Highway Route Optimization Based on Accessibility, Proximity, and Land-Use Changes

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Abstract: Accessibility, proximity, and land-use changes over time are important considerations in highway route selection. Highway users while benefiting from living closer to highways also pay a price for living close to them due to increased noise and pollution. Although noise and air pollution considerations have long been emphasized in land-use planning, their relative impacts in selecting a highway route are not fully understood. This research is motivated by a recent Federal Highway Administration initiative in which a national workshop involving participation from Departments of Transportation is proposed to understand current practices of including noise and air pollution in land-use planning. Formulations for accessibility, proximity, and land-use changes are developed and incorporated into a previously developed highway alignment optimization model by our research team. An example problem is presented to check the sensitivity of alignments to accessibility, proximity, and land-use change. The results indicate that accessibility, proximity, and land-use changes can greatly influence the selection of highway routes.

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Introduction

The highway development process is a complex and time-consuming process. It consists of five key stages: (1) planning; (2) project development; (3) final design; (4) right-of-way; and (5) construction. In the planning stage the project scope and changes in land-use patterns due to the proposed development should be carefully considered. While accessibility of highways may be thought of as an incentive to the highway users there is also a disutility associated with living closer to the highways due to increased noise and pollution. A new highway can attract new housing developments, business, and industry due to improved access, resulting in significant changes in land-use pattern. Effects of these changes over time should be considered in the planning stage since the decisions made at this stage could result in considerable time and money savings.

Federal Highway Administration Initiatives

The Federal Highway Administration's (FHwA) 1998 National Strategic Plan contains the strategic goal, "Protect and enhance the natural environment and communities affected by highway transportation." Thus the abatement of highway traffic noise is a FHwA priority, linked directly to the strategic planning process. Emphasis should be given to mitigating highway traffic noise through land-use controls.

The federal government has essentially no authority to regulate land-use planning or the land development process. However, the FHwA and other federal agencies can encourage state and local governments to practice land-use planning and control in the vicinity of highways. The FHwA advocates noise-compatible land-use planning, i.e., local governments using their power to regulate land development in such a way that noise-sensitive land-uses are either prohibited from being located adjacent to a highway, or that the developments are planned, designed, and constructed in such a way that noise impacts are minimized.

Some state and local governments have enacted legislative statutes for land-use planning and control. For example, the state of California has legislation on highway noise and compatible land-use development. This state legislation requires local governments to consider the adverse environmental effects of noise in their land development process. In addition, the law gives local governments broad powers to pass ordinances relating to the use of land, including, among other things, the location, size, and use of buildings and open space. Although other states and local governments have similar laws, the entire issue of land-use is extremely complicated, with a vast array of competing considerations entering into any actual land-use control decisions.

In this work we extend our highway alignment optimization (Jong et al. 2000; Jha 2003; Jong and Schonfeld 2003; Jha and Schonfeld 2004; Jha et al. 2006) research by considering accessibility, proximity, and land-use changes in the highway planning process. We formulate two costs associated with

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accessibility: cost of accessing the proposed highway (we call it access cost) and disutility associated with the proximity of the highway (we call it proximity cost).

Model Formulation

The access and proximity costs are formulated and used in the optimization algorithm previously developed by our research team (Jha and Schonfeld 2004; Jha et al. 2006). The description of highway alignment optimization approach, justification of genetic algorithms for optimization, as well as geographic information system application for working directly with real land-use maps are well-documented in our previous works (Jong and Schonfeld 2003; Jha and Schonfeld 2004). The accessibility cost (\$), C_A, can be specified as

$$C_A = C_u + C_b \tag{1}$$

where C_u=proximity cost (\$), i.e., disutility of living close to the proposed highway; and C_b=access cost (\$).

C_u and C_b can be intuitively defined as the dollar value of negative utility of living close to a highway and accessing a highway, respectively. They can be represented as functions of the access distance, d_i, which is defined as the instantaneous distance of a moving point along the proposed highway from the centroid of a property P_i (Fig. 1). It is noted that the actual distance to be traveled by users residing on property P_i may be longer since they may have to travel through an actual street network in order to access the highway. However, realistic formulation of d_i will require the availability of all design details of the highway, which is generally not available in the planning stages. If a sufficiently developed road network of the study area was available d_i can be calculated using standard geographic information system software with spatial analysis capability [see Samanta et al. (2005)]. Therefore consideration of the minimum distance as described in Fig. 1 may be reasonable for planning applications. However, it needs further refinement in our future works.

Conceptually, the disutility of living closer to a highway, C_u, will be higher for smaller d's and will decrease with increasing d (Fig. 2). The access cost, C_b, will increase with increasing d up to a maximum value after which it will become almost insensitive to d (Fig. 2). Thus, C_u can be expressed as

$$C_u = \sum_{P_i:i=1}^{n} \frac{\alpha}{d_i}(\delta_{ir} + \delta_{ic} + \delta_{iu})$$

where

$$\begin{aligned} \delta_{ir} &= 1 \quad \text{if } i = r \text{ (0 otherwise)} \\ \delta_{ic} &= 1 \quad \text{if } i = c \text{ (0 otherwise)} \\ \delta_{iu} &= 1 \quad \text{if } i = u \text{ (0 otherwise)} \end{aligned} \tag{2}$$

$$\alpha = \text{disutility cost coefficient } t \quad (\$ \text{ per km})$$

In Eq. (2) r, c, and u denote residential, commercial, and industrial properties, respectively. We use four land-use patterns in this work: commercial (c), rural (r), agricultural (a), and industrial (u). It is assumed that only residential, commercial, and industrial land-use types incur accessibility costs. Further, it is assumed that access and disutility costs only depend on the instantaneous distance and do not vary for different land-uses. Based on the above explanation, C_b can be expressed as

$$C_b = \sum_{P_i:i=1}^{n} \beta \ln(d_i)\{\delta_{ir} + \delta_{ic} + \delta_{iu}\}$$

where

$$\begin{aligned} \delta_{ir} &= 1 \quad \text{if } i = r \text{ (0 otherwise)} \\ \delta_{ic} &= 1 \quad \text{if } i = c \text{ (0 otherwise)} \\ \delta_{iu} &= 1 \quad \text{if } i = u \text{ (0 otherwise)} \end{aligned} \tag{3}$$

$$\beta = \text{access cost coefficient } t \quad (\$ \text{ per km})$$

Substituting Eqs. (2) and (3) in Eq. (1) the total accessibility cost, C_A, can be expressed as

$$C_A = \sum_{P_i:i=1}^{n} \{\delta_{ir} + \delta_{ic} + \delta_{iu}\}\left[\frac{\alpha}{d_i} + \beta \ln(d_i)\right] \tag{4}$$

The variations in access cost, disutility cost, and total accessibility cost with distance are graphically represented in Fig. 2.

The above formulation does not yet consider changes in land-use pattern over time. When a highway is constructed it is imperative that some of the agricultural or barren lands may be

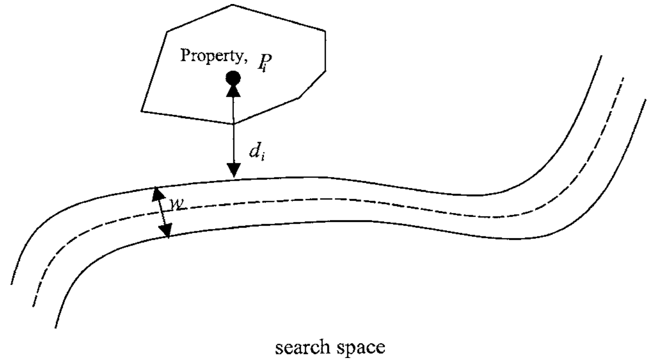

Fig. 1. Measurement of accessibility distance

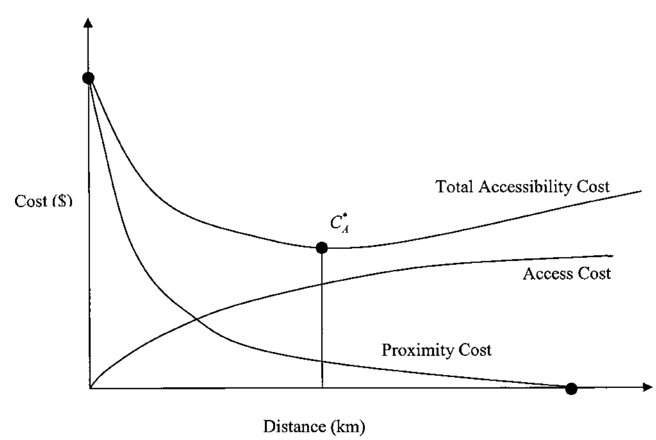

Fig. 2. Variation of access, proximity, and total accessibility costs with distance

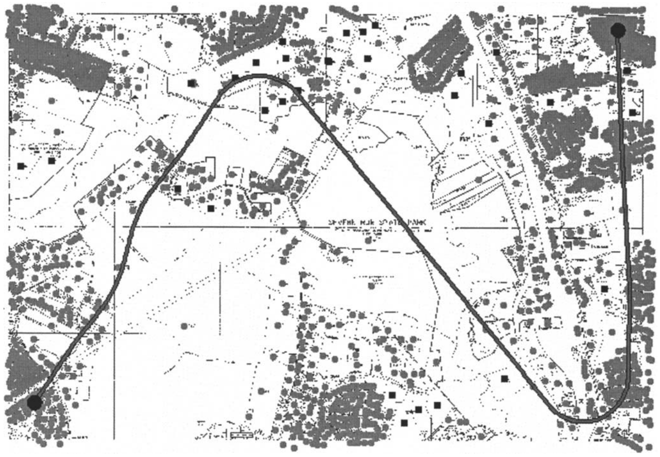

Fig. 3. Optimized alignment for Case 1

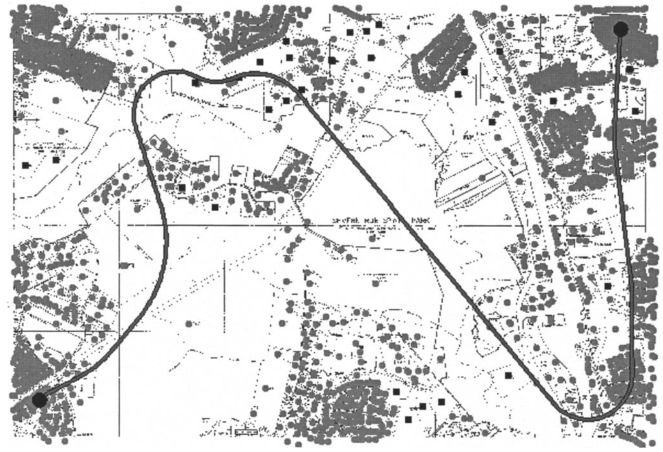

Fig. 4. Optimized alignment for Case 2

used for new residential, commercial, or industrial developments in the future. The model, therefore, should also account for effects of future changes in land-use pattern on accessibility cost. Also, the proposed methodology is only suitable to optimize alignments with access points and may not be appropriate for optimizing closed or semiclosed highways. Let n^1 be the total number of properties in year 1. It is assumed that only four land-use types are available: residential, commercial, industrial, and agricultural. Now let us define the following terms:

$$n_1^1 = \sum_{i=1}^{n} (\delta_{ir} + \delta_{ic} + \delta_{iu})$$

$$n_0^1 = \text{number of agricultural properties in year } 1 = n^1 - n_1^1 (\geqslant 0)$$

$$\begin{aligned} n_1^2 &= n_1^1 + \max(x_1^2, 0), \quad x_1^2 \leqslant n_0^1 \\ n_1^3 &= n_1^2 + \max(x_1^3, 0), \quad x_1^3 \leqslant (n_0^1 - x_1^2) \\ &\vdots \\ n_1^t &= n_1^{t-1} + \max(x_1^t, 0), \quad x_1^t \leqslant \left(n_0^1 - \sum_{k=1}^{t-1} x_1^k \right) \end{aligned} \tag{5}$$

where n_1^1=number of residential, commercial, and industrial properties in the current year; and x_1^2=agricultural or barren properties whose land-use pattern is changed to residential, commercial, or industrial in the second year. In general, x_1^t=agricultural or barren properties whose land-use pattern is changed to residential, commercial, or industrial in the tth year.

Thus the net present worth of total accessibility cost over T years can be expressed as

$$C_A = \sum_{P_i:i=1}^{n_1^1} (\delta_{ir} + \delta_{ic} + \delta_{ia}) \left[\frac{\alpha}{d_i} + \beta \ln(d_i) \right] + \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} \sum_{P_j:j=1}^{x_1^{t-1}} \left[\frac{\alpha}{d_j} + \beta \ln(d_j) \right] \tag{6}$$

where r= interest rate.

In order to test the sensitivity of a new alignment to the accessibility cost, C_A, as described in Eq. (6) above, we perform an example study using the real Geographic Information System (GIS) database from Anne Arundel County, Md.

Example

First, an ArcView GIS compatible property map is obtained (background map in Fig. 3) for the study section, which contains the geographic features and properties in the region of interest. The land-use types are also contained in the map. The study section contains 2,329 properties and occupies an area of about 1.94 km^2. Of those properties 31 are zoned agricultural and the remaining are zoned either residential, or commercial, or industrial. In the background map in Fig. 3 centroids of agricultural and nonagricultural properties are represented as rectangular and circular points, respectively. Dense residential, commercial, and industrial regions can be seen as clustered points. The given endpoints for alignment construction are shown as two thick points. The following four cases are designed:

- Case 1. Optimization using current year's land-use pattern, which considers the minimization of total accessibility cost;
- Case 2. Optimization using current year's land-use pattern, which considers the minimization of access cost only;
- Case 3. Optimization using current year's land-use pattern, which considers the minimization of proximity cost only; and
- Case 4. Optimization using future land-use pattern changes, which considers minimization of total accessibility cost.

Case 1

In this case we only consider current year's land-use patterns and perform an optimal search to minimize total accessibility cost. The search is performed for 200 generations. The optimized alignment at the 200th generation is shown in Fig. 3. It has a length of 3.41 km and its total accessibility cost is \$1.07133 million. The optimized alignment attempts to enhance accessibility of as many nonagricultural properties as possible while minimizing the disutility cost. The α and β values in Eq. (4) are taken as 50 and 80, respectively. It is noted that configuration of the optimized alignment may have been different if different α and β values were used since it will change the sensitivity of

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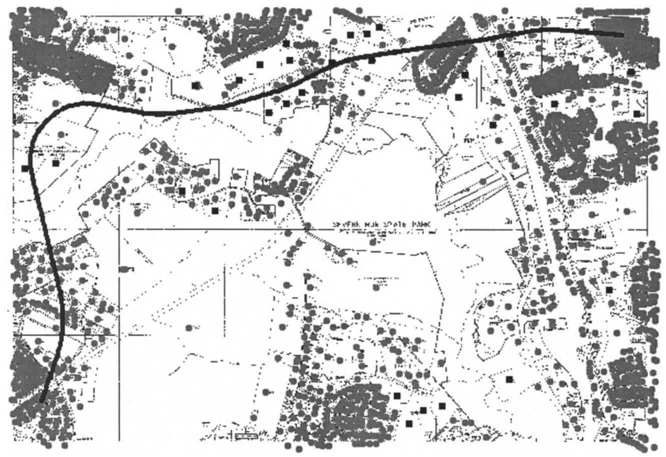

Fig. 5. Optimized alignment for Case 3

access and proximity costs on alignment selection. The algorithm attempts to obtain the best trade-off between access and proximity costs that minimizes the total accessibility cost.

Case 2

The model is run for 200 generations in this case to obtain an optimized alignment, which minimizes access cost only. The β

Table 1. Changes in Land-Use Pattern over Time for Example Study

Land-use type	Year 1	2	3	4	5
Agricultural (A)	31	23	17	8	3
Commercial (C) +industrial (I) + residential (R)	2,298	2,306	2,312	2,321	2,326

value is taken as 80. The optimized alignment which is shown in Fig. 4 has a length of 3.68 km and access cost of \$1.063 million. A comparison of the alignment configuration with that obtained in Case 1 indicates that the alignment attempts to serve as many nonagricultural properties as possible. The Case 1 optimized alignment is slightly different since proximity cost is also considered in that case.

Case 3

The model is again run for 200 generations in this case but only proximity cost is minimized this time. The α value is taken as 10,000. A higher value of α will force the alignment to stay as far as possible from residential, commercial, and industrial neighborhoods. The optimized alignment obtained after 200 generations is shown in Fig. 5. It can be seen that the alignment

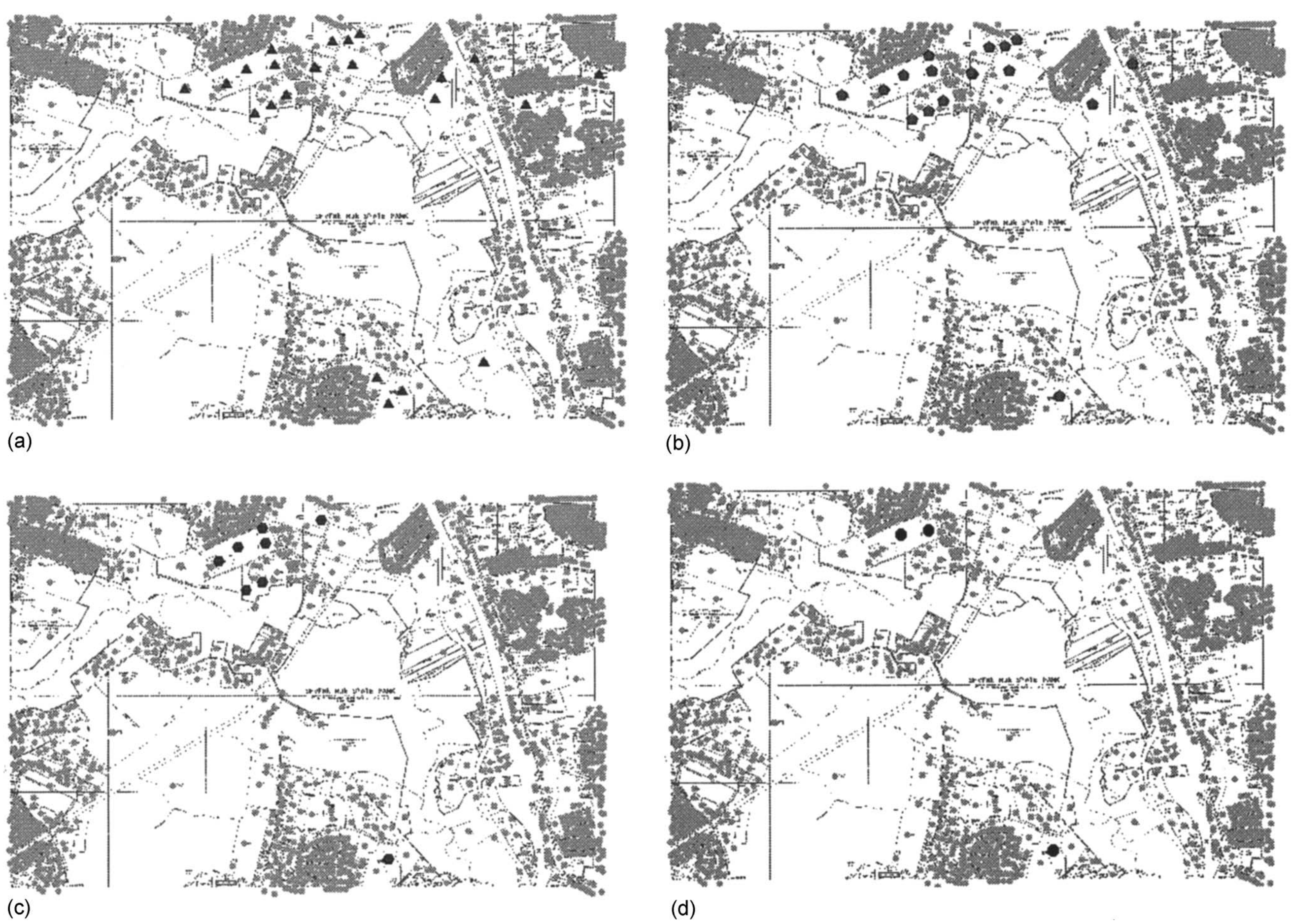

Fig. 6. Changes in land-use pattern over time: (a) land use pattern at the end of the second year; (b) land use pattern at the end of the third year; (c) land use pattern at the end of the fourth year; and (d) land use pattern at the end of the fifth year

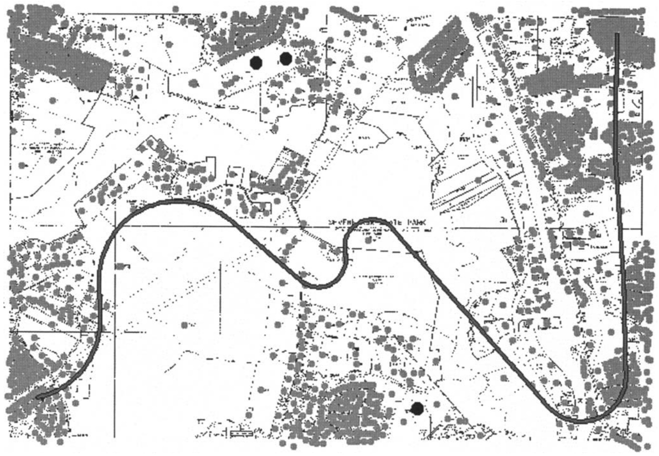

Fig. 7. Optimized alignment for Case 4

has a tendency to stay away from denser communities since the objective was to minimize proximity cost. The alignment length and proximity cost are found to be 2.4 km and $6,939.54, respectively. The alignment is much shorter in this case because it attempts to avoid impacts to larger residential, commercial, and industrial regions.

Case 4

In this case we consider the changes in land-use pattern over time. It is assumed that the changes occur over a 5-year period. The assumed interest rate is 6%. The changes in land-use pattern over time are shown in Table 1, they are also shown in Fig. 6. The centroids of agricultural properties at the end of every year are shown in dark. The total accessibility cost which is represented as Eq. (6) is used to perform the optimal search for 150 generations. The α and β values are taken as 80 and 10,000, respectively. The higher β value is taken to make the alignment selection more sensitive to proximity cost, to be able to clearly see its effects. The optimized alignment is shown in Fig. 7. The background map in Fig. 7 is the land-use pattern at the end of the 5th year. The length and accessibility cost of the optimized alignment are 3.29 km and $5.12 million, respectively. The higher accessibility cost is due to the consideration of future changes in land-use patterns.

Conclusions

The examples demonstrate that one can select different highway routes depending on the relative weights of access and proximity costs. The results also demonstrate that change in land-use pattern over time should be considered in alignment selection as its consideration may significantly change the alignment configuration. In future works we will use a more realistic calculation of access distances using an actual street network in the analysis region and using *ArcView* GIS's network analyst extension for performing spatial analysis for access distance calculation (Samanta et al. 2005). A more realistic value of unit access and proximity costs will also be considered in future works.

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