# Empirical Model with Environmental Considerations in Highway Alignment Optimization

Sabyasachee Mishra[1]; Min-Wook Kang, M.ASCE[2]; and Manoj K. Jha[3]

**Abstract:** The highway alignment optimization (HAO) process is a complex combinatorial optimization problem in which several conflicting factors, such as highway costs, user preferences, and environmentally sensitive factors, must be simultaneously considered. In previous studies, single-level and bi-level optimization approaches were developed to optimize three-dimensional highway alignments. One drawback of previous approaches is that environmental factors, such as vehicular emissions, were not adequately considered in conjunction with other factors (such as user preferences and highway costs) in the optimization process. This paper builds on our previous studies and proposes two separate approaches for considering environmental emissions in the HAO process. The first approach involves a separate analysis of user and decision-maker preferences, in which a conceptual formulation of various environmental factors is presented. In the second approach, a novel tri-level optimization framework is proposed for optimizing highway alignments. At the upper level, optimization is performed using the traditional criteria of cost minimization. At the intermediate level, total systems emission is calculated. Finally, at the lower level, the user equilibrium traffic flow is optimized. The developed approaches are illustrated through case study examples. The proposed approaches will be beneficial for designing highway alignments when considering environmental emissions. Future studies may make additional refinements to the formulation and sensitivity analyses. **DOI:** 10.1061/(ASCE)IS.1943-555X.0000194. © *2014 American Society of Civil Engineers.*

**Author keywords:** Highway alignment optimization; Bi-level optimization; Tri-level optimization; Highway cost; User cost; Environmental emission.



## Introduction

Road alignment optimization finds the most economical road alternative connecting two given endpoints on the basis of topography, soil conditions, socioeconomic factors, and environmental effect, while satisfying a set of design and operational constraints. Because of the complexity of this problem, various alternatives in traditional road alignment optimization need to be evaluated to determine the most promising one. Because the number of alternatives connecting two given endpoints is infinite, a manual method may arrive at a merely satisfactory solution rather than a near optimal one. Such road alignment optimization problems have attracted significant research interest during the past three decades.

Many studies (Steenbrink 1974; Trietsch 1987; Jong et al. 2000; Fwa et al. 2002; Jong and Schonfeld 2003; Jha and Schonfeld 2004; Chen and Yang 2004; Gao et al. 2005; Cheng and Lee 2006; Kang et al. 2007; Lee et al. 2009; Kang et al. 2009) proposed various mathematical methods for solving highway network design and route optimization problems. However, most models and proposed methods found in the literature are limited to alignment optimization and the geometric design of highways. Very few studies (e.g., Maji and Jha 2011 and Kang et al. 2010) considered the effect of new roads on the level of service (LOS) of the original road network. In actuality, a new road is not only an isolated transportation facility but also—obviously—a component of a road network. Thus, considering the effect of a new road on the original road network in road alignment optimization is valuable.

Prior literature employed various mathematical methods, such as dynamic programming, numerical search, and linear programming, to solve network optimization. Most methods are devoted to optimizing either the horizontal alignment or the vertical alignment. However, recently, along with the rapid development of computer and information technology, geographic information systems (GIS) and digital spatial data have been widely applied. Many new methods on the basis of GIS have been proposed. Jong and Schonfeld (2003) developed an evolutionary model for simultaneously optimizing three-dimensional (3D) highway alignments. The model emphasizes the application and realization of a genetic algorithm (GA) for highway alignment optimization. Jha (2003) developed a criteria-based decision support system on the basis of GIS for selecting highway alignments. In addition, Jha and Schonfeld (2004) developed an alignment optimization model on the basis of GIS and GA. In general, the characteristics of recent studies are as follows: (1) the models are developed on the basis of a GIS; (2) the models employ GA as a solution method; (3) the models emphasize the simultaneous optimization of 3D road alignment; and (4) in the selection process, a number of factors, such as user costs (such as cost of vehicle operation, travel time cost, accident cost), supplier costs (such as earthwork cost, construction cost), and environmental costs are introduced in the model to judge the alternatives.

## Study Objective

Although some methods perform well in certain aspects, all are limited in the factors that they consider. No previous model was found

[1]Assistant Professor, Dept. of Civil Engineering, Univ. of Memphis, 112D Engineering Science Building, 3815 Central Ave., Memphis, TN 38152 (corresponding author). E-mail: smishra3@memphis.edu

[2]Assistant Professor, Dept. of Civil Engineering, Univ. of South Alabama, Mobile, AL 36688. E-mail: mwkang@southalabama.edu

[3]Professor, Dept. of Civil Engineering, Morgan State Univ., Baltimore, MD 21251. E-mail: manoj.jha@morgan.edu

Note. This manuscript was submitted on March 22, 2013; approved on September 13, 2013; published online on September 16, 2013. Discussion period open until July 24, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Infrastructure Systems***, © ASCE, ISSN 1076-0342/04014017(12)/$25.00.

that jointly evaluates the traffic and environmental effects of a new highway and optimizes highway location, construction cost, and horizontal and vertical profiles. This study integrates all of these factors in optimizing highway alignments. Finding new highways that best improve an existing roadway system is described as a leader–follower game in which the system designers (i.e., highway planners and designers) are leaders and the highway users (i.e., motorists) who freely choose their paths are the followers. In this process, system designers influence but do not control the route choice behavior of highway users. System designers attempt to find an economical path that minimizes total construction cost when considering geometric design and geographical constraints. However, the traffic flow is determined by user decisions that are approximated with the user equilibrium principle. To realistically represent such characteristics in the highway route optimization process, a recent paper (Kang et al. 2010) proposed a bi-level optimization method. That method separated user preferences from the traditional cost minimization problem.

Because environmental considerations are key to planning and designing highways, this paper offers a significant departure from previous methods of considering environmental sensitivities. Previous methods imposed a user-defined penalty (see, for example, Jha and Schonfeld 2004) to keep the candidate alignments from crossing through environmentally sensitive regions. The optimization process did not comprehensively formulate and consider the recurring environmental pollution, such as noise and air pollution (see, for example, Jha and Kang 2009; and Jha and Kim 2006).

## Methodology

### *Separate Analysis of User and Decision Maker to Incorporate Environmental Emissions in Highway Alignment Optimization*

The concept of considering environmental emissions attributable to vehicular traffic in the highway alignment optimization process was realized by the second and third authors in some of their recent preliminary studies (see, for example, Jha et al. 2011). One approach is to present a modified equilibrium traffic assignment model that minimizes air, noise, and water pollutants derived from vehicular traffic and its surroundings. Fig. 1 illustrates this approach.

The conceptual formulation of the proposed assignment model is expressed as

$$\text{Minimize } Z = \begin{cases} \sum_a \int_0^{x_a} t_a(x_a)dx_a & \text{for user optimum based on travel time (case 1)} \\ \sum_a c_a(x_a, u_a, l_a, d_a, w_a, r_a) & \text{for decision-maker objective on the basis of cost (case 2)} \end{cases} \quad (1)$$

where $c_a(x_a, u_a, l_a, d_a, w_a, r_a)$ = air pollution + noise pollution + water pollution + travel time cost; $A$ = arc (index) set of a given highway network; $a \in A$; $x_a$ = flow on arc $a$; $\mathbf{x} = (\ldots, x_a, \ldots)$; $t_a$ = travel time on arc $a$; $\mathbf{t} = (\ldots, t_a, \ldots)$; $u_a$ = Land-use where arc $a$ is located; $\mathbf{u} = (\ldots, u_a, \ldots)$; $l_a$ = length of arc $a$; $\mathbf{l} = (\ldots, l_a, \ldots)$; $w_a$ = width of arc $a$; $\mathbf{w} = (\ldots, w_a, \ldots)$; $d_a$ = distance from arc $a$; and $p_a$ = rainfall intensity where arc $a$ is located; $\mathbf{p} = (\ldots, p_a, \ldots)$.

In this formula, the decision maker's scenario minimizes the effect of air, noise, and water pollution, in addition to user travel time. An illustrative example is presented to further explain the approach.

An example study area (Fig. 2) is created in which a new highway is evaluated on the basis of the combined effect of the various pollutions previously outlined, in conjunction with the traditional travel-time minimization objective. Note that residential, commercial, and business and industrial land-use areas have more impervious surfaces (i.e., paved surfaces); therefore, percolation is almost negligible, resulting in higher runoff. Therefore, water pollution is high in such areas. With respect to the noise effect, a higher the degree of urbanization results in higher noise pollution because of sound barriers and the reflection of sound waves. Additionally, the concentration of carbon monoxide and other poisonous gases is higher in highly urbanized areas because of the slower dissipation rate of these harmful gases into the atmosphere.

Table 1 shows the origin–destination (O–D) matrix of the study area, and provides a simple illustration of our approach. A genetic algorithm previously designed for the bi-level highway alignment optimization problem by the second and third authors (see Kang et al. 2010) was applied to find the equilibrium solution using user and decision-maker preferences. The algorithm is designed to work in a GIS environment. Fig. 3 and Table 2 show the results of the analysis.

Fig. 3 shows two bars on each road link of the study area. The red bars indicate traffic volume (vehicles per hour) assigned using the traditional (shortest path on the basis of minimum travel time) algorithm. The green bars indicate the traffic volumes assigned using the minimal pollution method (our algorithm). Fig. 3 shows that the red bars are taller in areas with higher pollution and the green bars are taller in areas with lower pollution. Our algorithm assigns more traffic on links that have lower pollution costs (Table 2).

Fig. 4 shows travel paths between specified end points resulting from separate analyses of the user optimum (Case 1: minimizing travel time only) and decision-maker cost (Case 2: minimizing travel time plus environmental pollution) formula. Fig. 4 shows that, whereas travel time is reduced in the user optimum scenario, the total pollution cost is decreased when both travel time and pollution are considered together in the analysis. The results have far reaching policy implications, particularly for the highway planning process, congestion pricing, and establishing varying tolling strategies on the basis of the combined effects of recurring pollution and traffic congestion.

### *Tri-Level Approach*

This section introduces a novel tri-level optimization framework by separating the environmental considerations from the traditional

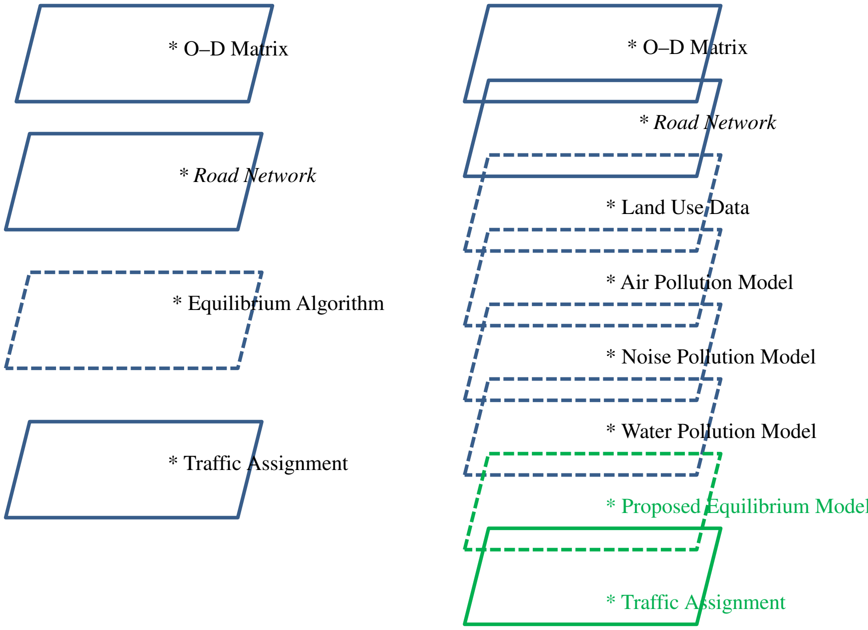
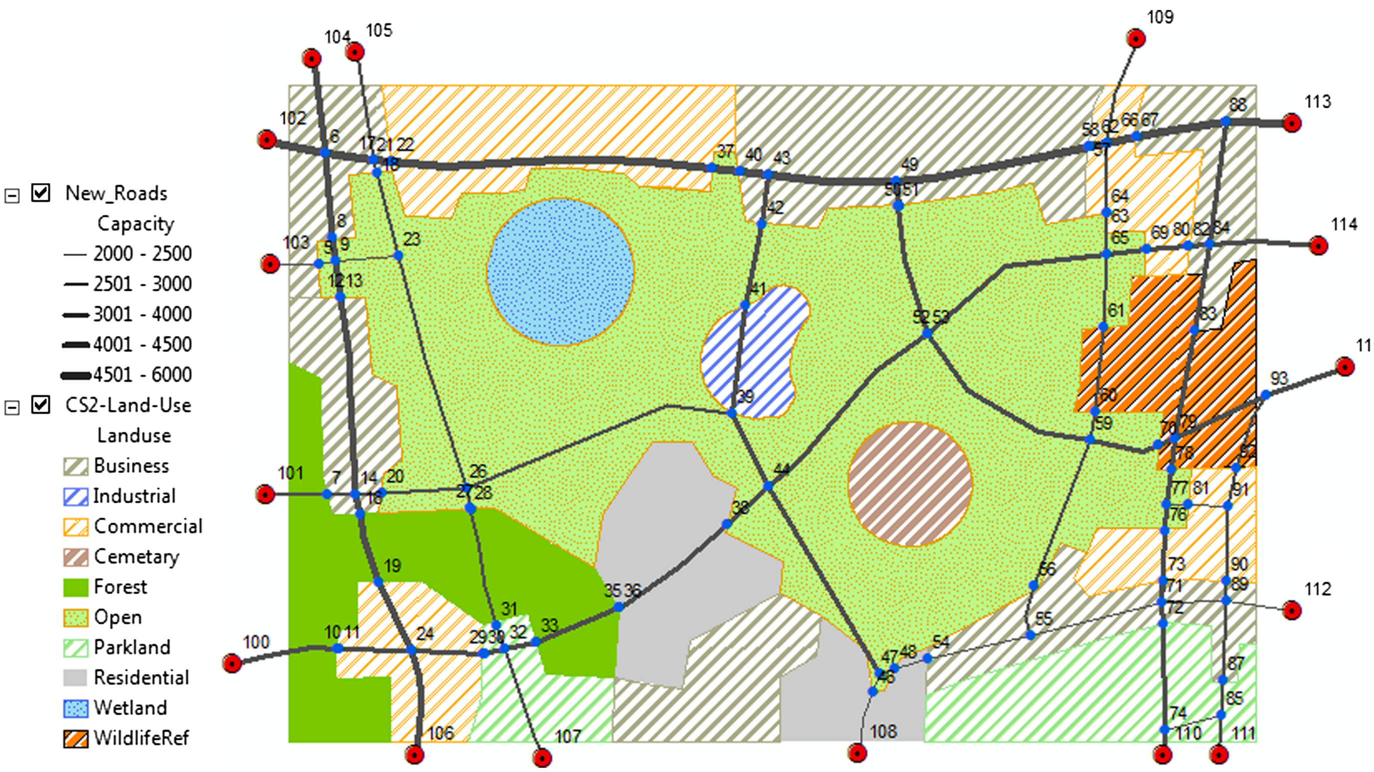



**Fig. 1.** Traditional versus proposed assignment models




Size of Study Area = 1.3 Mile x 1.0 Mile

**Fig. 2.** Example study area

cost minimization approach. The tri-level optimization approach incorporates various decision-making criteria in highway alignment optimization, such as cost minimization, emission consideration, and user equilibrium traffic flow. Table 3 shows the key differences between the traditional network design problem and various aspects of the highway alignment optimization problem. This tri-level approach is superior to a method that optimizes only highway construction costs; furthermore, it provides a much wider scope of objectives regarding various user costs including travel time, vehicle operation, and accident costs.

### *Tri-Level Formulation*

The upper level (i.e., first level) of the proposed tri-level approach is defined as the highway alignment optimization problem in which best highway alternatives are identified on the basis of a specified

**Table 1.** O–D Matrix in the Study Area

| O-D | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 | 114 | 115 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 0 | 40 | 35 | 15 | 75 | 60 | 85 | 45 | 30 | 60 | 55 | 20 | 40 | 65 | 185 | 40 | 850 |
| 101 | 40 | 0 | 15 | 25 | 110 | 15 | 65 | 40 | 30 | 45 | 50 | 20 | 30 | 70 | 105 | 90 | 750 |
| 102 | 35 | 15 | 0 | 40 | 50 | 30 | 100 | 20 | 60 | 35 | 125 | 80 | 75 | 130 | 35 | 120 | 950 |
| 103 | 15 | 25 | 40 | 0 | 100 | 15 | 30 | 30 | 50 | 90 | 50 | 45 | 55 | 40 | 55 | 45 | 685 |
| 104 | 75 | 110 | 50 | 100 | 0 | 10 | 100 | 55 | 80 | 40 | 100 | 85 | 75 | 120 | 75 | 125 | 1,200 |
| 105 | 60 | 15 | 30 | 15 | 10 | 0 | 105 | 50 | 100 | 35 | 80 | 70 | 85 | 45 | 80 | 70 | 850 |
| 106 | 85 | 65 | 100 | 30 | 100 | 105 | 0 | 10 | 10 | 50 | 40 | 30 | 20 | 45 | 55 | 30 | 775 |
| 107 | 45 | 40 | 20 | 30 | 55 | 50 | 10 | 0 | 5 | 15 | 10 | 15 | 5 | 10 | 55 | 10 | 375 |
| 108 | 30 | 30 | 60 | 50 | 80 | 100 | 10 | 5 | 0 | 10 | 5 | 25 | 15 | 75 | 55 | 50 | 600 |
| 109 | 60 | 45 | 35 | 90 | 40 | 35 | 50 | 15 | 10 | 0 | 50 | 50 | 65 | 30 | 60 | 65 | 700 |
| 110 | 55 | 50 | 125 | 50 | 100 | 80 | 40 | 10 | 5 | 50 | 0 | 25 | 35 | 95 | 40 | 90 | 850 |
| 111 | 20 | 20 | 80 | 45 | 85 | 70 | 30 | 15 | 25 | 50 | 25 | 0 | 40 | 60 | 65 | 70 | 700 |
| 112 | 40 | 30 | 75 | 55 | 75 | 85 | 20 | 5 | 15 | 65 | 35 | 40 | 0 | 15 | 20 | 25 | 600 |
| 113 | 65 | 70 | 130 | 40 | 120 | 45 | 45 | 10 | 75 | 30 | 95 | 60 | 15 | 0 | 100 | 130 | 1,030 |
| 114 | 185 | 105 | 35 | 55 | 75 | 80 | 55 | 55 | 55 | 60 | 40 | 65 | 20 | 100 | 0 | 35 | 1,020 |
| 115 | 40 | 90 | 120 | 45 | 125 | 70 | 30 | 10 | 50 | 65 | 90 | 70 | 25 | 130 | 35 | 0 | 995 |
| Total | 850 | 750 | 950 | 685 | 1,200 | 850 | 775 | 375 | 600 | 700 | 850 | 700 | 600 | 1,030 | 1,020 | 995 | 12,930 |

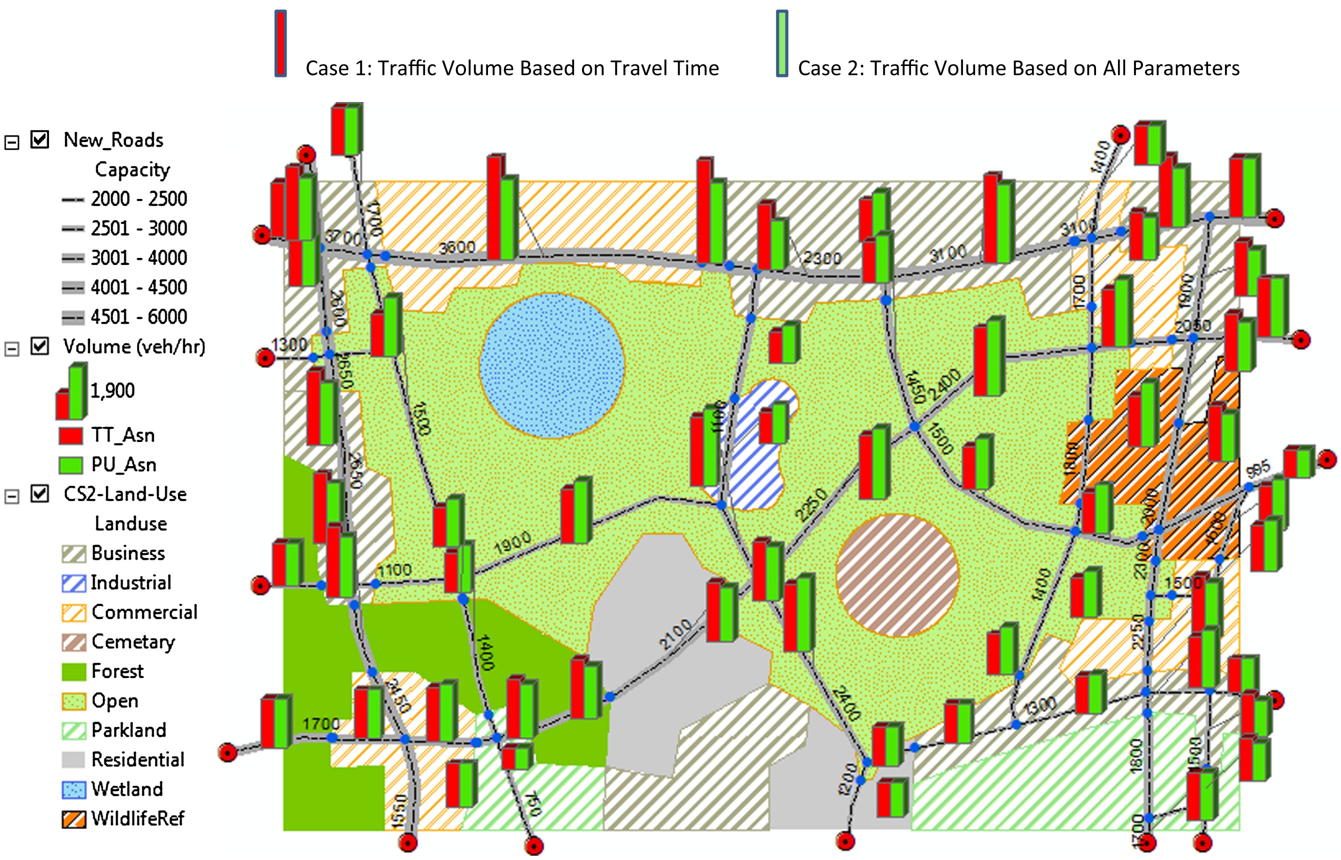



**Fig. 3.** Case study results

objective function (Kang et al. 2010, 2012). On the first level, optimal highway alignment is determined subject to highway design and environmental and geographical constraints. On the second level, total system emission is minimized considering the available speed profiles of highway alignments. On the third level, user equilibrium traffic flow is obtained by minimizing the composite cost. All notations are presented at the end of the paper. The tri-level model formulation is subsequently shown and explained.

## Upper Level

The objective is to determine the optimized highway alignments:

$$\text{Minimize:} \qquad Z_{UL} = C_{T\,\text{agency}} + C_{T\,\text{user}} + C_P \qquad (2)$$

Subject to:

1. Highway design constraints
2. Environmental and geographical constraints

**Table 2.** Case Study Results

| Road type | Length | Free speed | Land use | Capacity | Travel time | Noise cost | Air pollution cost | Water pollution cost | Travel time cost assigned[a] | Pollution cost assigned[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| Suburban/Urban Primary Arterial | 832.387 | 50 | Business | 3,600 | 11.351 | 0.135 | 0.056 | 0.5 | 2,050 | 2,050 |
| Urban freeway | 435.029 | 65 | Business | 6,000 | 4.563 | 0.039 | 0.092 | 0.5 | 1,900 | 1,900 |
| Urban freeway | 349.776 | 65 | Business | 6,000 | 63.669 | 0.039 | 0.092 | 0.5 | 3,700 | 3,250 |
| Urban freeway | 2,373.471 | 65 | Commercial | 6,000 | 24.897 | 0.039 | 0.092 | 0.7 | 3,600 | 2,800 |
| Urban freeway | 1,161.831 | 65 | Business | 6,000 | 12.187 | 0.039 | 0.092 | 0.5 | 2,300 | 1,700 |
| Urban freeway | 1,453.387 | 65 | Business | 6,000 | 415.245 | 0.039 | 0.092 | 0.5 | 3,100 | 2,800 |
| Urban freeway | 131.005 | 65 | Commercial | 6,000 | 1.374 | 0.039 | 0.092 | 0.7 | 3,100 | 2,800 |
| Urban freeway | 228.677 | 65 | Commercial | 6,000 | 2.399 | 0.039 | 0.092 | 0.7 | 2,500 | 2,100 |
| Urban freeway | 671.606 | 65 | Business | 6,000 | 7.045 | 0.039 | 0.092 | 0.5 | 2,500 | 2,100 |
| Urban freeway | 146.204 | 65 | Business | 6,000 | 1.534 | 0.039 | 0.092 | 0.5 | 3,600 | 2,800 |
| Urban freeway | 204.050 | 65 | Open | 6,000 | 2.140 | 0.039 | 0.092 | 0.1 | 3,600 | 2,800 |
| Urban freeway | 912.013 | 55 | Business | 4,000 | 11.306 | 0.141 | 0.059 | 0.5 | 1,900 | 1,600 |

[a]Traffic assignment using only travel time.
[b]Traffic assignment using all parameters.

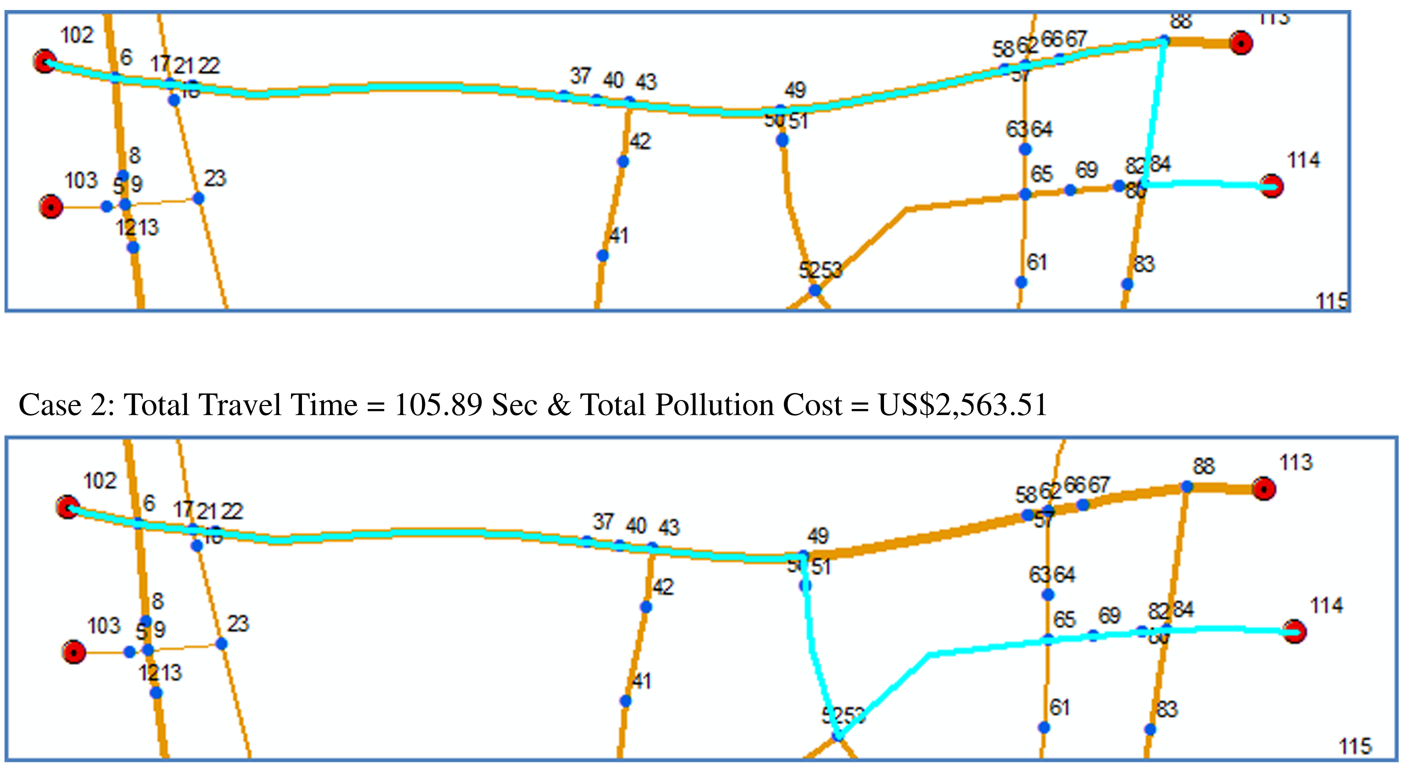



**Fig. 4.** Variation in total travel time and total pollution cost attributable to user and decision-maker preferences

**Intermediate Level**

The objective is to minimize total systems emission:

$$\text{Minimize:} \quad TE = \sum_a [x_a e f_a(v_a) l_a] \tag{3}$$

$$\text{Subject to:} \quad 0 \le e_a \le 1 \tag{4}$$

**Lower Level**

The objective is to determine user equilibrium traffic flow by minimizing the composite cost (Sheffi 1985)

$$\text{Minimize:} \quad \sum_a \int_0^{x_a} c_a(x_a, e_a) \tag{5}$$

$$\text{Subject to:} \quad \sum_{\forall k} f_k^{rs} = q^{rs} \tag{6}$$

$$x_a = \sum_r \sum_s \sum_k \delta_{a,k}^{rs} f_k^{rs} \tag{7}$$

$$f_k^{rs} \ge 0 \tag{8}$$

**Table 3.** Key Differences between Three Model Types

| Functionality | Characteristics | Network design problem | Highway alignment optimization | Highway alignment optimization with environmental effects |
|---|---|---|---|---|
| Scope | Macroscopic (Planning) | ✓ | ✓ | ✓ |
| | Microscopic (Design) | — | ✓ | ✓ |
| Objective | Minimize network travel cost | ✓ | ✓ | ✓ |
| | Optimal highway alignment with minimal cost | — | ✓ | ✓ |
| | Minimum emission, optimal highway alignment with minimal cost and minimum emission | — | | ✓ |
| Input | Highway design specification (for example, design speeds, maximum grades, and cut/fill slopes) | ✓ | ✓ | ✓ |
| | Spatial information (for example, land-use and topography) | — | ✓ | ✓ |
| | Link speed | — | ✓ | ✓[a] |
| | Emission profiles | — | — | ✓[a] |
| Output | Network travel cost | ✓ | ✓ | ✓ |
| | Conceptual road network with new links | ✓ | ✓ | ✓ |
| | Profiles of optimized highway alignments | — | ✓ | ✓ |
| | Detailed cost elements for highway construction | — | ✓ | ✓ |
| | Emission profile for links | — | — | ✓[a] |
| Advantage | Reflects drivers route choice behavior | ✓ | ✓ | ✓ |
| | Evaluate highway alignments | — | ✓ | ✓ |
| | Reflects construction cost in evaluation | — | ✓ | ✓ |
| | Estimate emission as one objective | — | — | ✓[a] |
| Disadvantage | Cannot consider actual highway cost and constraints associated with road construction | ✓ | — | — |
| | Cannot generate different highway alternatives | ✓ | — | — |
| | Cannot estimate emissions | ✓ | ✓ | — |
| | Longer computational time | ✓ | ✓ | ✓ |

[a]Represents advantages of highway alignment optimization with environmental effects over others.

$$x_a \geq 0 \tag{9}$$

$$k \in K; a \in A; r, s \in \Omega \tag{10}$$

## Upper Level Problem

The following three types of decision variables are used in the tri-level model structure: (1) points of intersection (PIs) of new highway alignments; (2) amount of total systems emissions; and (3) distributed traffic flows on the network. The objective function of the upper-level problem primarily depends on these variables along with many other factors such as unit pavement cost, earthwork quantity, fuel cost, and land use. Note that the decision variables—PI coordinates—are indirectly formulated in the upper-level objective function, similar to our previous approaches (see, for example, Jong et al. 2000). To solve the upper-level problem, the model employs a GA with customized genetic operators (Jong and Schonfeld 2003). The GA aims to generate the PIs of new highways and ultimately finds optimized ones through an evaluation procedure on the basis of the principles of natural evolution and survival of the fittest. The formulation of the upper-level alignment optimization problem includes an objective function and two constraints associated with new highway construction. Similar to our previous work (Kang et al. 2010), the objective function ($Z_{UL}$) is defined as the sum of (1) total agency cost, (2) total user cost, and (3) penalty cost. (Kang et al. 2010).

- Agency cost: Total agency cost consists of four major construction costs [length-dependent cost ($C_L$: a cost proportional to the length of a highway; e.g., pavement cost), right-of-way cost ($C_R$: a cost required for land acquisition), earthwork cost ($C_E$), and structure cost ($C_S$)] directly required during the initial stage of a new highway development and a maintenance cost ($C_M$) that occurs throughout the life of the road alignment. All of these cost components are important and sensitive to highway alignment and should be simultaneously evaluated in the highway alignment optimization process. The basic formulation of the total agency cost is expressed as

$$C_{T\_\text{Agency}} = C_L + C_R + C_E + C_S + C_M \tag{11}$$

where $C_L$, $C_R$, $C_E$, $C_S$, $C_M$ = length-dependent cost, right-of-way cost, earthwork cost, structures cost, and maintenance cost, respectively. The mathematical formulations of these agency cost components in Eq. (11) may be found in the authors' earlier publications (Kang et al. 2007, 2010; Kim et al. 2004; Jha and Schonfeld 2000; Jha and Schonfeld 2003; Kang 2008); thus, they were skipped in this paper.
- User cost: User cost consists of the cost of vehicle operation, travel-time delay cost, and accident cost, which are well formulated in our previous studies (see Jha et al. 2006; Kang et al. 2010). Note that the proposed tri-level highway alignment optimization model is designed with a modular structure in which various evaluation components are easily replaced without changing the rest of the model structure. Thus, any available accident prediction relations or models may be incorporated in the model to estimate the accident frequency of new highways.

## Intermediate Level Problem

At the intermediate level, total system emission is computed on the basis of traffic flow and speed obtained from the lower level. The total emission, $TE_e$, is the sum of the product of traffic flow $x_a$ and emission factor $ef_a(v_a)$ as a function of average speed $v_a$ on link $a$ and length of the link $l_a$. The emission pricing value $e_a$ for each link acts as an additional cost for a road user given by $c_a(x_a, e_a)$ as shown in Eq. (14). Thus, different values of $e_a$ lead to changes in travel costs and, hence, variations in the flows throughout the network. The real value variable $e_a$ is chosen such that it is within the value of 1 (that is, maximum increase in travel cost is 100%) and 0 (that is, no emission pricing at all). The change in flows because of emissions causes further changes in travel time, which varies the average speed on the link and, further, the emission factor and, hence, total emissions.

Typically, the emission function $ef_a(v_a)$ has a polynomial form with an average link speed $v_a$ as the dependent variable and is given as

$$ef_a(v_a) = b_1 v_a^2 + b_2 v_a + b_3 \tag{12}$$

where $b_1$, $b_2$, and $b_3$ = coefficients to be calibrated from the observed vehicular emission data. This paper considers the pollutant to be $CO_2$, a major green house gas (GHG), and adopts a polynomial function from El-Shawarby et al. (2005). The reason for considering only one pollutant is the present focus of agencies and policy makers on minimizing GHGs from vehicles.

### Lower-Level Problem

The lower level problem is a traffic assignment process used to evaluate the effect from a new highway being added to an existing road network. Alternatively, the lower level is an optimization process that allows highway users to adjust their travel paths by minimizing total travel cost (Kang et al. 2010). In the tri-level model structure, the lower level represents a static (or deterministic) user equilibrium assignment. The result of the user equilibrium assignment is distribution of traffic flows and travel times in the highway network. The resulted output from the lower level serves as input to the upper- and intermediate-level formula to evaluate the total emission and user costs.

The lower level of the tri-level formulation assigns the trip matrix into the network using the route choice algorithm. A user equilibrium assignment on the basis of Wardrop's first principle is proposed, which denotes that "no user can experience a lower travel time by unilaterally changing routes" (Wardrop 1952). In simple terms, equilibrium is achieved when the travel costs on all used paths are equal to one another. The travel time function $t_a(\cdot)$ is specific to a given link $a$ and the most widely used model is the Bureau of Public Roads (BPR) function given by

$$t_a(x_a) = t_o\left[1 + \alpha_a\left(\frac{x_a}{C_a}\right)\right]^{\beta_a} \tag{13}$$

where $t_a(\cdot)$ = free flow time on link $a$, and $\alpha_a$ and $\beta_a$ represent link-specific constants, normally calibrated using the observed field data. The BPR function is a monotonically increasing convex function. The emission price variable $e_a$ changes travel time into travel cost such that $\varphi$ is the value of time in monetary terms (\$/hr) (Sharma and Mishra 2013; Mishra and Welch 2012).

$$c_a(x_a, e_a) = \varphi(1 + e_a)t_a(x_a) = \varphi(1 + e_a)t_o\left[1 + \alpha_a\left(\frac{x_a}{C_a}\right)\right]^{\beta_a} \tag{14}$$

The constraint shown in Eqs. (6) through (10) for the lower level is for flow conservation, which states that the flow on all paths connecting each O–D pair has to be equal to the O–D trip rate. In other words, all trips have to be assigned to the network. The next constraint is a definitional constraint relating the link flows $x_a$ and path flows $f_k^{rs}$. The remaining two constraints are non-negativity conditions that are required to ensure that the solutions are physically meaningful.

With respect to the determination of traffic reassignments, note that the tri-level optimization approach may not be efficient in cases in which the assignment results for the networks updated with different highway alternatives are very similar. In such a case, the traffic re-assignment is wasteful. Thus, a preprocessed traffic

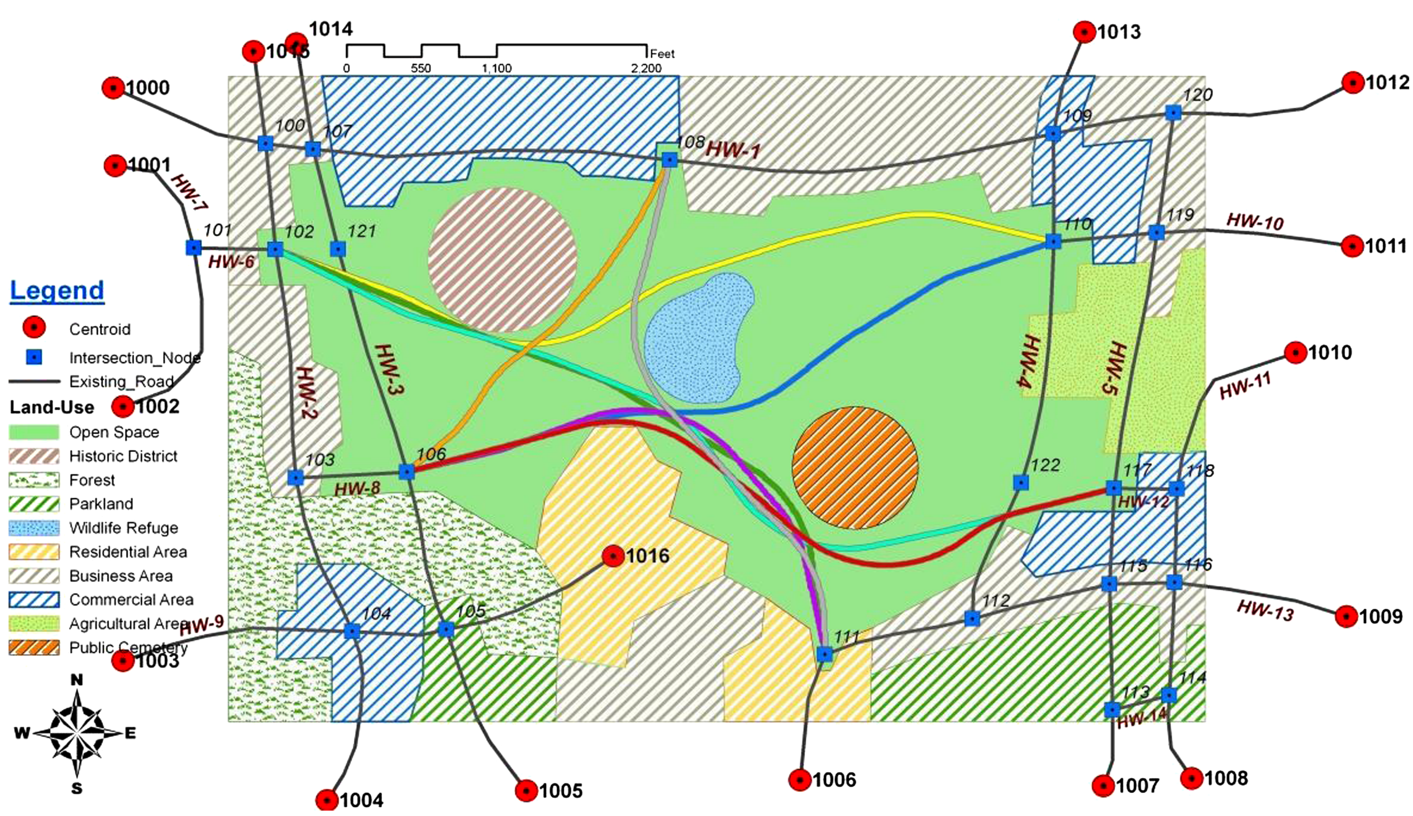



**Fig. 5.** Selected optimized highway alternatives

**Table 4.** Key Input Parameters and Base Year Origin/Destination Trip Matrix

| Input variable | Value | O–D | 1,000 | 1,001 | 1,002 | 1,003 | 1,004 | 1,005 | 1,006 | 1,007 | 1,008 | 1,009 | 1,010 | 1,011 | 1,012 | 1,013 | 1,014 | 1,015 | 1,016 | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Road width | 64 ft | 1,000 | 0 | 20 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 55 | 55 | 55 | 2,000 | 55 | 25 | 25 | 25 | 2,560 |
| Land width | 12 ft/lane | 1,001 | 25 | 0 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 25 | 25 | 25 | 620 |
| Shoulder width | 8 ft/shoulder | 1,002 | 25 | 25 | 0 | 20 | 20 | 20 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 25 | 25 | 25 | 625 |
| Design speed | 55 mph | 1,003 | 25 | 25 | 25 | 0 | 20 | 20 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 25 | 25 | 25 | 630 |
| Max. superelevation rate | 6% | 1,004 | 25 | 25 | 25 | 25 | 0 | 20 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 25 | 25 | 25 | 635 |
| Max. allowable grade | 6% | 1,005 | 25 | 25 | 25 | 25 | 25 | 0 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 25 | 25 | 25 | 640 |
| Coefficient of side friction | 0.12 | 1,006 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 635 |
| Longitudinal friction of coefficient | 0.28 | 1,007 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 670 |
| Fill/cut slope | 0.4,0.5 | 1,008 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 705 |
| Unit fill/cut cost | $20, 35/yd^3 | 1,009 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 20 | 20 | 55 | 55 | 55 | 740 |
| Earth shrinkage factor | 0.9 | 1,010 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 20 | 55 | 55 | 55 | 775 |
| Terrain height ranges | $100/ft | 1,011 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 55 | 55 | 55 | 810 |
| Unit land value in the study area | 418 ~ 522 ft | 1,012 | 2,000 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 0 | 55 | 55 | 55 | 2,770 |
| Cross structure with existing road | $0.01–$42/ft^2 | 1,013 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 55 | 55 | 55 | 880 |
| Annual traffic growth rate | 3% | 1,014 | 25 | 25 | 25 | 25 | 25 | 25 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 20 | 20 | 630 |
| Annual interest rate | 3% | 1,015 | 25 | 25 | 25 | 25 | 25 | 25 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 0 | 645 |
| Analysis period | 5 yr | 1,016 | 25 | 25 | 25 | 25 | 25 | 25 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 0 | 700 |
| | Sum | | 2,585 | 635 | 630 | 625 | 620 | 615 | 880 | 845 | 810 | 775 | 740 | 705 | 2,615 | 615 | 700 | 665 | 610 | 1,5670 |

Note: Data from Kang et al. 2010.

assignment procedure developed by Kang et al. (2010) is adapted to determine whether the tri-level optimization feature is needed during the alignment search process. "The preprocessed traffic assignment is intended to accelerate the alignment evaluation procedure, and enhance the model's computational efficiency accordingly" (Kang et al. 2010).

## Example Problem for the Tri-Level Approach

This section presents an example study to demonstrate the performance of the proposed tri-level highway alignment optimization method. A similar example performed by the second and third authors is extended to test a bi-level approach for highway alignment optimization that was previously published (see Kang et al. 2010). Therefore, except for environmental emission, all test case data are the same as those presented in Kang et al. (2010). Fig. 5 shows the land-use of the study area in which construction of a new highway is being considered to relieve the congestion in the existing highway system. The next section briefly describes land-use information and existing traffic conditions of the study area. Table 4 shows the key input parameters.

The situation description presents the hypothetical scenario of a new highway construction to alleviate traffic congestion in the study area. Currently, *HW-1* is the only access control link connecting east–west traffic in the study area and is operating at or near capacity during peak periods, causing severe traffic congestion. Furthermore, the number of trips within the study area is expected to increase in the near future as a result of new community developments. Thus, a local government is planning to construct a new highway to improve the level of service of the existing road, *HW-1*, and to reduce users' travel time between traffic endpoints (i.e., centroids represented by red dots in Fig. 5).

Table 4 presents key input parameters and the base year traffic information used for this case study. The baseline design standards of the new highway are a four-lane undivided highway with a 20-m cross-section (3.6 m for lanes and 2.8 m for shoulders), a 90-km/h design speed, 6% maximum allowable gradient, 6% maximum superelevation, 289 ($= 17 \times 17$) O/D trip pairs that operate in the existing road network, and demand between east–west traffic endpoints (shaded in Table 4) that is much higher than north–south traffic demand. Annual traffic growth rate is assumed to be 3%. The new highway should be constructed in an environmentally responsible manner because various socio-economic and environmentally sensitive areas (e.g., residential area, commercial area, historic district, and wildlife refuge) are mixed in the study area. Given all of these considerations, the objective of the local government for the new highway project is noted as follows:

- Should connect the existing and planned development areas and must be an economical path that minimizes the highway agency cost;
- Should relieve congestion on existing highways in the study area (that is, minimize total user cost);
- Should minimize the environmental effect;
- Should minimize the socio-economic effect (Kang et al. 2010); and
- Should minimize environmental emissions.

## Analysis Results

Eight highway alternatives are selected after the optimization model completes the optimization process. Each alternative is the best-obtained solution for a given pair of start and end points. Fig. 5 shows horizontal profiles of the selected highway alternatives, all of

**Table 5.** Optimized Selected Highway Alternatives

| Alternative | Node number | Length (ft) | Total agency cost | Total user cost | Penalty cost | Link flow (vehicle/h)[a] | Emissions (gm/h) |
|---|---|---|---|---|---|---|---|
| Alt-1 | 102, 110 | 6,079 | 39.0 | −567.1 | 0 | 7,955 (0.99) | 2.38 |
| Alt-2 | 102, 111 | 5,451 | 63.1 | −571.7 | 0 | 7,892 (0.99) | 1.06 |
| Alt-3 | 102, 117 | 6,907 | 39.4 | −568.0 | 0 | 6,898 (0.86) | 1.69 |
| Alt-4 | 106, 108 | 3,080 | 39.0 | −267.4 | 0 | 3,204 (0.40) | 0.41 |
| Alt-5 | 106, 110 | 5,147 | 40.2 | −570.3 | 0 | 3,574 (0.45) | 0.44 |
| Alt-6 | 106, 111 | 4,263 | 63.3 | −569.4 | 0 | 4,502 (0.56) | 0.45 |
| Alt-7 | 106, 117 | 5,854 | 39.6 | −569.2 | 0 | 4,193 (0.52) | 1.92 |
| Alt-8 | 108, 111 | 4,246 | 62.6 | −293.3 | 0 | 4,502 (0.56) | 0.49 |

[a]Value in parenthesis is the volume to capacity ratio.



which fully avoid the restricted areas (for example, wildlife refugee, residential areas, and public cemeteries) located in the middle of the study area and, thus, do not have any environmental and socio-economic effects (that is, no penalty cost).

Among the alternatives, highway designers would rule out Alt-2, Alt-6, and Alt-8 if the project budget is limited to $45 million. Alt-8 is the worst option among the selected alternatives because it requires almost the entire highest agency cost and saves less user cost compared with the other alternatives. Alt-4 requires the lowest agency cost and, thus, is the best alternative if user cost is not included in the evaluation criteria. However, Alt-4 is also ruled out because it does not significantly improve existing traffic operations (that is, the lowest user cost savings). Thus, Alt-1, Alt-3, Alt-5, and Alt-7 are preferable options because their agency costs are within the project's budget and their user costs are significantly lower than that of the other alternatives. Table 5 shows the equilibrium link flows operating on both the existing and new highways before and after the implementation of the new highways. The results demonstrate that highway alignment has a significant effect on equilibrium link flows, particularly in terms of distance and intersection points (that is, whether it connects within the network). Table 5 also shows that Alt-1 and Alt-3 should be excluded from the preferable alternative set (that is, Alt-1, Alt-3, Alt-5, and Alt-7) because some existing highways (for example, *HW-3*, *HW-4*, and *HW-5*) may operate slightly over the capacity if these alternatives are implemented.

Fig. 6 presents the equilibrium link flows on the existing highway and new highways. The results show that highway alignments have a significant effect on equilibrium flows. HW-5 and HW-1 have the highest and lowest flows, respectively, among all of the alternatives. Alt-1 and Alt-3 should not be considered preferable because some existing highways such as HW-3, HW-4, and HW-5 may operate over capacity. Alt-5 appears to be the best alternative because it provides reasonable volume with the least objective function.

Fig. 7 shows the emission levels on the existing highway and the new highways. Emission is shown in grams per hour for all alternatives and corresponding links. HW-5 has the highest emissions for all alternatives compared. Similarly, HW-1 has the lowest emissions. From an emission viewpoint, Alt-5 appears to be the best alternative because it provides a least objective function value. Among the alternatives, Alt-3 produces the highest emission and may not be considered preferable. This observation is consistent with the flow estimates. The proposed tri-level model provides insights into emission estimates at the link level for highway alignment optimization. Such a tool is beneficial for decision making by simultaneously analyzing optimal design, traffic equilibrium, and emission objectives. A desktop PC (Intel dual core processor, 3.2 GHz with 4-gigabyte random access memory) is used to execute the alignment optimization model, and approximately six hours are needed to complete 300 generations of search. Please note that these six hours are established after multiple initial

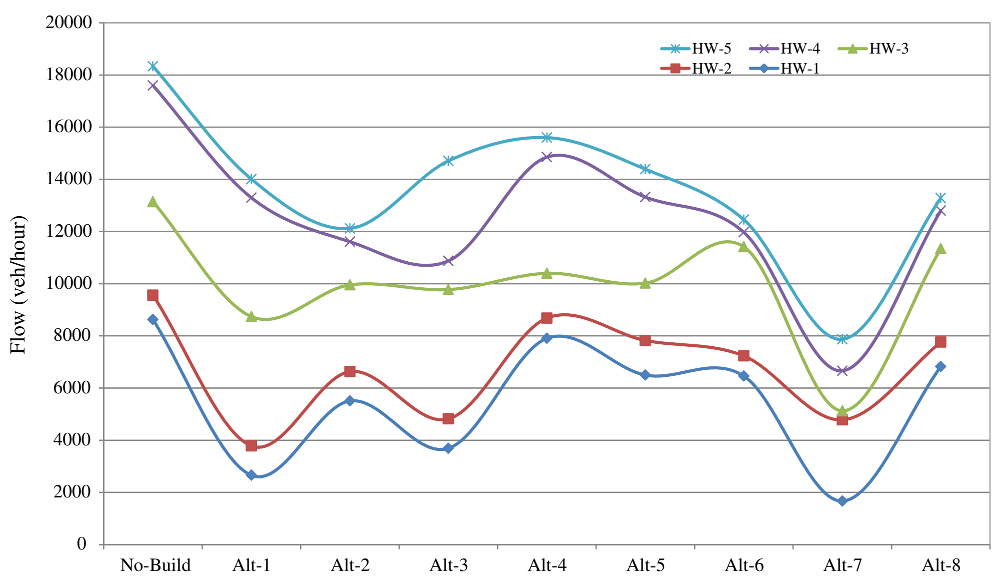



**Fig. 6.** Flow predictions on existing highways by alternatives (including no-build)

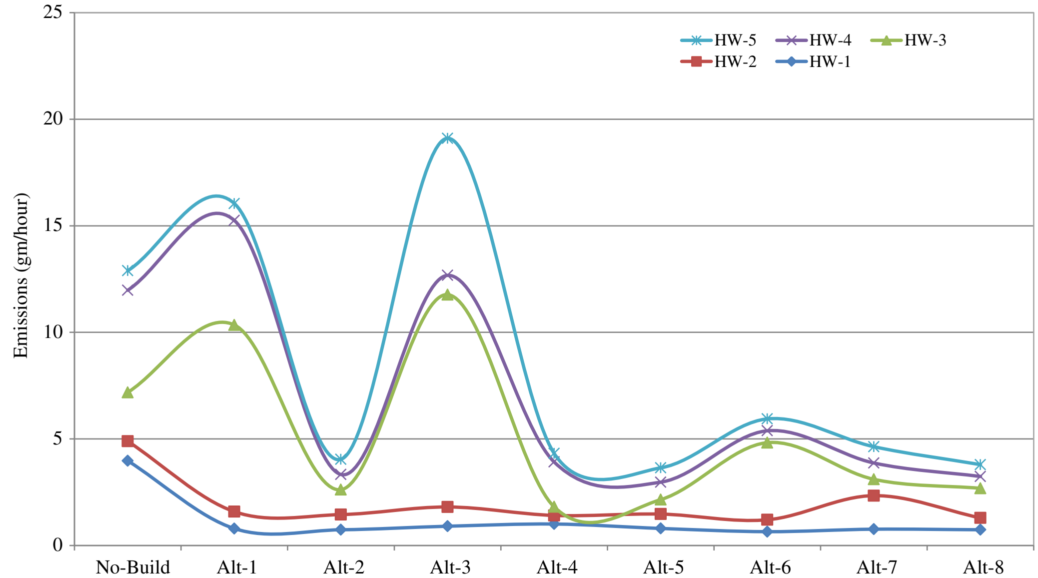



**Fig. 7.** Predicted emissions on existing highways by alternatives (including no-build)

attempts to finalize a model used in the paper. A minimum of 50 initial attempts was made to reach a model with reasonable results. To solve the upper- and intermediate-level problems, the model employs customized GAs for highway alignment optimization by Jong and Schonfeld (2003). The lower-level problem is solved using a modified Frank–Wolf algorithm. Approximately 40 alternative alignments are generated in each generation of the upper level and are sent to the lower level to find the equilibrium traffic flow of the network. The total emission is then the computed on the basis of the result from the lower level. For every generation, the individual alternative alignments compete with one another to reproduce offspring on the basis of their fitness (that is, the total cost including agency, user, and emission costs). After an adequate number of generations, the fittest individuals should survive, whereas poor solutions are discarded and the population finally converges to an optimized solution (Kang et al. 2012). The proposed tri-level optimization model is programmed in the C programming language. A termination criterion of 10-4 is used in the tri-level optimization problem, indicating that if no significant improvement exists in the objective function value during a certain number of generations, the alignment optimization process is terminated.

## Conclusions and Future Works

Emissions modeling and the selection of new highways, including their geometric design, a cost-benefit analysis, and an analysis of their effects on the existing land-use system, are very complex and challenging because of the large number of conflicting factors that must be resolved, the significant amount and variety of information that must be compiled and processed, and the numerous evaluations that must be performed. Because of the significant expense and time consumed by the process of evaluating even one candidate alternative with existing methods, typical studies are able to afford only an evaluation of very few alternative alignments.

This paper proposes a method to consider environmental emissions in the highway alignment optimization process called tri-level highway alignment optimization. In the tri-level model structure, the upper-level problem represents a decision-making process of system designers in which possible highway alternatives are generated and evaluated. At the intermediate level, emission on the networks is estimated. The lower-level problem represents highway users' route choice behavior under the designer's decision. The model optimizes the location of a new highway, including its intersection points with existing roads, and searches for the best trade-off among the various highway cost components. An equilibrium traffic assignment is incorporated in the tri-level model framework to realistically reflect the traffic effect of the new highway in the alternative evaluation process. The performance of the tri-level optimization model is demonstrated using a case study.

The results show that the model is able to find optimized solutions within reasonable computation times, and that new highway locations are sensitive to traffic distributed to the road network and to their construction costs. This finding confirms that all relevant highway cost components should be simultaneously evaluated for effective highway alignment optimization although most highway agencies in the field tend to ignore the user cost items during the planning phase for new highways. The proposed model is able to simultaneously optimize highway alignments, emissions, and route choices. The robustness of the proposed tri-level model is examined using the case study, and the framework may be used to solve medium- to large-scale city networks. Although this paper studied only $CO_2$ because it is a GHG and pollutant of immediate concern, the proposed models are generalizable and applicable to various other pollutants. Future studies may undertake various sensitivity analyses.

## Acknowledgments

The authors acknowledge Dr. James Hunter of Morgan State University and Professor Ramesh Buddharaju of MVGR College, India for their contribution of the first illustrative example. This study was jointly conducted at the Center for Advanced Transportation and Infrastructure Engineering Research-Morgan State University, University of Memphis, and the University of South Alabama.

## Notation

*The following symbols are used in this paper:*

$A$ = set of arcs in the highway network;
$C_{AB}$ = annual bridge operation cost (\$/year);
$A_k$ = area of $k$th land parcel affected by highway alignment;
$A_k^T$ = total area of $k$th land parcel;
$C_{BO}$ = bridge operating cost;
$C_E$ = earthwork cost;
$C_{HM}$ = maintenance cost for basic highway segments;
$C_L$ = length-dependent cost;
$C_M$ = maintenance cost;
$C_R$ = right-of-way cost;
$C_S$ = structures cost;
$C_T$ = travel time cost;
$C_{T\,\text{agency}}$ = agency cost;
$C_{T\,\text{user}}$ = user cost;
$C_V$ = vehicle operating cost;
$C_p$ = penalty associated with environmental and/or socio-economic areas;
$C^0_{T\_\text{User}}$ = total user costs before new highway construction;
$C^1_{T\_\text{User}}$ = total user costs after new highway construction;
$d_a$ = distance from arc $a$;
$ef_a(v_a)$ = speed-dependent emission factor for link a (gm/miles) where $v_a$ is link speed;
$f_{a\_\text{Auto}}$, $f_{a\_\text{Truck}}$ = fuel consumption of autos and trucks, and is estimated using their average travel speed on arc $a$;
$I_k^{ES}$ = vector representation of dummy variables indicating whether;
$K_{AM}$ = annual maintenance cost per unit length;
$L_a$ = length of arc $a$ in the highway network;
$L_n$ = total length of new highway alignment;
$l_a$ = length of link $a$;
$l_{BG}$ = bridge length;
$\text{Max}A_k$ = maximum allowable area of $k$th land parcel for the alignment; $0 \le \text{Max}A_k \le A_k^T$;
$m_{\text{Auto}}$, $m_{\text{Truck}}$ = maintenance cost of autos and trucks, respectively;
$n_{BG}$ = number of highway bridges;
$n_y$ = analysis period (\$/year);
$o$ = vector of average vehicle occupancy for autos and trucks;
$P_{\text{Auto}}$, $P_{\text{Truck}}$ = fuel prices for autos and trucks, respectively;
$p_a$ = rainfall intensity at location of arc $a$; $p = (\ldots, p_a, \ldots)$;
$T$ = traffic composition vector;
$TE$ = total systems emission;
$T_{\text{Truck}}$ = fraction of trucks;
$t_a$ = travel time on arc $a$;
$u$ = $(\ldots, u_a, \ldots)$;
$u_a$ = land use at location of arc $a$;
$uf_a$ = vector of unit vehicle operating cost for autos and trucks on arc $a$;
$\mathbf{v}$ = vector of unit travel time values for auto and truck users;
$v_a$ = link speed;
$x_a$ = average traffic volume;
$x_a$ = vector equilibrium link flows;
$Z_{UL}$ = sum of total agency cost, total user cost, and penalty cost;
$\rho$ = assumed interest rate (decimal fraction); and
$\cdot$ = inner (dot) product.

## References


AASHTO. (2004). *A policy on geometric design of highways and streets*, AASHTO, Washington, DC.

Chen, A., and Yang, C. (2004). "Stochastic transportation network design problem with spatial equity constraint." *Transp. Res. Rec.*, 1882(1), 97–104.

Cheng, J. F., and Lee, Y. (2006). "Model for three-dimensional highway alignment." *J. Transp. Eng.*, 10.1061/(ASCE)0733-947X(2006)132:12(913), 913–920.

El-Shawarby, I., Ahn, K., and Rakha, H. (2005). "Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions." *Transp. Res. Part D*, 10(1), 13–30.

Fwa, T. F., Chan, W. T., and Sim, Y. P. (2002). "Optimal vertical alignment analysis for highway design." *J. Transp. Eng.*, 10.1061/(ASCE)0733-947X(2002)128:5(395), 395–402.

Gao, Z., Wu, J., and Sun, H. (2005). "Solution algorithm for the bi-level discrete network design problem." *Transp. Res. B*, 39(6), 479–495.

Jha, M. K. (2003). "Criteria-based decision support system for selecting highway alignments." *J. Transp. Eng.*, 10.1061/(ASCE)0733-947X(2003)129:1(33), 33–41.

Jha, M. K., and Kang, M.-W. (2009). "A GIS-based model for highway noise analysis." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2009)15:2(88), 88–94.

Jha, M. K., and Kim, E. (2006). "Highway route optimization based on accessibility, proximity, and land-use changes." *J. Transp. Eng.*, 10.1061/(ASCE)0733-947X(2006)132:5(435), 435–439.

Jha, M. K., Namdeo, A., Shiva Nagendra, S. M., and Li, J. (2011). "Investigating the relative impacts of travel-time delay and vehicular emission on road user choice behavior: Case studies from US, UK, and India." *Proc. 1st Conf. of Transportation Research Group of India*, Bangalore, India.

Jha, M. K., and Schonfeld, P. (2000). "Geographic information system-based analysis of right-of-way cost for highway optimization." *Transp. Res. Rec.*, 1719(1), 241–249.

Jha, M. K., and Schonfeld, P. (2003). "Trade-offs between initial and maintenance costs of highways in cross-slopes." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2003)9:1(16), 16–25.

Jha, M. K., and Schonfeld, P. (2004). "A highway alignment optimization model using geographic information systems." *Transp. Res. A*, 38(6), 455–481.

Jha, M. K., Schonfeld, P., Jong, J.-C., and Kim, E. (2006). *Intelligent road design*, WIT Press, Boston, MA.

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. (2003). "An evolutionary model for simultaneously optimizing three-dimensional highway alignments." *Transp. Res. B*, 37(2), 107–128.

Kang, M.-W. (2008). "An alignment optimization model for a simple highway network." Ph.D. thesis, Univ. of Maryland, College Park, MD.

Kang, M.-W., Jha, M. K., and Schonfeld, P. (2012). "Applicability of highway alignment optimization models." *Transp. Res. Part C*, 21(1), 257–286.

Kang, M.-W., Schonfeld, P., and Jong, J.-C. (2007). "Highway alignment optimization through feasible gates." *J. Adv. Transp.*, 41(2), 115–144.

Kang, M.-W., Schonfeld, P., and Yang, N. (2009). "Prescreening and repairing in a genetic algorithm for highway alignment optimization." *Comput. Aided Civ. Infrastruct. Eng.*, 24(2), 109–119.

Kang, M.-W., Yang, N., Schonfeld, P., and Jha, M. K. (2010). "Bilevel highway route optimization." *Transp. Res. Rec. J. Transp. Res. Board*, 2197(1), 107–117.

Kim, E., Jha, M. K., Lovell, D. J., and Schonfeld, P. (2004). "Intersection cost modeling for highway alignment optimization." *Comput. Aided Civ. Infrastruct. Eng.*, 19(2), 136–146.

Lee, Y., Tsou, Y.-R., and Liu, H.-L. (2009). "Optimization method for highway horizontal alignment design." *J. Transp. Eng.*, 10.1061/(ASCE)0733-947X(2009)135:4(217), 217–224.

Maji, S., and Jha, M. K. (2011). "Highway alignment optimization using cost-benefit analysis under user equilibrium." *Int. J. Oper. Res. Inform. Syst.*, 2(4), 19–33.

Mishra, S., and Welch, T. (2012). "A joint travel demand and environmental model to incorporate emission pricing for large transportation networks." *Transp. Res. Rec. J. Transp. Res. Board*, 2302(1), 29–42.

Sharma, S., and Mishra, S. (2013). "ITS enabled optimal emission pricing models for reducing carbon footprints in a bi-modal network." *J. Intell. Transp. Syst.*, 17(1), 54–64.

Sheffi, Y. (1985). *Urban transportation networks: Equilibrium analysis with mathematical programming methods*, Prentice-Hall, Englewood Cliffs, NJ.

Steenbrink, A. (1974). "Transport network optimization in the Dutch integral transportation study." *Transp. Res.*, 8(1), 11–27.

Trietsch, D. (1987). "A family of methods for preliminary highway alignment." *Transp. Sci.*, 21(1), 17–25.

Wardrop, J. (1952). "Some theoretical aspects of road traffic research." *Proc. ICE Eng. Div.*, 1(3), 325–362.