■ 論 文 ■

Alignment Optimization Considering Characteristics of Intersections

교차로의 특성을 고려한 도로선형최적화

KIM, Eungcheol
(Research Professor, Advanced Highway Research Center, Hanyang University)

SON, Bongsoo
(Research Professor, Advanced Highway Research Center, Hanyang University)

CHANG, Myungsoon
(Professor, Department of Transportation Engineering, Hanyang University)

목 차

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요 약

본 연구에서는 교차로의 비용 및 특성을 고려한 도로선형최적화 모형을 유전자 알고리즘(Genetic Algorithms)을 이용하여 개발하였다. 기존의 도로선형최적화 모형은 교차로 특성을 고려하지 못해서 실제 적용에 심대한 문제점을 내재하고 있다. 본 논문에서는 특정 도로선형에 교차로 건설의 필요가 있을 경우, 민감(Sensitive)하고 지배적인(Dominating) 교차로 비용 항목들 즉, 토공비용, 보상비, 포장비, 사고비용, 지체 및 연료소모비용 등의 산정이 시도되었다. 또한, 비교적 우수한 도로선형 대안을 유전자 알고리즘을 이용한 탐색과정 중에서 비효율적으로 강제 퇴화시키는 단점 보완을 위한 교차로 국소 최적화 방법(Local Optimization of Intersections)이 개발되어 기존 모형을 보완하였다. 공간상의 도로선형은 매개변수적 묘사(Parametric Representation)를 통하여 구현하였으며 벡터운영(Vector Manipulation)을 통해 교차로비용 산정의 근간인 교차점과 다른 중요점들의 좌표를 찾을 수 있었다. 개발된 교차로 비용산정 모형이 보다 정밀하게 교차로 비용을 산정함이 증명되었으며 궁극적으로는 기존의 최적화 모형의 단점을 보완할 수 있음이 제시되었다. 또한, 새로이 제시된 교차로 국소 최적화 방법이 최적대안 탐색과정의 유연성을 증대하였으며, 결과적으로 효율적인 교차로의 유지에 기여함을 알 수 있었다. 제시된 교차로 국소 최적화 방법은 추후 단일노선이 아닌 도로망 최적화시의 기초를 제시함은 주목할 만 하다. 두개의 예제에서 도출된 최적노선 및 교차로 비용 등의 검토 결과, 도로상의 교차로 건설 비용은 도로선형 최적화에 큰 영향을 미치는 실질적이며 민감한 비용 항목임이 검증되었으며 이는 도로선형최적화 모형이 교차로 비용을 반드시 검토 및 평가할 수 있어야 함을 반증한다.

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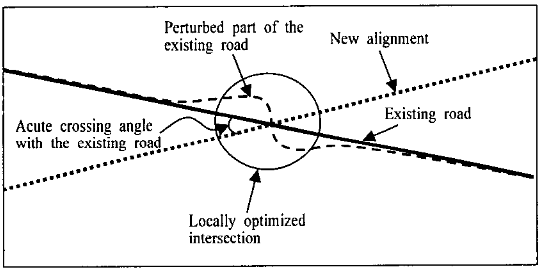
Ⅰ. Introduction

It has been widely accepted that intersections are important to the performance and costs of highway systems. Therefore, when developing highway alignment optimization processes, intersection cost functions should be included in them.

This study develops cost functions for highway intersections which are usable in highway alignment optimization algorithms. These functions can alleviate a serious weakness in previous alignment optimization algorithms, which neglect the characteristics and costs of intersections. Besides, it is conceivable that an automated design procedure might produce is the intersection of highways at an overly acute angle. However, the new alignment shown in ⟨Figure 1⟩ might be superior to other alternatives and discarding it simply because of the intersection angle might be inefficient. It might be desirable to pursue a method that could perturb the local geometry to produce a better intersection, yet retain the broader geometry of the good alignment. ⟨Figure 1⟩ shows an example of how a better solution might be produced. In this paper, we describe a method to locally optimize intersection geometry in the larger context of alignment optimization.



⟨Figure 1⟩ A Locally Optimized Intersection for an Intersection with an Acute Angle

Ⅱ. Literature Review

Many highway alignment optimization models have been developed using mathematical models and computer programs(OECD, 1973; Shaw and Howard, 1982; Fwa, 1989). There have been three types of models for optimizing highway alignments (Jong, 1998; Jha, 2000): (1) horizontal alignment optimization models, (2) vertical alignment optimization models and (3) models for simultaneously optimizing horizontal and vertical alignments. The search methods used in above models can further be classified into seven methods: (1) genetic algorithms, (2) calculus of variations (3) network optimization, (4) dynamic programming, (5) enumeration, (6) linear programming and (7) numerical search. None of the previous studies found had incorporated intersection cost functions in highway alignment optimization and local optimization of intersections. This deficiency clearly limits the reliability of the existing models. The scope of this study is limited to intersections where two lane rural highways cross but extensions to other types of roads can be accomplished similarly.

In Korea, studies on alignment optimization considering various costs are very rare. Specifically, integrating intersection characteristics into alignment optimization might not be easily found. Recently, an effort for developing a model to evaluate highway geometric design consistency using speed profiles on vertical and horizontal alignments has been performed to have safer highways(Choi, 1998).

Intersection cost components can be divided into four groups(AASHTO, 2001): (1) construction costs, (2) operational costs, (3) environmental costs and (4) drainage costs. This paper presents a method for formulating intersection cost functions including construction components(earthwork, right-of-way, pavement costs) and operating costs(accident, delay and fuel consumption costs).

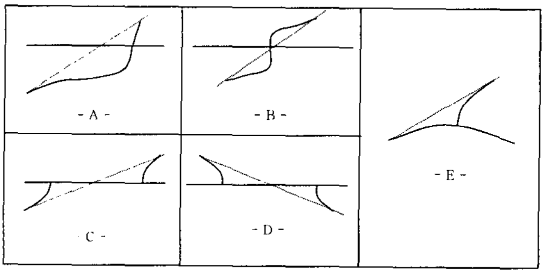
A parametric representation is useful to describe an alignment in space(Mortenson, 1997; Swokowski, 1979) and was successfully adopted in other studies (Kim and Schonfeld, 2001; Lovell, 1999). Boldface capital letters will be used to denote vectors in space. Let $\mathbf{P}(u) = [x(u), y(u), z(u)]^T$ be a position vector along the alignment L, where

$$u = \frac{\int_0^u \|\mathbf{P}'(t)\| dt}{\int_0^1 \|\mathbf{P}'(t)\| dt} \text{ and } \|\mathbf{P}'(u)\| = \sqrt{(x'(u))^2 + (y'(u))^2 + (z'(u))^2}.$$

Basically, $\mathbf{P}$ is parameterized by u, which represents the fraction of arc length traversed to that point. If L is an alignment connecting $\mathbf{S} = [x_S, y_S, z_S]^T$ and $\mathbf{E} = [x_E, y_E, z_E]^T$, then the position vector $\mathbf{P}(u)$ must satisfy $\mathbf{P}(0) = \mathbf{S}$, and $\mathbf{P}(1) = \mathbf{E}$. $\mathbf{P}(u)$ must also be continuous and continuously differentiable in the interval $u \in [0,1]$.

III. Methods for Local Intersection Optimization

Intersections can vary greatly based on the number of legs, degree of channelization, control types and locations. ⟨Figure 2⟩ shows realignment variations at intersections where overly acute crossings would otherwise occur. Although there is no fixed crossing angle constraint, AASHTO(2001) suggests that it should be in the range of approximately 60 to 120 degrees. At the same time, however AASHTO (2001) also recommends that "intersecting roads should generally meet at or nearly at right angles." In this paper, we focus on cases such as A or B in ⟨Figure 2⟩, and assume that right-angle crossings can be constructed.



⟨Figure 2⟩ Realignment Variations at Intersections (AASHTO, 2001)

1. Mathematical Expressions for a Perturbed intersection

It is assumed that the local optimization process described herein resides within a larger alignment optimization framework. For local optimization to take place, it must be the case that an alignment alternative has been generated that crosses an existing road at an unacceptable angle, θ, as described earlier. The existing roadway presumably is described in a database, and the most common form would be piecewise linear, with points $\{\mathbf{E}_i\}$ representing the segment endpoints. The proposed new alignment can be described similarly. We assume that station points, $\{\mathbf{D}_i\}$ are defined along this new alignment at regular intervals specified by the user.

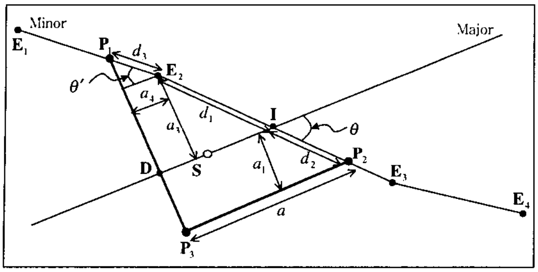
The collection of station points in the vicinity of the proposed intersection constitutes the domain of our decision variable, which is the location of the newly aligned intersection. The point, $\mathbf{I}$, is the crossing point(intersection) of the existing and new roadways. A way of determining $\mathbf{I}$ will be discussed later. On either side of the proposed intersection, $\mathbf{I}$, we consider at least one of the existing roadway nodes, $\{\mathbf{E}_i\}$. These need not fall within our vicinity. However, if several of them happen to do so, then they all must be considered. This is described in an example later in the paper.

The decision variable $\mathbf{D}$ represents the potential location of the perturbed intersection. If discrete optimization is being used, then the domain of $\mathbf{D}$ could be the set of station points $\{\mathbf{D}_i\}$ described earlier; else, it must be constrained to fall along the alignment that they describe.

⟨Figure 3⟩ shows a general alternative for local intersection optimization. Since $\mathbf{P}_1$ is between $\mathbf{E}_1$ and $\mathbf{E}_2$, we need to know θ'. It can be obtained as follows:

$$\theta' = \cos^{-1}\left(\frac{(\mathbf{E}_2 - \mathbf{E}_1)\cdot(\mathbf{I} - \mathbf{D})}{\|\mathbf{E}_2 - \mathbf{E}_1\|\|\mathbf{I} - \mathbf{D}\|}\right) \quad (1)$$

Then, using $a_3 = d_1 \sin\theta$, $a_4 = \|\mathbf{I} - \mathbf{D}\| - \sqrt{(d_1)^2 - (a_3)^2}$,



〈Figure 3〉 Interesting Points for a General Alternative

$d_3 = \dfrac{a_4}{\cos\theta'}$ and $d_2 = \dfrac{a_1}{\cos(90-\theta)}$, all the remaining coordinates can be obtained as follows :

$$\mathbf{P}_1 = \mathbf{E}_2 + \left(\frac{\mathbf{E}_2 - \mathbf{E}_1}{\|\mathbf{E}_2 - \mathbf{E}_1\|}\right)(-d_3),$$

$$\mathbf{P}_2 = \mathbf{I} + \left(\frac{\mathbf{I} - \mathbf{E}_2}{\|\mathbf{I} - \mathbf{E}_2\|}\right)(d_2), \text{ and}$$

$$\mathbf{P}_3 = \mathbf{D} + \left(\frac{\mathbf{D} - \mathbf{P}_1}{\|\mathbf{D} - \mathbf{P}_1\|}\right)(a_1) \quad (2)$$

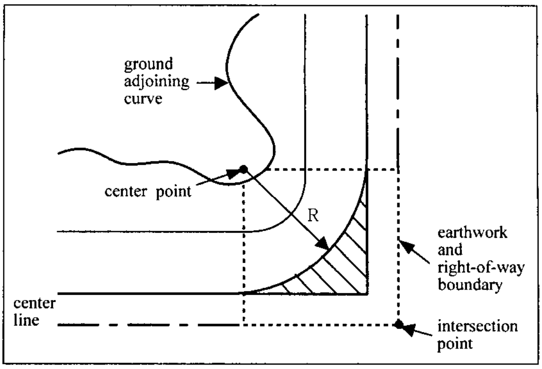
Based on these coordinates, any point on the newly evaluated intersection legs can be obtained. This helps formulate each cost item by easily identifying where the legs and the crossing point (intersection) are located within a study area.

Ⅳ. Developing Cost Functions for Intersections

To estimate various intersection cost items, the boundaries of intersections should be reasonably found. Carefully drawn boundaries also insure that costs for approach sections and intersections are not double-counted.

1. Earthwork and right-of-way boundaries

To describe how earthwork boundaries, a typical fill intersection is introduced, as shown in 〈Figure 4〉.



〈Figure 4〉 A Simplified Quadrant of a Typical Fill Intersection

Clearly, boundaries depend on the location of the center point of flared parts.

2. Earthwork cost estimation

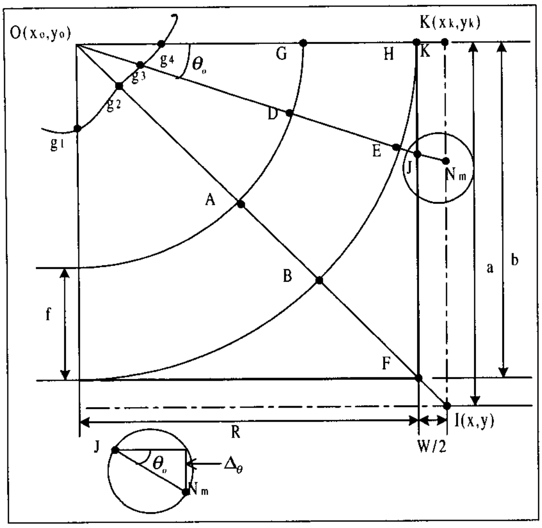
In estimating earthwork volumes and costs, the basic idea is to find the coordinates of the points in 〈Figure 5〉. An example shows how the coordinates of important points in 〈Figure 5〉 (A, B, D, E, F, G, H, I, J, K, N_m, g_1, g_2, g_3 and g_4) are found. If it is possible to find the coordinates of all these points, subdividing the area into arbitrarily many slices can be done easily. Among many points in 〈Figure 5〉, it should be mentioned that the coordinates of $I(x, y)$ are already found from the previous section, and the coordinates of $O(x_o, y_o)$ and $K(x_k, y_k)$ are given by design standards.

Finding 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 for the flared area, can be done simply using vector operations:

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

where, $\| \ \|$: norm(or length) of a vector (3)

$$\mathbf{B} = \mathbf{O} + R\frac{\mathbf{I} - \mathbf{O}}{\|\mathbf{I} - \mathbf{O}\|} \quad (4)$$



〈Figure 5〉 Important Points for Determining Coordinates

$$\mathbf{F}=\mathbf{O}+\left[\|\mathbf{I}-\mathbf{O}\|-\frac{W}{\sqrt{2}}\right]\frac{(\mathbf{I}-\mathbf{O})}{\|\mathbf{I}-\mathbf{O}\|} \tag{5}$$

For more general cases such as points D, E, J and N_m, introducing a small value(i.e., $\Delta y=\frac{b}{n}$) is needed, where n is a user-selected value. Next, let m be any multiple number of Δy ($\Delta y \le m \le b$) 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 :

$$\mathbf{D}=\mathbf{O}+(R-f)\frac{\mathbf{N_m}-\mathbf{O}}{\|\mathbf{N_m}-\mathbf{O}\|} \tag{6}$$

$$\mathbf{E}=\mathbf{O}+R\frac{\mathbf{N_m}-\mathbf{O}}{\|\mathbf{N_m}-\mathbf{O}\|} \tag{7}$$

$$\mathbf{N_m}=\mathbf{I}+m\frac{\mathbf{K}-\mathbf{I}}{\|\mathbf{K}-\mathbf{I}\|} \tag{8}$$

Now, the only remaining point needed is J. Finding J's coordinates requires finding the angle θ_o between two vectors, $\mathbf{N_m}-\mathbf{O}$ and $\mathbf{K}-\mathbf{O}$.

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

where, $\cdot$: inner (dot) product (9)

Therefore,

$$\Delta_\theta=\frac{W}{2}\tan\theta_o=\frac{W}{2}\tan\left[\cos^{-1}\frac{(\mathbf{N_m}-\mathbf{O})\cdot(\mathbf{K}-\mathbf{O})}{\|\mathbf{N_m}-\mathbf{O}\|\|\mathbf{K}-\mathbf{O}\|}\right] \tag{10}$$

and the size of vector $\mathbf{N_m}-\mathbf{J}$ is :

$$\|\mathbf{N_m}-\mathbf{J}\|=\sqrt{\frac{W^2}{4}+\left(\frac{W}{2}\tan\theta_o\right)^2} \tag{11}$$

Finally, the coordinates of point J are :

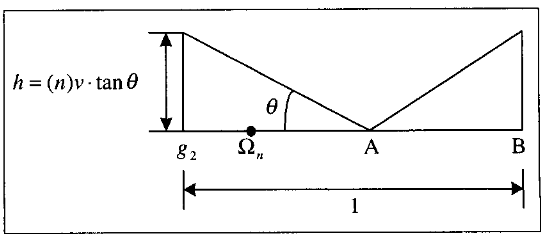
$$\mathbf{J}=\mathbf{O}+\left[\|\mathbf{N_m}-\mathbf{O}\|-\sqrt{\frac{W^2}{4}+\left(\frac{W}{2}\tan\theta_o\right)^2}\right]\frac{(\mathbf{N_m}-\mathbf{O})}{\|\mathbf{N_m}-\mathbf{O}\|} \tag{12}$$

The next important task is to find the coordinates of adjoining ground points, g_i. As an example, 〈Figure 6〉, which shows the vertical profile between g_2 and B, illustrates how the coordinates of g_2 can be found.

Suppose l is cut into several segments using a small unit distance, v. Let $\mathbf{\Omega}_n$'s be the consecutive coordinates specified by increasing v, such as $(1)v$, $(2)v$,......,$(n)v$. Then those coordinates can be found using information already obtained above:

$$\mathbf{\Omega}_n=\begin{bmatrix}x_{\Omega_n}\\ y_{\Omega_n}\end{bmatrix}=\mathbf{A}+(n(v))\frac{\mathbf{O}-\mathbf{A}}{\|\mathbf{O}-\mathbf{A}\|} \tag{13}$$

This process continues until the ground elevation of $\mathbf{\Omega}_n$, $(z^g_{\Omega_n})$, is no less than the height h, i.e.,



〈Figure 6〉 Vertical Profile between g_2 and B

$$Z^{g}_{\Omega_n} \geq h = (n)v\tan\theta \quad (14)$$

g_2 can be found using Equations(13) and (14) iteratively.

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 ⟨Figure 7⟩, that shape needs to be approximated into a simplified form, as shown in the right part of ⟨Figure 7⟩, for easy subdivision into triangles. Based on the simplified shape, two triangles, ADE and ABE, can be created(alternatively BAD and BDE would be possible). Then, the base areas (A_b, m^2) are obtained as follows :

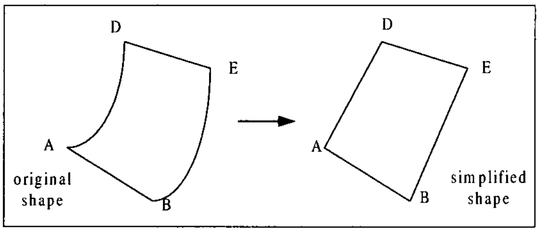
$$A_b = \left(\frac{1}{2}\right)\left[\|(\mathbf{B}-\mathbf{A})\times(\mathbf{E}-\mathbf{A})\| + \|(\mathbf{E}-\mathbf{A})\times(\mathbf{D}-\mathbf{A})\|\right]$$

where, $\times$: vector product (15)

To find the earthwork volumes, two elevations are needed : (1) base elevation and (2) ground elevation. Methods for effectively finding corresponding ground elevations have been developed by Kim and Schonfeld (2001).

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

$$E_V = \sum_{i=1}^{T} A_i^b \left(Z_{b_i}^{ave} - Z_{g_i}^{ave}\right) \quad (16)$$



⟨Figure 7⟩ Simplified Shape of the Area ABED

where,

A_i^b : base area of cell i

$Z_{g_i}^{ave}$: average ground elevation of cell i

$Z_{b_i}^{ave}$: average base elevation of cell i

Therefore, total earthwork costs (C_E) is :

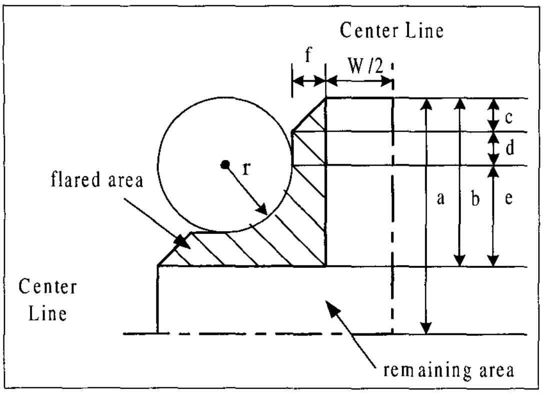
$C_E = K_C E_V$, where K_C : filling cost per cubic meter (\$/m^3) (17)

3. Right-of-way cost estimation

By adding intersections to alignments, it is expected that the alignment right-of-way costs may increase. The coordinates of 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 Maryland State'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. Generally, 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. A detailed right-of-way cost formulation can be found in Jha(2000).

4. Pavement cost estimation

Estimating pavement costs is relatively simple.



〈Figure 8〉 Flared and Remaining Areas of a Typical Four-Legged Intersection

AASHTO(2001) design standards supply geometric specifications of additional flared areas providing paths for turning movements as shown in 〈Figure 8〉.

Hence, the total pavement area (A_p) is :

$$A_p = 4\left(\frac{W^2}{4} + bW\right) + 4\left[f(c+2d) + e^2 - \frac{\pi r^2}{4}\right] = W^2 + 4bW + 4f(c+2d) + 4e^2 - \pi r^2 \qquad (18)$$

Then, total pavement costs (C_P) can be estimated using a unit cost, K_P.

5. Accident cost estimation

It is conceivable to occur more accidents when intersections are added to an alignment. Hence, additional accident costs attributable to new intersections should be estimated. This study is not intended to develop accident models but will adopt the most suitable models from other studies.

Many different models have been developed to predict frequencies of accidents based on different intersection configurations(Lau and May, 1988; Vogt and Bared, 1998; Sayed and Rodriguez; 1999; Khan et al., 1999).

Based on thorough reviews of the safety literature, this study employs two different methods for two representative intersection types on two-lane highways. Lau and May's model(1988) is used for signalized intersections while Vogt and Bared's model(1998) is adopted for two-way stop controlled (TWSC, on minor road) unsignalized intersections. All-way stop controlled(AWSC) types are excluded since those are less likely to be employed for two-way rural highways.

6. Intersection delay cost estimation

Also, Intersections inherently generate additional delays. Webster's method to estimate the delays of isolated signalized intersections is adopted since our interest is in rural intersections where oversaturated conditions are rare. (TRANSYT and HCM methods can deal with oversaturated conditions while the Webster's method cannot.) and HCM method is used for an unsignalized intersection. Intersection delay costs are finally calculated by introducing unit delay costs, U_s.

Estimating delay costs of an intersection requires determining the signal type for that intersection. This study develops a method to determine in advance the signal type in a way that sufficiently supports intersection cost estimation.

Three references are available to determine whether signal installation at intersections is warranted : the 2000 Manual on Uniform Traffic Devices(FHWA), the 1988 Manual on Uniform Traffic Devices(FHWA), and Manual of Traffic Signal Design(MTSD) by Institute of Transportation Engineers(ITE, 1991).

The 1988 MUTCD lists 11 warrants: (1) minimum vehicle volume, (2) interruption of continuous traffic, (3) minimum pedestrian volume, (4) school crossings, (5) progressive movement, (6) accident experience, (7) systems, (8) combination of warrants, (9) four hour volumes, (10) peak hour delay and (11) peak hour volume.

The updated 2000 MUTCD reduced the 11 lists to 8 warrants : (1) eight-hour vehicular volume, (2) four-hour vehicular volume, (3) peak hour, (4) pedestrian volume, (5) school crossings, (6) 〈Table 1〉 Minimum Vehicular Volumes for Warrant 1

Number of lanes for moving traffic on each approach		Vehicles per hour on major street(total of both approaches)	Vehicles per hour on higher-volume minor-street approach (one direction only)
Major street	Minor street		
1	1	500	150
2 or more	1	600	150
2 or more	2 or more	600	200
1	2 or more	500	200

coordinated signal system, (7) accident experience and (8) roadway network.

The MTSD(ITE, 1991) suggests verifying the requirements of the warrants in the following order based on the 1988 MUTCD warrants(McDonald Jr., 2001) :

(1) Warrants 1, 2, 8, 9 and 11 if the available volume data is available;(2) Warrant 6 after collecting accident data;
(3) Warrant 3 after collecting pedestrian data;
(4) Warrant 8 (combination warrant);
(5) Warrant 4 after collecting specialized school data; and then
(6) Warrants 5 and 7(controlling arterial and system flow).

In this study, warrant 1 of the MUTCD 1988 is simply employed. 〈Table 1〉 shows how warrant 1 can be applied.

If some signalization is warranted for an intersection, the signal cycle should be optimized in order to estimate delay costs later. Webster's equation (McShane et al., 1990) is used to optimize the cycle.

7. Vehicle fuel cost estimation

Additional fuel costs caused by new intersections were not considered within the context of highway alignment optimization. There are four types of fuel cost models : (1) Instantaneous models(Akcelik et al., 1983; Bowyer, 1986; Biggs, 1988), (2) Delay type models(FHWA, 1984; Bauer 1975; Courage and Parapar, 1975), (3) Speed type models(Evans et al., 1976; Herman and Ardekani, 1985) and (4) Analytical Models(Liao and Machemehl, 1998).

In this study, speed-type and delay-type models are used to build up a new model incorporating Jong's approach. Jong(1998) basically developed a fuel consumption model for a basic highway segment using multiple regression :

$$F = \alpha_0 + \alpha_1 \overline{G} + \alpha_2 \overline{V} + \alpha_3 \overline{V}^2 \tag{19}$$

where,

F : fuel consumption(gallons/1000 miles)

$\overline{G}$: grade of road section(%)

$\overline{V}$: vehicle average running speed(mph)

Then, he multiplied by total traveled miles when calculating actual fuel consumption costs. Equation(19) addresses traffic and geometric characteristics but not intersection effects such as delays and stops.

FHWA(1984) introduced a delay type model when developing TRANSYT-7F traffic macroscopic simulation model. This model predicts fuel consumption based on the MOE's produced by the simulation. Those MOEs are : (1) vehicle mile traveled, (2) total delays and total stops.

$$F_{TRANSYT} = \beta_1 TT + \beta_2 D + \beta_3 S \tag{20}$$

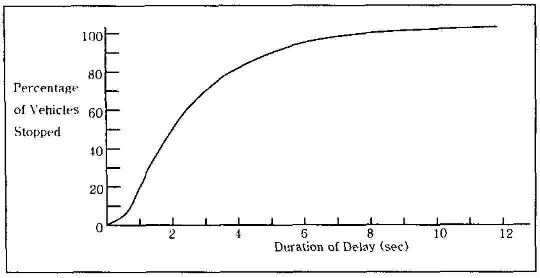
where,

$F_{TRANSYT}$: fuel consumption in gallons per hour

TT : total travel in vehicle-miles per hour

D : total delay in vehicle-hours per hour

S : total stops per hour



〈Figure 9〉 Reduction of Stops as a Function of Length of Delay

FHWA(1984) further developed a figure providing reduction of stops as a function of delays.

Using 〈Figure 9〉 and Equations(19) and (20), the associated number of stops can be obtained. Then, the remaining problem is to estimate β_2 and β_3 in Equation(20). Fortunately, there are average fuel consumption rates reported by Liao and Machemehl(1998). They estimated fuel consumption rates for each case from vehicle speed and acceleration/deceleration profile models and corresponding EPA fuel consumption data. 〈Table 2〉 shows only four interesting values from that study.

8. Genetic algorithms for optimal search

As discussed in "Literature Review", seven search methods are used for the three types of alignment optimization models. Six methods(those other than genetic algorithms) have some critical defects for the highway alignment optimization problem whose cost functions are non-differentiable, noisy and implicit(e.g., user costs cannot be calculated until alignments are finally determined). Therefore, this study adopts genetic algorithms for the optimal search process. 〈Table 3〉 summarizes these defects of the existing optimization methods.

Goldberg(1989) states four important distinctions of GAs over other search methods :

〈Table 2〉 Average Fuel Consumption Rate from Speed V_i to Speed V_j

Definition	Fuel consumption rate	
	Grams/sec	Gallons (10-5)/sec
Idle fuel consumption rate	0.3310	13.00
Change speed from desired speed to stop	0.6000	23.56

〈Table 3〉 Defects of the Existing Highway Alignment Optimization MethodsMethods

Methods	Defects
Calculus of variations	· Requires differentiable objective functions · Not suitable for discontinuous factors · Tendency to get trapped in local optima
Network optimization	· Outputs are not smooth · Not for continuous search space
Dynamic programming	· Outputs are not smooth · Not suitable for continuous search space · Not applicable for implicit functions · Requires independencies among subproblems
Enumeration	· Not suitable for continuous search space · Inefficient
Linear programming	· Not suitable for non-linear cost functions · Only covering limited number of points for gradient and curvature constraints
Numerical research	· Tendency to get trapped in local optima · Complex modeling · Difficulty in handling discontinuous cost items

Sources : Adopted from Jong(1998) and partly revised.

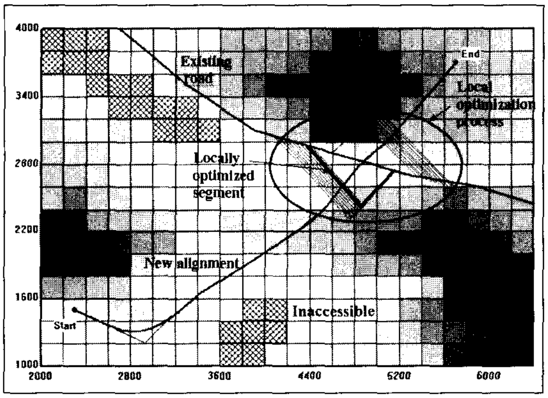
(1) GAs work with a coding of the parameter set, not the parameters themselves.
(2) GAs search from a population rather than a single point.
(3) GAs use payoff(objective function) information, not derivatives or other auxiliary knowledge.
(4) GAs use probabilistic transition rules, not deterministic rules.

There is no rigorous proof to show that GAs will converge the global optimum. However, the schema theorem and the building block hypothesis introduced by Michalewicz(1996) and Goldberg(1989) explain the power of GAs(Details about terms and vocabularies may be found in any GAs textbooks and are not covered in this study.). Genetic algorithms are a class of general-purpose search methods combining elements of directed and stochastic search which can achieve a remarkable balance between exploration and exploitation of the search space (Gen and Cheng, 1997; Michalewicz, 1996)In spite of the advantages above, it should be mentioned that GAs do not always find an absolute global optimum and are not the best search algorithm for all problem types. Rather, GAs can be considered very effective approaches for finding near optimal solutions relatively quickly. Indeed, the solution approach should be problem-oriented rather than tool-oriented. This study adopts GAs as search algorithms because highway alignment optimization problems are implicit, non-differentiable and noisy in nature.

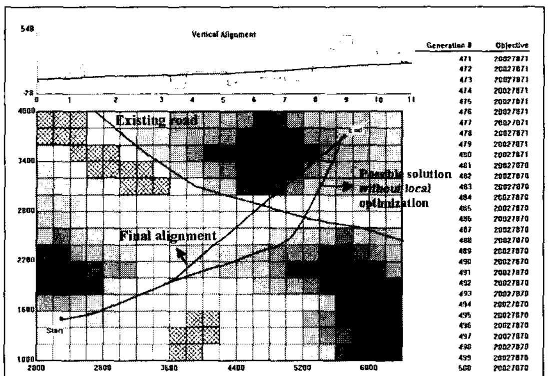
V. Example Study

Two artificial example studies are presented to show performance of the proposed methods. In ⟨Figure 10⟩, a darker cell means a higher elevation. The cross-patterned areas of the map represent inaccessible or environmentally untouchable regions, through which no new alignment is allowed. To check how the local intersection optimization performs in this artificial study area, just 30 generations were run. The results in ⟨Figure 10⟩ demonstrate the usefulness of the developed method, since the alignment in ⟨Figure 10⟩ might have been discarded without local intersection optimization due to its unacceptable crossing angle(approximately 58 degrees). (The acceptable range is between 60 to 120 degrees.) After that, 500 generations were run and the final solution was obtained, as shown in ⟨Figure 11⟩. The figure shows three main window areas : (1) horizontal alignment, (2) vertical alignment and (3) generation number and best solution value.

As we can see in ⟨Figure 11⟩, the optimized solution might have been discarded since its crossing angle with the existing road is not still acceptable. However, the developed local intersection optimi-



⟨Figure 10⟩ Artificial Study Area with 30 Generations

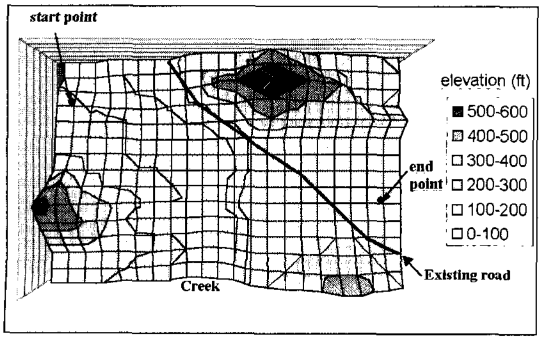


⟨Figure 11⟩ An Artificial Study Area with 500 Generations zation method kept this solution through the end of 500 generations. The total costs of the new alignment are about $20 million. We can easily imagine that without the developed method the final solution would be different. The possible solution in ⟨Figure 11⟩ looks better than the final solution. However, it should be noted that the objective function for alignments include user costs that normally account for 70-80% of total alignment costs. Therefore a longer alignment costs more for fuel and travel time even if it costs less for construction.

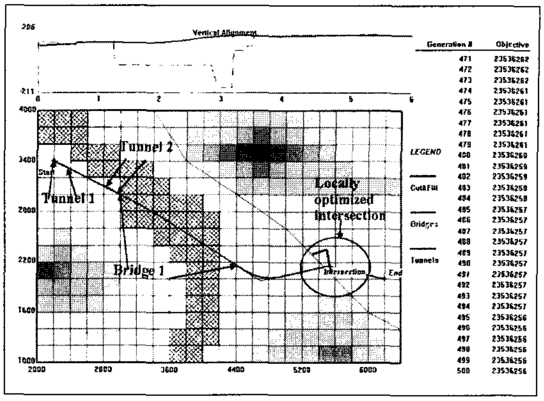
Another fairly complex artificial study area is employed to test applicability of the developed methods. ⟨Figure 12⟩ shows the quite complex topography of the artificial study area which includes a two-lane rural highway from the center of North to South East, three hills and a creek crossing from North East edge to South. Our plan is to build a two-lane rural highway connecting two specified end points while allowing the existing road to be re-optimized.

After alignment optimization processes, an optimized solution is obtained in which local optimization is applied, as shown in ⟨Figure 13⟩. The solution is obtained at generation 500 and total costs(see ⟨Table 4⟩) and computation time are found to be 23.54 million, 33 minutes and 54 seconds, respectively. The crossing angle is approximately 48 degrees.

With local optimization of intersections, it is



⟨Figure 12⟩ A More Complex Example



⟨Figure 13⟩ The Optimized Solution Involving Local Intersection Optimization

⟨Table 4⟩ Cost Breakdown of the Solution before Local Optimization of the Intersection

Cost items	Costs($) and fractions(%)
Total costs	24,554,573(100.00)
Intersection	3,608,136(14.69)
Pavement	1,598,651(6.51)
Right-of-way	5,984,036(24.37)
Vehicle operation	790,614(3.22)
User time value	4,997,932(20.35)
Accidents	242,485(0.99)
Tunnels	2,606,358(10.61)
Bridges	3,857,584(15.71)
Earthwork	859,343(3.50)
Penalty costs	9,434(0.04)

observed that approximately $\$10^6$ are saved. (The estimated original intersection costs were $3.61 million and the newly perturbed intersection costs were $2.59 million.)

More importantly, the best solution found is not discarded during successive generations just because of the unacceptable crossing angle between the existing road and the new alignment.

Ⅵ. Conclusions

A model for locally optimizing intersections and estimating intersection costs such as construction costs(pavement, earthwork and right-of-way costs)

〈Table 5〉 Cost Comparison between Original and Locally Optimized Intersections

Original intersection costs		Local optimization costs	
Cost items	Costs($) and fractions(%)	Cost items	Costs($) and fractions(%)
Total costs	3,608,136(100.00)	Total costs	2,589,819(100.00)
Pavement	11,809(0.33)	Link earthwork	261,765(10.11)
Earthwork	314,358(8.71)	Link right-of-way	312,793(12.08)
Right-of-way	680,150(18.85)	Link pavement	41,579(1.61)
Delay	509,549(14.12)	New intersection earthwork	185,185(7.15)
Fuel	27,416(0.76)	New intersection right-of-way	506,622(19.56)
Accidents	2,064,854(57.23)	New intersection delay	254,775(9.84)
		New intersection fuel	24,673(0.95)
		New intersection accident	1,002,427(38.71)

and operational costs(accident, delay, fuel consumption costs) has been developed for highway alignment optimization. The proposed method is more suitable than other, more laborious, methods for estimating intersection costs, which would not be adaptable in an automated optimal search process. Moreover, the developed method can be used without any optimization process for just evaluating highway alignment alternatives.

By adding the feature of local intersection optimization to the existing highway alignment optimization, we can avoid wastefully discarding a good alignment alternative that crosses an existing road with an overly acute angle. Moreover, the method can produce a more practical alignment and accurate cost estimates with considering two parts : (1) determining the best alignment between two fixed points and (2) refining the local geometry of intersections.

The developed model for local optimization of intersections and intersection cost estimation still has much room for improvement, although its performance is already acceptable. It should be noted that the developed cost functions for intersections are good enough for preliminary analysis but not for detailed design. There is much room left for future research to develop more detailed and efficient cost functions.

It can be found from 〈Figure 3〉 that perturbed segments of new alternatives are not smooth. In real design processes, only smooth segments following design constraints are acceptable. Thus, additional efforts are needed to fix this. Another extension would consider more alternatives. In the developed method, only those crossing type with a right angle are evaluated. In reality, variations from 60 to 120 degrees could be possible. A final extension for local intersection optimization would be to model several other types of crossing configurations, especially types C and D in 〈Figure 2〉.

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