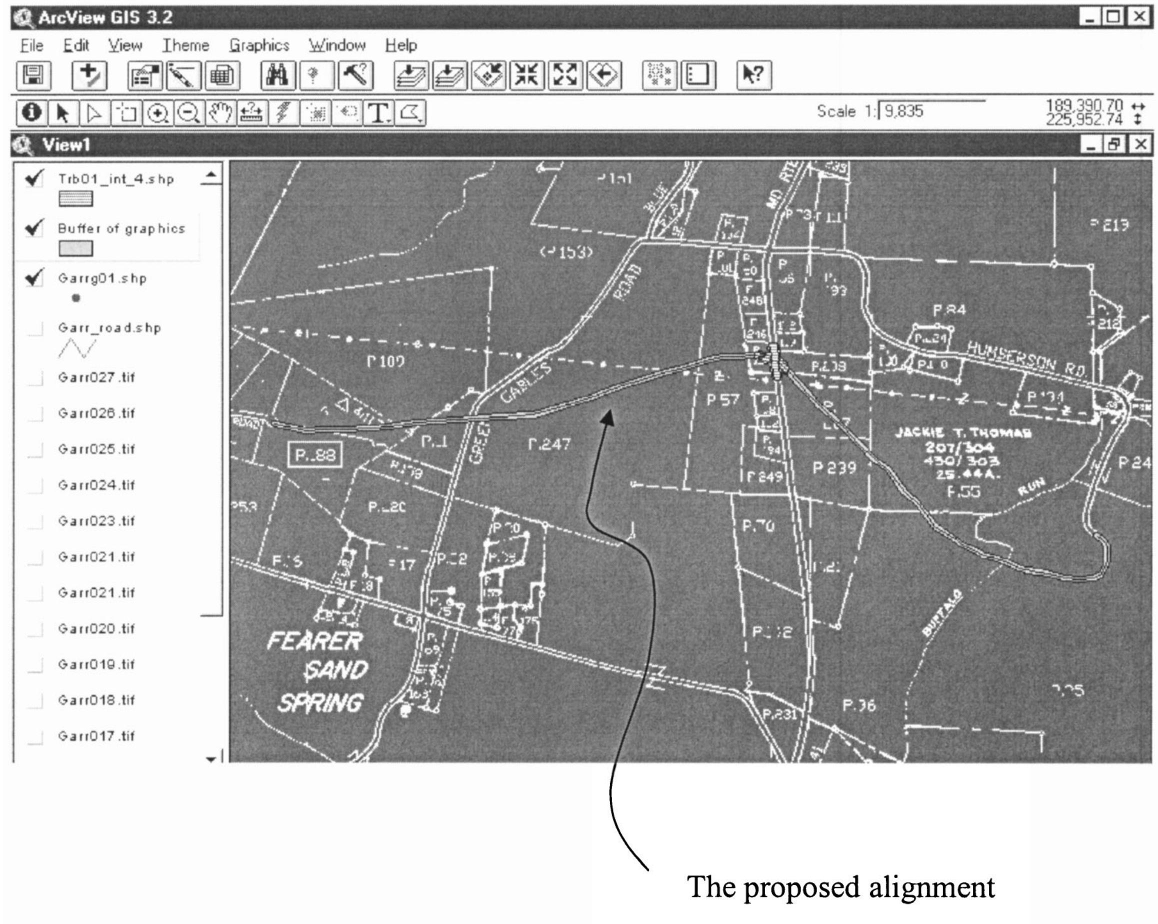

Fig. 11. Configuration of proposed alignment

additional boundaries can be found in previous sections. Ground adjoining curves already give us ways of finding right-of-way cost calculation boundaries.

Given newly found boundary information, a method is needed to estimate right-of-way costs by identifying the properties affected by the new intersection design. Jha (2000) developed such a method based on the state of Maryland's GIS databases and its method of estimating right-of-way cost. In it, the right-of-way costs are divided into three subitems: (1) temporary easement costs, which are defined as the partial taking of a property during the construction; (2) just compensation costs combining damage, site improvements, and cost of the fraction of property taken by the alignment; and (3) appraisal fees. In other words:

$$C_{RW}=\sum_{i=1}^{n} C_{RW_i}=\sum_{i=1}^{n} (C_{TE_i}+C_{JC_i}+C_{AF_i}) \tag{27}$$

where C_{TE_i} = cost of the fraction of property i taken for temporary easement; C_{JC_i} = just compensation paid for property i; C_{AF_i} = appraisal fees for property i; and

$$C_{JC_i}=C_{DP_i}+C_{DS_i}+C_{SI_i}+C_{F_i} \tag{28}$$

where C_{DP_i} = cost of damage to the value of property i; C_{DS_i} = cost of damage to structures on property i; C_{SI_i} = cost associated with site improvements of property i; and C_{F_i} = cost of the fraction of property i taken for the alignment or intersection.

Generally, the computation takes into account the residual values of properties and pieces of properties left when a given alignment or an intersection is implemented. These values are affected by the size, shape, and relative isolation of properties. The estimation procedures largely automate and computerize the existing appraisal process of the Maryland State Highway Administration's Office of Real Estate. Detailed right-of-way cost formulations can be found in Jha (2000) and in Jha and Schonfeld (2000). In this paper, an example using Jha's method is developed and discussed. Discussion of the user costs (i.e., cost of travel time, vehicle operation, and accident) considered in the example is skipped here; it can be found in Jong and Schonfeld (1999b).

Example Study

In order to illustrate the application of the proposed highway alignment optimization method, we consider the design of a new two-lane highway to connect two existing roads, Hollis-Beaulieu Road and Humberson Road in Garrett County, Maryland, to reduce congestion along Maryland Route 42. An optimized alignment is obtained and shown in Fig. 11. It is observed that the optimized alignment intersects Green Gables Road and Maryland Route 42.

The proposed intersection of the new alignment and Maryland Route 42 affects five properties, namely, 57, 208, 119, 136, and 207 (Fig. 12). In these, the land uses are either agricultural or

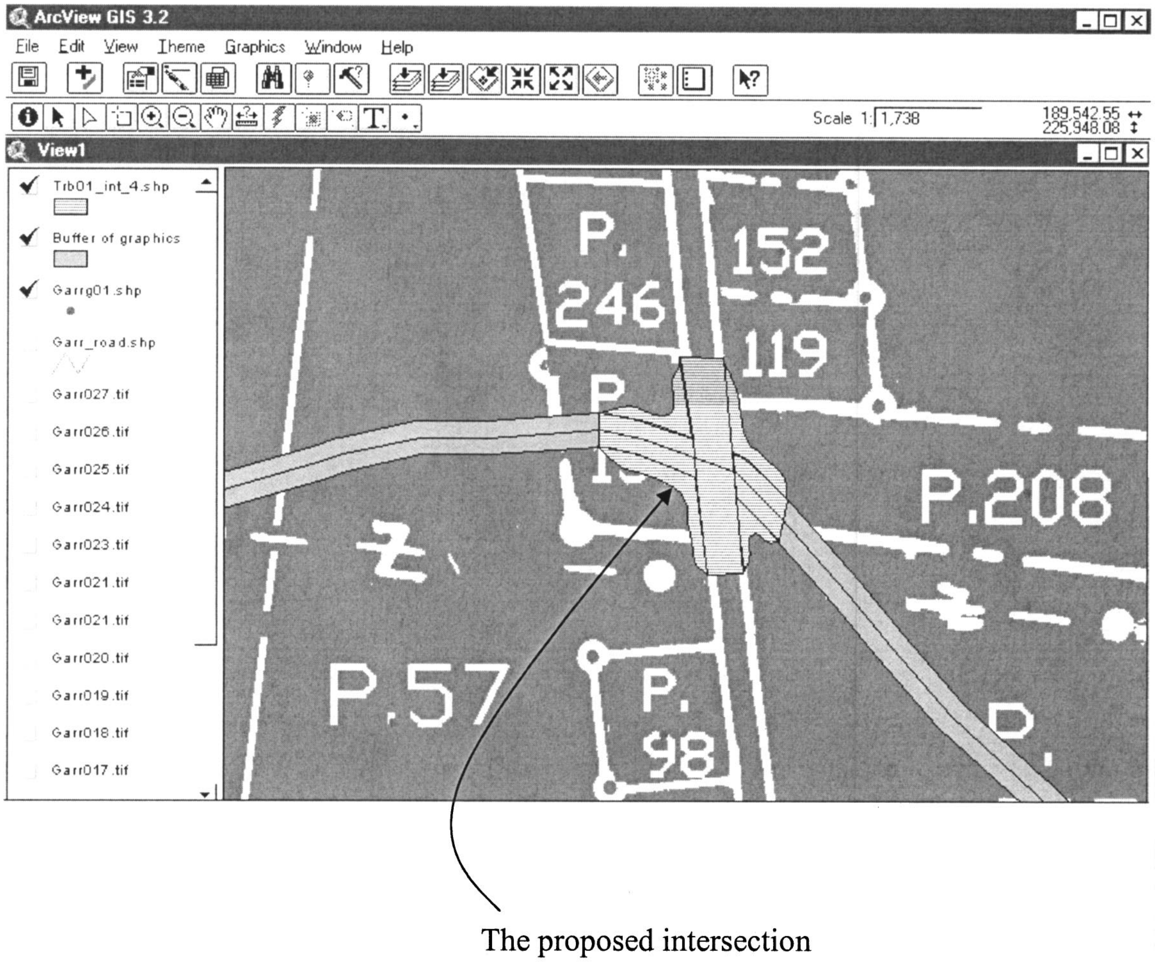

Fig. 12. Right-of-way occupied by new intersection

residential and their unit land values range from \$0.038/m^2 to \$3.089/m^2 (Table 2). Some of the properties have structures whose values must be considered in right-of-way cost computation. Costs due to temporary occupation of surrounding lands during construction (also known as temporary easement) should also be considered. Using the proposed method, the coordinates of points defining the boundary of the proposed intersection (including the additional flared area) are obtained and input to Jha's algorithm. The total right-of-way cost thus obtained is \$117,209.10. The flared areas increase the right-of-way costs due to the affected structures nearby. The cost of the additional right-of-way to be acquired due to the flared areas required for intersection construction, including damages to structures if any, accounted for 55% of the total right-of-way cost for the highway construction. The alignment length was found to be 1.76 km, and its total cost was \$2 million. Thus, the example suggests that each intersection might add \$66,596 or 6% to the alignment cost per km.

The intersection cost breakdown is shown in Table 2. The total intersection area (including the flared area) is 2,144.28 m^2. In this case, while the land for the right-of-way is relatively inexpensive, some structures are quite expensive. In urban areas, where land and structure values are fairly high, the right-of-way cost may be significantly higher.

Another artificial study area is designed to see what fraction of overall construction costs are attributable to the total intersection costs. Fig. 13 shows the quite complex topography of the artificial study area, which includes a two-lane rural highway from the center of north to southeast, three hills and a creek crossing from the northeast edge to the south. Darker cells represent higher el-

Table 2. Property and Cost Data for Example Study

Property number	Unit cost (dollars/m^2)	Land use	Structure cost (dollars)	Area (m^2)	Land cost (dollars)	Easement cost (dollars)	Total cost (dollars)
57	0.038	Agricultural	0.00	30.65	1.17	0.12	1.29
208	0.744	Agricultural	0.00	402.71	299.64	29.96	329.61
119	3.089	Residential	7,830.00	23.05	71.20	7.12	7,908.32
136	2.808	Residential	65,260.00	736.42	2,068.15	206.82	67,534.97
207	0.728	Residential	41,350.00	103.50	75.38	7.54	41,432.91

Note: Total cost = 117,207.10 dollars.

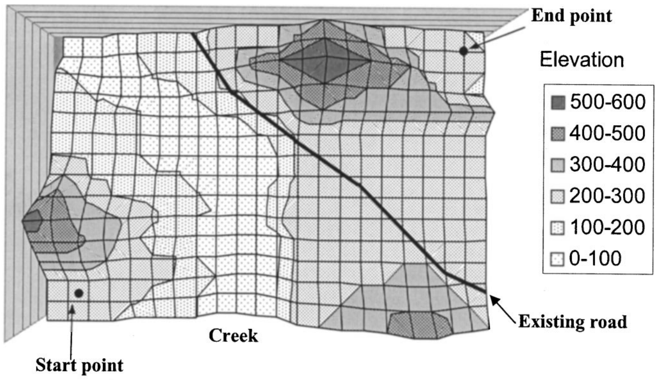

Fig. 13. Topography of artificial study area

Table 3. Cost Breakdown for Optimized Solution

Item	Optimized alignment [dollars (%)]	Intersection [dollars (%)]
Total cost	21,032,874 (100.00)	1,488,056 (100.00)
Intersection	1,488,056 (7.07)	—
Pavement	1,944,525 (9.25)	11,809 (0.79)
Right-of-way	4,583,726 (21.79)	279,953 (18.81)
Earthwork	1,722,632 (8.19)	34,625 (2.33)
Vehicle operation	957,023 (4.55)	27,415 (1.84)
User time value	5,685,093 (27.03)	509,549 (34.24)
Accident	195,153 (0.93)	624,705 (41.98)
Bridges	2,110,944 (10.04)	—
Tunnels	2,345,722 (11.15)	—
Fuel	—	27,415 (1.84)
Delay	—	509,549 (34.24)

evations and each cell has its own unit right-of-way costs. Our plan is to build a two-lane rural highway connecting two specified end points.

Fig. 14 shows the optimized solution, containing two bridges and two tunnels. The methods and algorithms for selecting and refining these structures can be found in Kim (2001). Fig. 14 has three parts: (1) horizontal alignment at the center; (2) vertical alignment at the top; and (3) objective (cost) function values on the right.

Table 3 shows cost breakdowns for the optimized solution and the intersection crossing with the existing road. Total alignment costs are found to be $21 million. Of those, intersection costs account for 7.07%. It is also found that approximately 22% of the total intersection costs are attributable to construction costs. Because only one intersection was encountered in this example, this cost was relatively low. As the density of the intersections increases, the increasing intersection cost may substantially affect the alignment selection. Therefore, it can be argued that intersection costs on highways and construction cost as a fraction of total intersection costs are substantial enough to affect the final alignment configurations.

Such evaluations are useful for a single intersection and would become especially useful when incorporated in automated highway alignment optimization models. It is notable that optimizing highway alignments without intersection modeling may produce unrealistic results.

Conclusions

A method has been introduced for estimating intersection construction costs such as pavement costs, earthwork costs, and right-of-way costs within a highway alignment optimization model. A numerical example shows how intersection construction costs are estimated. Ongoing work focuses on more refined modeling of

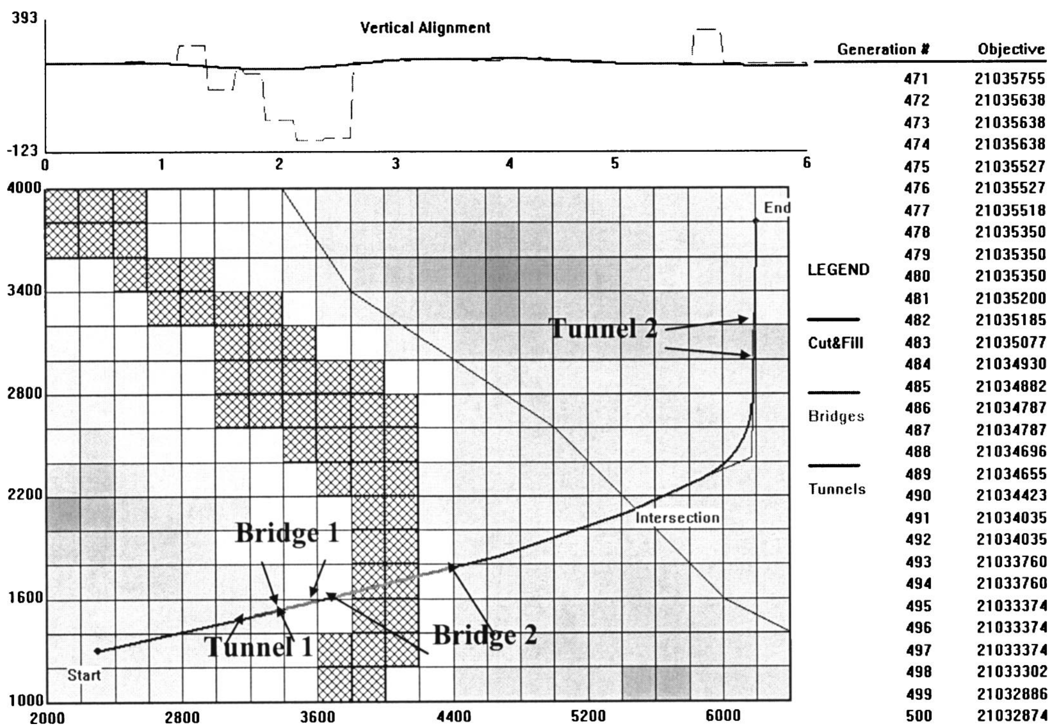

Fig. 14. Optimized solution for artificial study area

J. Transp. Eng. 2004.130:194-203.

earthwork and pavement costs. For earthwork costs, the formulation developed here only considers fill components of intersections, but cuts or transition components can be developed similarly.

The example studies demonstrate that the effects of the additional intersection costs can be quite substantial. Because acquisition of additional right-of-way due to flared areas may also impact nearby structures, the overall right-of-way cost may increase significantly. This increase may not be linear, because land and structure costs depend on many factors, including land-use type and locational characteristics. Inclusion of the proposed formulation in highway alignment optimization models (Jong 1998; Jha 2000) produces more reliable alignment evaluations based on more precise cost estimates.

Acknowledgments

The writers wish to thank the anonymous reviewers for their valuable comments. Further research in highway alignment optimization and highway network optimization with GIS and Artificial Intelligence is ongoing at the Korea Transport Institute, Morgan State University, and the University of Maryland, College Park, Md.

Notation

The following symbols are used in this paper:

A_f = flared areas of intersection;
A_i^b = base area of cell i;
A_P = total paved areas of intersections;
A_r = remaining areas of intersection;
C_{AF_i} = appraisal fees for property i;
C_{DP_i} = cost of damage to value of property i;
C_{DS_i} = cost of damage to structures for property i;
C_E = total earthwork costs;
C_{F_i} = cost of fraction of property i taken for alignment or intersection;
C_i = coordinate of point of curvature at ith circular curve;
C_{JC_i} = just compensation paid for property i;
C_P = total pavement costs;
C_{RW} = total right-of-way costs;
C_{RW_i} = total right-of-way costs for property i;
C_{SI_i} = cost associated with site improvement of property i;
C_{TE_i} = cost of fraction of property i taken for temporary easement;
E_V = total earth fill volumes;
$g_{(.)}$ = ground adjoining points;
$I(x,y)$ = coordinate of intersecting point;
K_F = unit earth filling cost;
K_P = unit pavement cost;
$K(x_k,y_k)$ = coordinate of starting point of intersection's flared part, obtained from design standards;
L_a = set of points defined by position vector $\mathbf{P}(u)$;
$L_T(i)$ = tangent length from C_i to P_i (P_i to T_i);
M_i = middle point of line section between C_i and T_i;
n_T = maximum search generations (integer);
$O(x_o,y_o)$ = center point associated with intersection flared part, given by design standards;
$\mathbf{P}(u)$ = position vector;
$\mathbf{P}'(u)$ = tangent vector to L_a at $\mathbf{P}(u)$;
$\mathbf{P}(0)$ = starting point of alignment;
$\mathbf{P}(1)$ = ending point of alignment;
P_i = ith point of intersection;
R_i = radius of ith circular curve;
r = turning radius of flares part by design standards;
SP = ending point of alignment, $\mathbf{P}(0)$;
T_i = coordinate of point of tangency at ith tangent section;
u = parameter for normalizing;
v = unit distance for finding ground adjoining points;
W = road width;
$Z_{b_i}^{\mathrm{ave}}$ = average base elevation of cell i;
$Z_{g_i}^{\mathrm{ave}}$ = average elevation of cell i;
Δ_i = angle between C_i and T_i;
Δ_θ = distance, $\|\overline{JN_m}\| \sin\theta_0$;
δ_i = center of ith circular curve; and
θ_0 = user defined angle between $\overline{OK}$ and $\overline{OI}$.

References

American Association of State Highway and Transportation Officials (AASHTO). (2001). *A policy on geometric design of highways and streets*, Washington, D.C.

Easa, S. M. (1988). "Selection of roadway grades that minimize earthwork cost using linear programming." *Transp. Res., Part A*, 22(2), 121–136.

Fwa, T. F. (1989). "Highway vertical alignment analysis by dynamic programming." *Transportation Research Record 1239*, Transportation Research Board, Washington, D.C., 1–9.

Goh, C. J., Chew, E. P., and Fwa, T. F. (1988). "Discrete and continuous models for computation of optimal vertical highway alignment." *Transp. Res. Part B: Methodol.*, 22(6), 399–409.

Hayman, R. W. (1970). "Optimization of vertical alignment for highways through mathematical programming." *Highway Research Record*, 306, Highway Research Board, Washington, D.C., 1–9.

Hickerson, T. F. (1964). *Route location and design*, 5th Ed., McGraw-Hill, New York.

Jha, M. K. (2000). "A geographic information systems-based model for highway design optimization." PhD thesis, Univ. of Maryland, College Park, Md.

Jha, M. K. (2001). "Using a GIS for automated decision-making in highway cost analysis." *Transportation Research Record 1768*, Transportation Research Board, Washington, D.C., 260–267.

Jha, M. K. (2003). "Criteria-based decision support system for selecting highway alignments." *J. Transp. Eng.*, 129(1), 33–41.

Jha, M. K., and Schonfeld, P. (2000). "Geographic information system-based analysis of right-of-way cost for highway optimization." *Transportation Research Record 1719*, Transportation Research Board, Washington, D.C., 241–249.

Jong, J.-C. (1998). "Optimizing highway alignments with genetic algorithms." PhD thesis, Univ. of Maryland, College Park, Md.

Jong, J.-C., Jha, M. K., and Schonfeld, P. (2000). "Preliminary highway design with genetic algorithms and geographic information systems." *Comput. Aided Civ. Infrastruct. Eng.*, 15(4), 261–271.

Jong, J.-C., and Schonfeld, P. (1999a). "Optimizing vertical alignments with genetic algorithms." *Proc., 78th Annual TRB Meeting*, Transportation Research Board, Washington, D.C.

Jong, J.-C., and Schonfeld, P. (1999b). "Cost functions for optimizing highway alignments." *Transportation Research Record 1659*, Transportation Research Board, Washington, D.C., 58–67.

Jong, J.-C., and Schonfeld, P. (2003). "An evolutionary model for optimizing three-dimensional highway alignments." *Transp. Res., Part B: Methodol.*, 37(2), 107–128.

Kim, E. (2001). ''Modeling intersections and other structures in highway alignment optimization.'' PhD thesis, Univ. of Maryland, College Park, Md.

Lovell, D. J. (1999). ''Automated calculation of sight distance from horizontal geometry.'' *J. Transp. Eng.*, 125(4), 297–304.

Mortenson, M. E. (1997). *Geometric modeling*, 2nd Ed., Wiley, New York.

Murchland, J. D. (1973). ''Methods of vertical profile optimisation for an improvement to an existing road.'' *Proc., Seminar on Cost Models and Optimisation in Highways*, PTRC, London.

Pearman, A. D. (1973). ''Investigation of the objective function in problems of optimising highway vertical alignment.'' *Proc., Seminar on Cost Models and Optimisation in Highways*, PTRC, London.

Puy Huarte, J. (1973). ''OPYGAR: Optimisation and automatic design of highway profiles.'' *Proc., Seminar on Cost Models and Optimisation in Highways*, PTRC, London.

ReVelle, C. S., Whitlatch, E. E., and Wright, J. R. (1997). *Civil and environmental systems engineering*, Prentice-Hall, Englewood Cliffs, N.J.

Swokowski, E. W. (1979). *Calculus with analytic geometry*, 2nd Ed., Prindle, Weber, and Schmidt, Boston.

Wright, P. H. (1996). *Highway engineering*, 6th Ed., Wiley, New York.

J. Transp. Eng. 2004.130:194-203.