A Tri-Level Model with Environmental Considerations in Highway Alignment Optimization

by

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ABSTRACT

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 will have to be simultaneously considered. In previous works, single level and bi-level optimization approaches have been 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 upon our previous works and proposes two separate approaches for considering the environmental emissions in the highway alignment optimization process. The first approach involves a separate analysis of user's and decision maker's preferences in which a conceptual formulation of various environmental factors are 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 while considering environmental emissions. Additional refinement to the formulation and sensitivity analyses can be undertaken in future works.

***Key-words**: highway alignment optimization, bi-level optimization, tri-level optimization, highway cost, user cost, environmental emission.*

INTRODUCTION

Road alignment optimization problem is to find the most economical road alternative connecting two given end points based on topography, soil conditions, socioeconomic factors and environmental impacts, while satisfying a set of design and operational constraints. Because of the complexity of this problem, in traditional road alignment optimization various alternatives need to be evaluated in order to determine the most promising one. Since the number of alternatives connecting two given end points 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 much research interest over the past three decades.

Many studies (*1-12)* have 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 geometric design of highways. Very few studies (*13*, *14*) have considered the impact of new road on Level of Service (LOS) of the original road network. But actually, as for the new road, it is not only an isolated transportation facility, but also obviously a component of a road network. Thus, it is valuable that the effect of new road on original road network can be considered in road alignment optimization.

Various mathematical methods, such as dynamic programming, numerical search, and linear programming have been employed to solve network optimization in earlier literature. Most methods are devoted to optimizing either the horizontal alignment or the vertical alignment. However, along with the rapid development of computer and information technology, Geographic Information System (GIS) and digital spatial data have been widely applied recently. Many new methods based on GIS have been put forward. Jong and Schonfeld (*5*) have developed an evolutionary model for simultaneously optimizing three-dimensional highway alignments. The model emphasizes the application and realization of Genetic Algorithm (GA) in highway alignment optimization. Jha (*15*) developed a criteria-based decision support system based on GIS for selecting highway alignments. In addition, Jha and Schonfeld (*6*) have developed an alignment optimization model based on GIS and GA. In general, the characteristics of recent studies are listed as follows: (1) The models are developed based on a GIS; (2) The models employ GA as a solution method; (3) The models emphasize to optimize simultaneously three-dimensional road alignment; (4) In the selection process, a number of factors, such as user costs (cost of vehicle operation, travel time cost, accident cost, etc.), supplier costs (earthwork cost, construction cost, etc.) 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. We find no previous model that jointly evaluates traffic and environmental impacts of the new highway as well as optimizes highway location, construction cost, and horizontal and vertical profiles. This study integrates all these factors in optimizing highway alignments. Finding new highways that best improve an existing roadway system can be 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 can freely choose their paths are the followers. In this process the system designers can influence but not control the route choice behavior of highway users. The system designers try to find an economical path that minimizes the total construction cost, while considering geometric design and geographical constraints. However, the traffic flow is determined by user decisions which can be approximated by the user equilibrium principle. To realistically represent such characteristics in the highway route optimization process, a recent paper by the authors (*13*) proposed a bi-level optimization method. In that method, the user preferences were separated from the traditional cost minimization problem.

Since the environmental consideration is a key to planning and designing highways, this paper offers a significant departure from previous methods of considering environmental sensitivities. In previous methods, a user defined penalty was imposed (*6*) to keep the candidate alignments from crossing through environmentally sensitive regions. The recurring environmental pollutions, such as noise and air pollution were not comprehensively formulated and considered in the optimization process.

METHODOLOGY

Separate Analysis of User and Decision Maker to Incorporate Environmental Emission in Highway Alignment Optimization

The idea of considering environmental emission due to vehicular traffic in the highway alignment optimization process was realized by the second and third authors in some of their recent preliminary works (see for example, *16*). One approach is to present a modified equilibrium traffic assignment model which minimizes air, noise and water pollutants derived from Vehicular traffic and its surroundings. The conceptual formulation of the proposed assignment model can be expressed as:

$$Minimize\ Z = \begin{cases} \sum_a \int_0^{x_a} t_a(x_a)dx_a & for\ User\ Optimum\ based\ on\ Travel\ Time \text{ (case 1)} \\ \sum_a c_a(x_a, u_a, l_a, d_a, w_a, r_a) & for\ Decision\ Maker\ Objective\ based\ on\ Cost \text{ (case 2)} \end{cases} \quad (1)$$

where

$c_a(x_a, u_a, l_a, d_a, w_a, r_a) = Air\ pollution + Noise\ pollution + Water\ pollution + Travel\ time\ cost$
$A = Arc(index) set\ of\ a\ givern\ highway\ network; a \in \boldsymbol{A}$
$x_a = Flow\ on\ arc\ a; \mathbf{x} = (\cdots, x_a, \cdots)$
$t_a = Travel\ time\ on\ arc\ a; \mathbf{t} = (\cdots, t_a, \cdots)$
$u_a = Land - use\ where\ arc\ a\ is\ located; \mathbf{u} = (\cdots, u_a, \cdots)$
$l_a = Lenth\ of\ arc\ a; \mathbf{l} = (\cdots, l_a, \cdots)$
$w_a = Width\ of\ arc\ a; \mathbf{w} = (\cdots, w_a, \cdots)$
$d_a = Distance\ from\ arc\ a;$
$p_a = Rainfall\ intensity\ where\ arc\ a\ is\ located; \mathbf{p} = (\cdots, p_a, \cdots)$

In Eq. (1), the decision maker's scenario minimizes the impact of air, noise, and water pollution, in addition to user travel-time. An illustrative example is presented below to further explain the approach.

An Illustrative Example

An example study area (Figure 1) is created in which a new highway is evaluated based on the combined impact of various pollutions outlined above, in conjunction with the traditional travel-time minimization objective. It is noted that residential, commercial, and business and industrial land-use areas have more impervious surfaces (i.e., paved surfaces) and therefore percolation is almost negligible resulting in higher runoff. Therefore, Water pollution is high in such areas. As far as noise impact is concerned, higher the degree of urbanization, higher the noise pollution because of sound barriers and reflection of sound waves. Also, concentration of carbon monoxide and other poisonous gases is higher in highly urbanized areas because the dissipation rate of these harmful gases into atmosphere is slower.

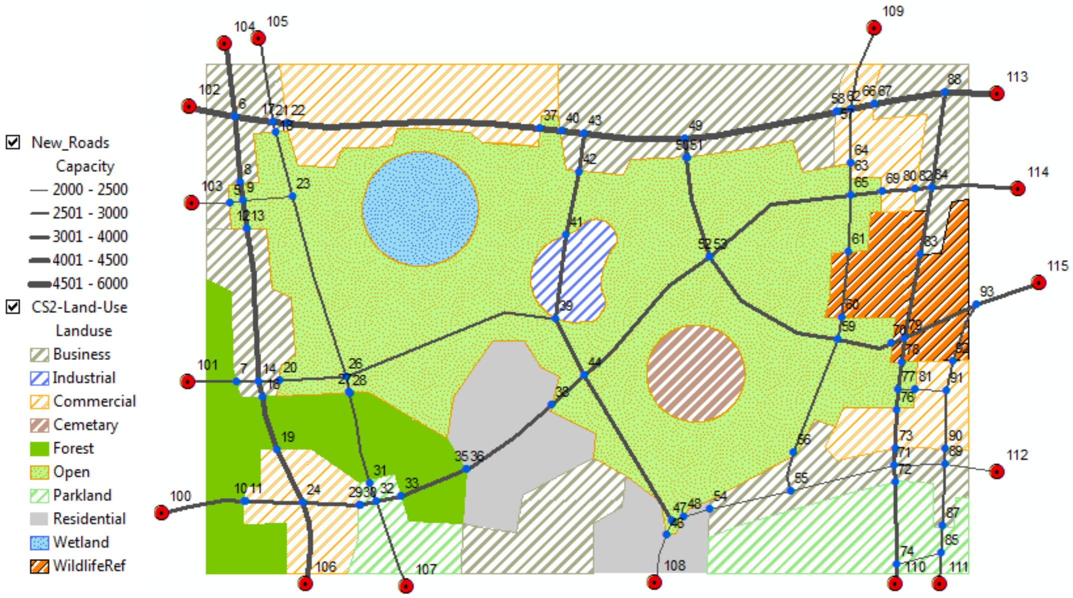


FIGURE 1 Example Study Area

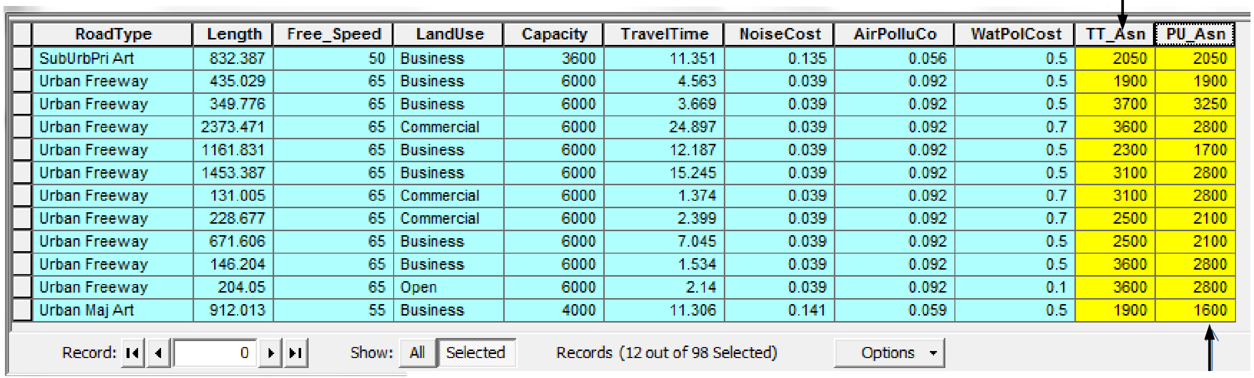
The origin-destination (O-D) matrix for the example is shown in Figure 1. We have considered a symmetric O-D Matrix for simple illustration of our approach. A genetic algorithm previously designed for the bi-level highway alignment optimization problem by the second and third authors (*13*) have been applied to find the equilibrium solution using user and decision maker's preference. The algorithm is designed to work in a GIS environment. The results of the analysis are shown in Figure 2 and Table 2.

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	
100	0	40	35	10	75	60	85	45	30	60	55	20	40	65	185	40	**850**
101	40	0	15	20	110	15	65	40	30	45	50	20	30	70	105	90	**750**
102	35	15	0	15	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	**650**
104	75	110	50	100	0	10	100	55	80	40	100	85	75	120	75	125	**1200**
105	60	15	30	15	10	0	105	50	100	35	80	70	85	65	60	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	**1050**
114	185	105	35	55	75	80	55	55	55	60	40	65	20	100	0	35	**1000**
115	40	90	120	45	125	70	30	10	50	65	90	70	25	130	35	0	**995**
	850	**750**	**950**	**650**	**1200**	**850**	**775**	**375**	**600**	**700**	**850**	**700**	**600**	**1050**	**1000**	**995**	**12895**

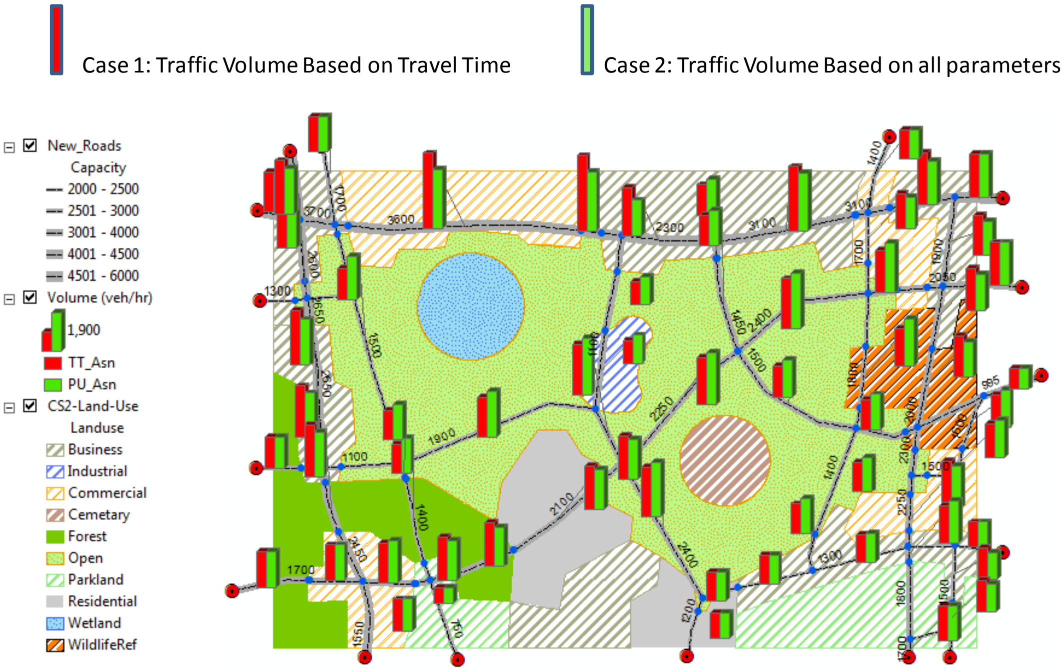
TABLE 2 Case Study Results

Traffic assignment result (volume) based only on travel time (Case 1)



RoadType	Length	Free_Speed	LandUse	Capacity	TravelTime	NoiseCost	AirPolluCo	WatPolCost	TT_Asn	PU_Asn
SubUrbPri Art	832.387	50	Business	3600	11.351	0.135	0.056	0.5	2050	2050
Urban Freeway	435.029	65	Business	6000	4.563	0.039	0.092	0.5	1900	1900
Urban Freeway	349.776	65	Business	6000	3.669	0.039	0.092	0.5	3700	3250
Urban Freeway	2373.471	65	Commercial	6000	24.897	0.039	0.092	0.7	3600	2800
Urban Freeway	1161.831	65	Business	6000	12.187	0.039	0.092	0.5	2300	1700
Urban Freeway	1453.387	65	Business	6000	15.245	0.039	0.092	0.5	3100	2800
Urban Freeway	131.005	65	Commercial	6000	1.374	0.039	0.092	0.7	3100	2800
Urban Freeway	228.677	65	Commercial	6000	2.399	0.039	0.092	0.7	2500	2100
Urban Freeway	671.606	65	Business	6000	7.045	0.039	0.092	0.5	2500	2100
Urban Freeway	146.204	65	Business	6000	1.534	0.039	0.092	0.5	3600	2800
Urban Freeway	204.05	65	Open	6000	2.14	0.039	0.092	0.1	3600	2800
Urban Maj Art	912.013	55	Business	4000	11.306	0.141	0.059	0.5	1900	1600

Traffic assignment result (volume) based on all parameters (Case 2)

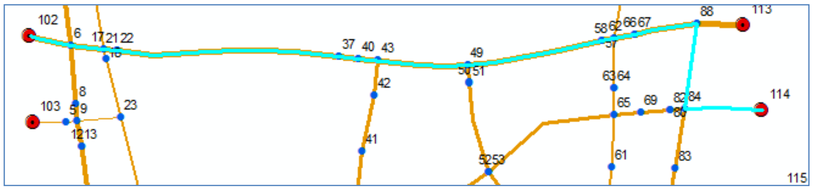


Result of the case study:

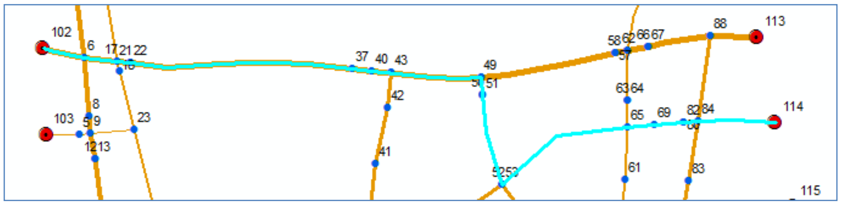
- The number of vehicle-miles increased by about 7.7%.
- The pollution cost reduced by about 8.4%
- Total Savings in Pollution Cost = $1054 per hour.

FIGURE 2 Case Study Results

Case 1: Total Travel Time = 97.71 Sec & Total Pollution Cost = US$ 2,795.51



Case 2: Total Travel Time = 105.89 Sec & Total Pollution Cost = US$ 2,563.51



Total Travel Time Increase = 7.73% & Total Pollution Cost Decrease = 8.3%

FIGURE 3 Variation in Total Travel Time and Total Pollution Cost due to User and Decision Maker's Preferences

In Figure 3, there are 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 based on minimum travel time) algorithm. The green bars indicate the traffic volumes assigned using the minimal pollution method (our algorithm). It can be seen that, in areas where pollution is higher, red bars are taller and in areas where pollution is lower, green bars are taller. Our algorithm assigns more traffic on links which have lower pollution costs (Table 2). Figure 3 shows travel paths between specified end points resulting from separate analyses of user optimum (Case 1: minimizing travel time only) and decision maker's cost (Case 2: minimizing travel time plus environmental pollution) formula. It can be seen that while 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, especially in the areas of highway planning process, congestion pricing, and establishing varying tolling strategies based on the combined impacts of recurring pollution and traffic congestion.

TABLE 3 Key Differences between Three Model Types

Functionality	**Characteristics**	**Network Design Problem**	**Highway Alignment Optimization**	**Highway Alignment Optimization with Environmental Impacts**
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 (e.g., design speeds, maximum grades, and cut/fill slopes)	√	√	√
	Spatial Information (e.g., land-use and topography)		√	√
	Link speed		√	√*
	Emission Profiles			√*
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			√*
Advantage	Reflects drivers route choice behavior	√	√	√
	Evaluate highway alignments		√	√
	Reflects construction cost in evaluation		√	√
	Estimate emission as one objective			√*
Disadvantage	Cannot consider actual highway cost and constraints associated road construction	√		
	Cannot generate different highway alternatives	√		
	Cannot estimate emissions	√	√	
	Longer computational time	√	√	√

* Represents advantages of Highway Alignment Optimization with Environmental Impacts over others.

The Tri-Level Approach

In this section, we introduce a novel tri-level optimization framework by separating the environmental considerations out from the traditional 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 below 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 which optimizes only highway construction costs; furthermore, it can provide a much wider scope of objectives regarding various user costs including travel time, vehicle operation, and accidents costs.

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 based on a specified objective function (*13* and *17*). In the first level, optimal highway alignment is determined subjected to highway design, environmental and geographical constraints. In the second level, total system emission is minimized considering available speed profiles of highway alignments. In the third level, user equilibrium traffic flow is obtained by minimizing the composite cost. The tri-level model formulation is shown in Eqs. (2) to (10). All notations are presented in Table 4.

Upper Level

Objective: Determine Optimized Highway Alignments

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

Subject to:

1. Highway Design Constraints
2. Environmental and geographical constraints

Intermediate Level

Objective: Minimize Total Systems Emission

Minimize: $TE = \sum_{\boldsymbol{a}} (x_a e f_a(v_a) l_a)$ (3)

Subject to:

$0 \le e_a \le 1$ (4)

Lower Level

Objective: Determine user equilibrium traffic flow by minimizing the composite cost

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

Subject to:

$\sum_{\forall k} f_k^{rs} = q^{rs}$ (6)

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

$f_k^{rs} \ge 0$ (8)

$x_a \ge 0$ (9)

$k \in K;\ a \in A\ ;\ r, s \in \Omega$ (10)

The Upper Level Problem

Three types of decision variables are used in the tri-level model structure: (i) points of intersection (PI's) of new highway alignments; (ii) amount of total systems emission, and (iii) 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 (i.e., PI coordinates) are indirectly formulated in the upper-level objective function, similar to our previous approaches (*3*). To solve the upper-level problem, a genetic algorithm (GA) with customized genetic operators (*5*) is employed in the model. The GA aims to generate the PI's of new highways, and ultimately finds optimized ones through an evaluation procedure based on 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 (*13*), the objective function (Z_{UL}) is defined as the sum of (i) the total agency cost, (ii) the total user cost, and (iii) the "penalty cost." *(13)*

TABLE 4 Notations and their Explanation

Notation		Explanation
Z_{UL}	:	Sum of the total agency cost, the total user cost, and the penalty cost.
$C_{T\ agency}$	:	Agency cost
$C_{T\ user}$	:	User Cost
C_P	:	Penalty associated with environmental and socio-economic areas
TE	:	Total Systems Emission
x_a	:	Vector equilibrium link flows
$ef_a(v_a)$	:	The speed dependent emission factor for link "a" (gm/miles) where v_a is link speed.
v_a	:	Link speed
l_a	:	Length of link a
C_L	:	Length-dependent cost
C_R	:	Right-of-way cost
C_E	:	Earthwork cost
C_S	:	Structures cost
C_M	:	Maintenance cost
C_{HM}	:	Maintenance cost for highway basic segments
C_{BO}	:	Bridge operating cost
L_n	:	Total length of a new highway alignment
l_{BG}	:	Bridge length
n_{BG}	:	Number of highway bridges
K_{AM}		Annual maintenance cost per unit length
ρ	:	Assumed interest rate (decimal fraction)
n_y	:	Analysis period (\$/yr)
C_{AB}	:	Annual bridge operation cost (\$/yr)
$C^0_{T\_User}$	:	Total user costs before new highway construction
$C^1_{T\_User}$	:	Total user costs after new highway construction
C_T	:	Travel time cost
C_V	:	Vehicle operating cost
x_a	:	Average traffic volume
t_a	:	Travel time on arc a
A	:	A set of arcs in the highway network
$\boldsymbol{v}$	:	A vector of unit travel time values for auto and truck users
T	:	Traffic composition vector
o	:	A vector of average vehicle occupancy for auto and truck
$\bullet$	:	Inner (dot) product
T_{Truck}	:	Fraction of trucks
uf_a	:	A vector of unit vehicle operating cost for auto and truck on arc a
$\boldsymbol{L}_a$	:	Length of arc a in the highway network
$\boldsymbol{P}_{Auto}, \boldsymbol{P}_{Truck}$	:	Fuel prices of auto and truck, respectively
f_{a_Auto}, f_{a_Truck}	:	Fuel consumption of auto and truck, and can be estimated with their average travel speed on arc a
m_{Auto}, m_{Truck}	:	Maintenance cost of auto and truck, respectively
C_p	:	Penalty associated with environmental and/or socio-economic areas
A_k	:	Area of kth land parcel affected by highway alignment
A_k^T	:	Total area of the kth land parcel
$MaxA_k$	:	Maximum allowable area of kth land parcel for the alignment; $0 \leq \text{Max } A_k \leq A_k^T$
I_k^{ES}	:	Vector representation of dummy variables indicating whether
p_a	:	Rainfall intensity where arc a is located; $p = (\ldots, p_a, \ldots)$
d_a	:	Distance from arc a
u_a	:	Land-use where arc a is located; $u = (\ldots, u_a, \ldots)$

Agency Cost: The 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), structure cost (C_S)) directly required at the initial stage of a new highway development and a maintenance cost (C_M) occurring throughout the life of the road alignment. All of these cost components are important and sensitive to highway alignments, and should be simultaneously evaluated in the highway alignment optimization process. The basic formulation of the total agency cost can be expressed as:

$$C_{T\_Agency} = C_L + C_R + C_E + C_S + C_M \tag{11}$$

where: C_L, C_R, C_E, C_S, C_M = Length-dependent cost, right-of-way cost, earthwork cost, structures cost, maintenance cost, respectively.

The mathematical formulations of these agency cost components in Eq. (11) may be found in the authors' earlier publication (*10, 13*, and *18-21*) and thus have been skipped in this paper.

User Cost: The user cost consists of cost of vehicle operation, travel-time delay cost, and accident cost which are well formulated in our previous works (*5, 6, 13*, and *17*). Note that the proposed tri-level highway alignment optimization model is designed with a modular structure in which various evaluation components can be easily replaced without changing the rest of the model structure. Thus, any available accident prediction relations or models can be incorporated in the model for estimating the accident frequency of new highways.

The Intermediate Level Problem

In the intermediate level, total system emission is computed based on traffic flow and speed obtained from the lower level. The total emission 'TE_e' is the sum of product of traffic flow 'x_a' and emission factor '$ef_a(v_a)$' as 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 change in travel cost and hence variation in the flows throughout the network. The real value variable 'e_a' is chosen such that it is within the value of 1 (i.e. maximum increase in travel cost is 100%) and 0 (i.e. no emission pricing at all). The change in flows because of emission further causes changes in travel time which varies the average speed on the link and further emission factor and hence total emissions.

The emission function $ef_a(v_a)$ typically 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 are the coefficients to be calibrated from the observed vehicular emission data.

In this paper we consider the pollutant as CO_2, a major green house gas (GHG) and adopt a polynomial function from (*22*). The reason for considering only one pollutant is present focus of agencies and policy makers on minimizing the GHGs from vehicles.

The Lower-Level Problem

The lower level problem is a traffic assignment process used to evaluate impact caused if a new highway is 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 (*13*). 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 based on Wardrop's first principle is proposed, which denotes that "no user can experience a lower travel time by unilaterally changing routes" (*23*). In simple terms the equilibrium is achieved when the travel cost on all used paths is equal. The travel time function $t_a(.)$ is specific to a given link 'a' and the most widely used model is 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 $t_a(.)$ is free flow time on link 'a', and α_a and β_a are 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 to travel time into travel cost such that φ is value of time in monetary terms ($/hr).

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

The constraint shown in the lower level formulation (Eqs. (6) to (10)) 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.

Determination of Traffic Re-assignment

It should be noted that the tri-level optimization approach may not be efficient in cases when 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 assignment procedure developed by Kang et al. (*13*) is adapted here 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." (*13*)

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. It is an extension of a similar example performed by the second and third authors to test a bi-level approach for highway alignment optimization that has been previously published in (*13*). Therefore, except the environmental emission all test case data are the same as those presented in (*13*). Figure 4 shows the land-use of the study area in which construction of a new highway is being considered for relieving the congestion in the existing highway system. Land-use information and existing traffic condition of the study area are briefly described in the next section. Table 5 shows the key input parameters.

TABLE 5 Key Input Parameters and Base Year O/D Trip Matrix (*13*)

Input Variable	Value	O/D	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	Sum
Road Width	64 feet	1000	0	20	20	20	20	20	55	55	55	55	55	55	2000	55	25	25	25	2560
Land width	12 ft/lane	1001	25	0	20	20	20	20	55	55	55	55	55	55	55	55	25	25	25	620
Shoulder width	8ft/shoulder	1002	25	25	0	20	20	20	55	55	55	55	55	55	55	55	25	25	25	625
Design speed	55mph	1003	25	25	25	0	20	20	55	55	55	55	55	55	55	55	25	25	25	630
Max. superelevation rate	6%	1004	25	25	25	25	0	20	55	55	55	55	55	55	55	55	25	25	25	635
Max. allowable grade	6%	1005	25	25	25	25	25	0	55	55	55	55	55	55	55	55	25	25	25	640
Coefficient of side friction	0.12	1006	55	55	55	55	55	55	0	20	20	20	20	20	20	20	55	55	55	635
Longitudinal friction of coefficient	0.28	1007	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	1008	55	55	55	55	55	55	55	55	0	20	20	20	20	20	55	55	55	705
Unit fill/cut cost	$20, 35/yd3	1009	55	55	55	55	55	55	55	55	55	0	20	20	20	20	55	55	55	740
Earth shrinkage factor	0.9	1010	55	55	55	55	55	55	55	55	55	55	0	20	20	20	55	55	55	775
Terrain height ranges	$100/feet	1011	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	1012	2000	55	55	55	55	55	55	55	55	55	55	55	0	0	55	55	55	2770
Cross structure with existing road	$0.01-$42/ft2	1013	55	55	55	55	55	55	55	55	55	55	55	55	55	0	55	55	55	880
Annual traffic growth rate	3%	1014	25	25	25	25	25	25	55	55	55	55	55	55	55	55	0	20	20	630
Annual interest rate	3%	1015	25	25	25	25	25	25	55	55	55	55	55	55	55	55	55	0	0	645
Analysis period	5 years	1016	25	25	25	25	25	25	55	55	55	55	55	55	55	55	55	55	0	700
		Sum	2585	635	630	625	620	615	880	845	810	775	740	705	2615	615	700	665	610	15670

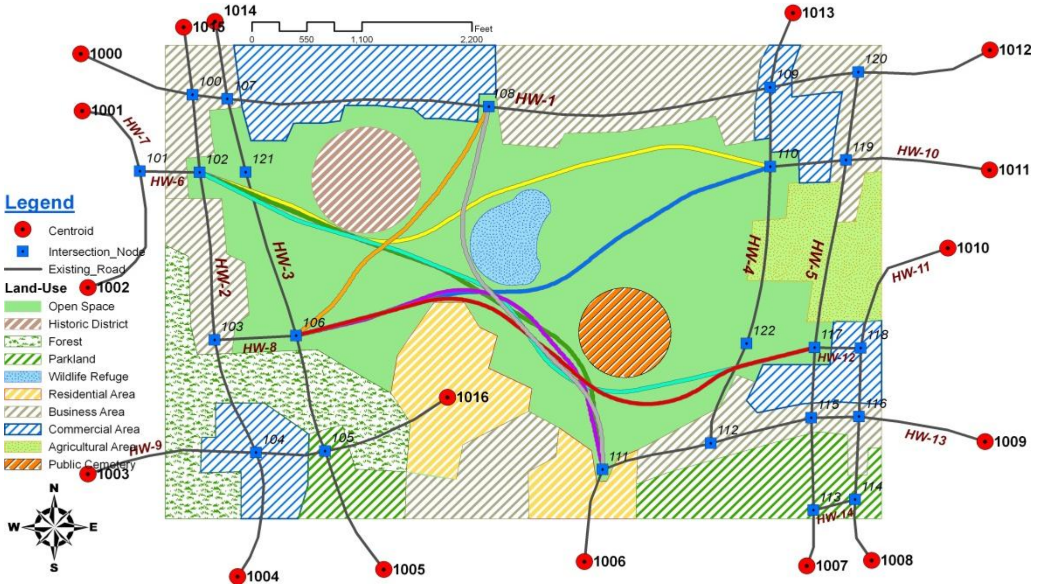


FIGURE 4 Selected Optimized Highway Alternatives

The situation description presents a 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 of 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 due to new community developments. Thus, a local government is planning to construct a new highway for improving the level of service of the existing road, ***HW-1,*** as well as for reducing users travel time between traffic endpoints (i.e., Centroids represented by red dots in Figure 4).

Key input parameters and the base year traffic information used for this case study are presented in Table 5. The baseline design standards of the new highway are a four-lane undivided highway with a 20 meter cross-section (3.6 meter for lanes and 2.8 meter for shoulders), a 90 kph design speed, 6% maximum allowable gradient, 6% maximum superelevation. 289 (=17×17) O/D trip pairs operate in the existing road network, and demand between east and west traffic endpoints (shaded in Table 5) is much higher than north-south traffic demand. The annual traffic growth rate is assumed to be 3%. The new highway should be constructed in an environmentally responsible way since various socio-economic and environmentally sensitive areas (e.g., residential area, commercial area, historic district, and wildlife refuge) are mixed in the study area. With all these considerations, the objective of the local government to the new highway project can be as follows:

- The new highway should connect the existing and planned development areas and must be an economical path that minimizes the highway agency cost.
- It should relieve congestion on existing highways in the study area (i.e., minimize total user cost).
- It should minimize environmental impact.
- It should minimize socio-economic impact. (*13*)
- It should minimize environmental emissions.

ANALYSIS RESULTS

Eight highway alternatives are selected after the optimization model completes the optimization process. Each of them is the best-obtained solution for a given pair of start and end points. Figure 4 shows horizontal profiles of the selected highway alternatives. As shown in the figure, all of them fully avoid the restricted areas (e.g., wildlife refuge, residential area, and public cemetery) located in the middle of study area, and thus do not have any environmental and socio-economic impacts (i.e., no penalty cost).

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

Table 6: Optimized Selected Highway Alternatives

Alternative	Node Number	Length (feet)	Total Agency Cost	Total User Cost	Penalty Cost	Link Flow (veh/hr)*	Emissions (gm/hr)
Alt-1	102, 110	6,079	39.0	-567.1	0	7955 *(0.99)*	2.38
Alt-2	102, 111	5,451	63.1	-571.7	0	7892 *(0.99)*	1.06
Alt-3	102, 117	6,907	39.4	-568.0	0	6898 *(0.86)*	1.69
Alt-4	106, 108	3,080	39.0	-267.4	0	3204 *(0.40)*	0.41
Alt-5	106, 110	5,147	40.2	-570.3	0	3574 *(0.45)*	0.44
Alt-6	106, 111	4,263	63.3	-569.4	0	4502 *(0.56)*	0.45
Alt-7	106, 117	5,854	39.6	-569.2	0	4193 *(0.52)*	1.92
Alt-8	108, 111	4,246	62.6	-293.3	0	4502 *(0.56)*	0.49

Note: * Value in parenthesis is volume to capacity ratio

Equilibrium link flows on the existing highway and new highways are presented in Figure 5. The results show that the highway alignments have significant impact on the equilibrium flows. HW-5 and HW-1 have the highest and lowest flow, respectively among all alternatives. Alternative 1 and 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 as it provides reasonable volume with least objective function.

Figure 6 shows the emission levels on the existing highway and 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 least emission. From emission viewpoint, Alt-5 appears to be the best as it provides least objective function value. Among the alternatives, Alt-3 produces highest emission and may not be considered as preferable. This observation is consistent with the flow estimates. The proposed tri-level model provides insights to emission estimates at link level for highway alignment optimization. Such a tool can be 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-GB RAM) is used for executing the alignment optimization model, and about 4 hours are taken to complete 300 generations of search. The optimization model is solved using C algorithm.

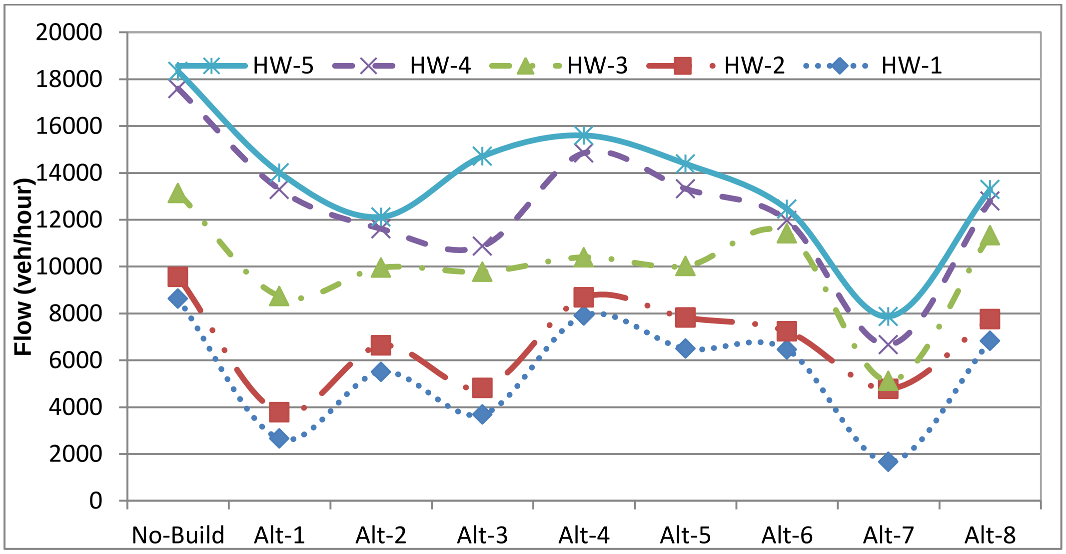


FIGURE 5 Flow Predictions on Existing Highways by Alternatives (Including No-Build)

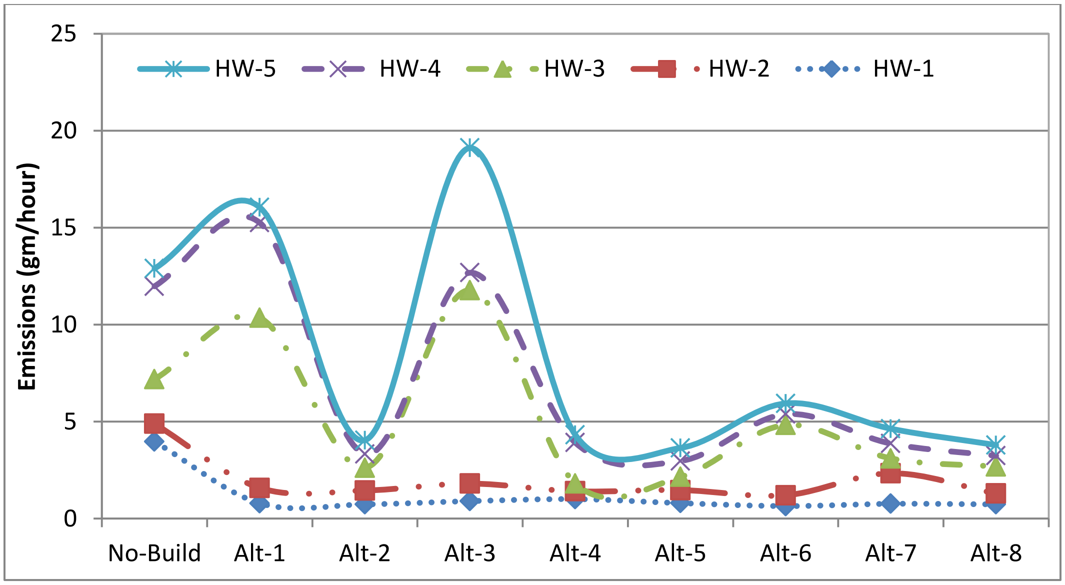


FIGURE 6 Predicted CO_2 Emissions on Existing Highways by Alternatives (Including No-Build)

CONCLUSIONS AND FUTURE WORKS

Emissions modeling along with selection of new highways including their geometric design, cost-benefit analysis, and analysis of their impacts to the existing land-use system is a very complex and challenging problem because of the large number of conflicting factors that must be resolved, the great amount and variety of information that must be compiled and processed, and the numerous evaluations that must be performed. The process of evaluating even one candidate alternative with existing methods is so expensive and time consuming, that typical studies can only afford to evaluate 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. In 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 the best trade-off between the various highway cost components. An equilibrium traffic assignment is incorporated in the tri-level model framework to realistically reflect the traffic impact of the new highway in the alternative evaluation process. The performance of the tri-level optimization model is demonstrated with a case study.

The results show that the model can find optimized solutions within reasonable computation times, and that locations of new highways are sensitive to traffic distributed to the road network besides their construction costs. This confirms that all relevant highway cost components should be simultaneously evaluated for an effective highway alignment optimization although most highway agencies in the field tend to ignore the user cost items in the planning phase of new highways. The proposed model can optimize highway alignments, emission, and route choice simultaneously. The robustness of the proposed tri-level model is examined with the case study, and the framework can be used to solve medium to large scale city networks. Although only CO_2 has been studied in this paper as it being a GHG and pollutant of immediate concern, the proposed models are generalizable and applicable for various other pollutants. Various sensitivity analyses can be undertaken in future works.

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REFERENCES

1. Steenbrink, A. Transport Network Optimization in the Dutch Integral Transportation Study. *Transportation Research B*, Vol. 8, 1974, pp.11-27.
2. Trietsch, D. A Family of Methods for Preliminary Highway Alignment. *Transportation Science*, Vol. 21, No. 1, 1987, pp. 17-25.
3. Jong, J.-C., M.K. Jha, and P. Schonfeld. Preliminary Highway Design with Genetic Algorithms and Geographic Information Systems. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, No. 4, 2000, pp. 261-271.
4. Fwa, T.F., W.T. Chan, and Y.P. Sim. Optimal Vertical Alignment Analysis for Highway Design. *Journal of Transportation Engineering - ASCE*, Vol. 128, No. 5, 2002, pp. 395-402.

5. Jong, J.-C. and P. Schonfeld. An Evolutionary Model for Simultaneously Optimizing Three-Dimensional Highway Alignments. *Transportation Research Part B,* Vol. 37, No. 2, 2003, pp. 107-128.
6. Jha, M.K. and P. Schonfeld. A Highway Alignment Optimization Model using Geographic Information Systems. *Transportation Research A,* Vol. 38, No. 6, 2004, pp. 455-481.
7. Chen, A. and C. Yang. Stochastic Transportation Network Design Problem with Spatial Equity Constraint. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1882*, Transportation research Board of the National Academies, Washington, D.C., 2004, pp. 97-104.
8. Gao, Z., J. Wu, and H. Sun. Solution Algorithm for the Bi-level Discrete Network Design Problem. *Transportation Research B,* Vol. 39, No. 6, 2005, pp. 479-495.
9. Cheng, J.F. and Y. Lee. Model for Three-Dimensional Highway Alignment. *Journal of Transportation Engineering - ASCE,* Vol. 132, No. 12, 2006, pp. 913-920.
10. Kang, M.-W., P. Schonfeld, and J.-C. Jong. Highway Alignment Optimization through Feasible Gates. *Journal of Advanced Transportation*, Vol. 41, No. 2, 2007, pp. 115-144.
11. Lee, Y., Y.-R. Tsou, and H.-L. Liu. Optimization Method for Highway Horizontal Alignment Design. *Journal of Transportation Engineering - ASCE*, Vol. 135, No. 4, 2009, pp. 217-224.
12. Kang, M.-W., P. Schonfeld, and N. Yang. Prescreening and Repairing in a Genetic Algorithm for Highway Alignment Optimization, *Computer-Aided Civil and Infrastructure Engineering,* Vol. 24, No. 2, 2009, pp. 109-119
13. Kang, M.-W., N. Yang, P. Schonfeld, and M.K. Jha. Bilevel Highway Route Optimization. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2197*, Transportation research Board of the National Academies, Washington, D.C., 2010, pp. 107-117.
14. Maji, S. and M.K. Jha. Highway Alignment Optimization Using Cost-Benefit Analysis Under User Equilibrium, *International Journal of Operations Research and Information Systems,* Vol. 2, No. 4, 2011, pp. 19-33.
15. Jha, M.K. Criteria-Based Decision Support System for Selecting Highway Alignments, *Journal of Transportation Engineering*, Vol. 129, No. 1, 2003, pp.33-41.
16. Jha, M.K., A. Namdeo, S.M. Shiva Nagendra, and J. Li. Investigating the Relative Impacts of Travel-Time Delay and Vehicular Emission on Road User Choice Behavior: Case Studies from US, UK, and India, In *proceedings of the 1st Conference of Transportation Research Group of India*, Bangalore, India, Dec. 7-10, 2011.
17. Kang M.-W., M.K. Jha, and P. Schonfeld. Applicability of Highway Alignment Optimization Models, Transportation Research, Part C, Vol. 21, No. 1, 2012, pp. 257-286.
18. Kim, E., M.K. Jha, D.J. Lovell, and P. Schonfeld. Intersection Cost Modeling for Highway Alignment Optimization. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 19, No. 2, 2004, pp. 136-146.
19. Jha, M.K. and P. Schonfeld. Geographic Information System-Based Analysis of Right-of-Way Cost for Highway Optimization. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1719*, Transportation research Board of the National Academies, Washington, D.C., 2000, pp. 241-249.
20. Jha, M.K. and P. Schonfeld. Trade-offs Between Initial and Maintenance Costs of Highways in Cross-Slopes. *Journal of Infrastructure Systems - ASCE*. Vol. 9, No. 1, 2003, pp. 16-25.
21. Kang, M.-W. *An Alignment Optimization Model for A Simple Highway Network*. Ph.D. Dissertation, University of Maryland, College Park, Maryland, 2008.
22. El-Shawarby, I., Ahn, K., and Rakha, H. Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Transportation Research Part D, Vol.10, 2005, pp. 13-30.
23. Wardrop, J. Some Theoretical Aspects of Road Traffic Research. *Proceedings of the Institution of Civil Engineers*, Part 2, 1952, pp. 325-378.