An Empirical Model with Environmental Considerations in Highway Alignment Optimization

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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.

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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 (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*)* 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 (e.g., Maji and Jha 2011, Kang et al. 2010) 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 (2003) 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 (2003) developed a criteria-based decision support system based on GIS for selecting highway alignments. In addition, Jha and Schonfeld (2004) 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 (Kang et al. 2010) proposed a bi-level optimization method. In that method, the user preferences were separated from the traditional cost minimization problem.

Since environmental considerations are 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 (see for example, Jha and Schonfeld 2004) 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 (see for example, Jha and Kang 2009; and Jha and Kim 2006).

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, Jha et al., 2011). 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. This approach is illustrated in Figure 1.

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 the above formula, 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 2) 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.

The origin-destination (O-D) matrix of the study area is shown in Table 1. We have considered a symmetric Origin – Destination 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 (see, Kang et al. 2010) 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 3 and Table 2.

In Fig. 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 4 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.

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.

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 based on a specified objective function (Kang et al., 2010 and 2012). 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 Table 4. All notations are presented in Appendix-A.

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 (see for example, Jong et al., 2000). To solve the upper-level problem, a genetic algorithm (GA) with customized genetic operators (Jong and Schonfeld 2003) 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 (Kang et al., 2010), 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." (Kang et al., 2010)

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 Equation (11) may be found in the authors' earlier publication (Kang et al. 2007 and 2010; Kim et al. 2004; Jha and Schonfeld 2000; Jha and Schonfeld 2003; Kang 2008) 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 (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 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 equation (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 El-Shawarby et. al. (2005). 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 (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 based on 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 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 Table 4 for 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.

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., (2010) 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." (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. 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 (see, Kang et al. 2010). Therefore, except the environmental emission all test case data are the same as those presented in Kang et al. (2010). Figure 5 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.

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 5).

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. (Kang et al., 2010)
- 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 5 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.

Equilibrium link flows on the existing highway and new highways are presented in Figure 6. 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 7 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 6 hours are taken to complete 300 generations of search. Please note that these six hours are established after multiple initial attempts to finalize a model which was used in the paper. A minimum of 50 initial attempts are 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. About 40 alternative alignments are generated in each generation of the upper level, and they are sent to the lower level to find equilibrium traffic flow of the network. The total emission is then the computed based on the result from the lower level. Every generation, the individual alternative alignments compete with each other to reproduce offspring based on their ‘‘fitness’’ (i.e., the total cost including agency, user, and emission costs). After enough generations, the fittest individuals should survive, whereas poor solutions get discarded, and the population will finally converge to an optimized solution (Kang et al. 2012). The proposed tri-level optimization model is programmed in C. A termination criterion of 10-4 is used in the tri-level optimization problem, which means if there is no significant improvement in the objective function value during a certain number of generations; the alignment optimization process is terminated.

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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Appendix-A

Table A1. 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	:	is the 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; $u=(\ldots, u_a, \ldots)$

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