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A continuous bi-level model for the expansion of highway networks

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ABSTRACT

Adding new corridors to a highway network represents a multicriteria decision process in which a variety of social, environmental and economic factors must be evaluated and weighted for a large number of corridor alternatives. This paper proposes a new bi-level continuous location model for expansion of a highway network by adding several highway corridors within a geographical region. The upper level problem determines the location of the highway corridors, taking into account the budgetary and technological restrictions, while the lower level problem models the users' behavior in the located transport network (choices of route and transport system). The proposed model takes into account the demand in the area served by the new network highway corridors, the available budget and the user behavior. This model uses geographical information in order to estimate the length-dependent costs (such as pavement and construction costs) and the cost of earth movement. The proposed method is tested using the standard particle swarm optimization algorithm and applied to the Castilla–La Mancha geographic database. The previous methodology has been extended to a multiobjective approach in order to handling uncertainty in demand.

1. Introduction

Addition of new highways to an existing road network is a complex problem that involves many factors (construction, environmental and user costs, political issues, etc.). It belongs to the field of network expansion problems and investment decision-making, one of the suggested topics of applications for this special issue of computers and operation research. Traffic network management problems involve optimal decisions about the improvement of a transportation system considering user's behavior. Notable examples of this type of problem are: *Continuous Network Design Problem* (CNDP), *Toll Pricing Problem*, *Signal Setting Problem*, *OD matrix Adjustment Problem* (*DAP*), etc.

The framework for the formulation of this type of problems is bi-level programming. The so-called lower-level problem is defined by a traffic assignment model and includes user behavior (the followers in a Stackelberg game) in a traffic network while the upper-level problem models the decisions of the transport planner (the leader in a Stackelberg game). This is a hierarchical decision process which cannot be modeled by a bi-objective approach in which the objectives of each follower and of the leader are placed in the same level.

Traffic network design problems can be divided into two categories:

(i) Enhancement capacity of sub/urban road networks. This problem is known as the continuous network design problem (CNDP) [55]. CNDP assumes that the topology of the network is fixed and that the intention is to establish an optimal parametrization of the network for the existing demand. CNDP considers urban networks in which congestion is present and that travel times are flow-dependent in modeling mathematically the effect of congestion in the network.
(ii) Design of the layout of suburban traffic networks, such as rural highway networks. This problem deals with the building of new roads to improve existing road networks. In this type of problem the topology of the network is modified and it is assumed that congestion is negligible.

Refs. [54,21] propose also two bi-level programming models that solve with particle swarm optimization but for congested urban networks.

In this paper the problem of adding new highway corridors to an existing rural highway network in a given geographical context is addressed. We have reviewed a large collection of

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papers in the existing literature and the most common hypothesis is to consider that congestion is negligible for this type of situation. (see references [26,28,30,33,34]). A review of this topic is the work in [35].

Initially, we can classify the different approaches to solve the problem in two main groups: the discrete network design problem (DNDP) and the highway alignment optimization (HAO) problem (see [38]).

The DNDP consists of a macroscopic highway design, but the number of possible solutions in space is finite. A good example, can be seen in [14] who proposed a discrete location approach to solve a wider range of problems. This model has been widely applied to transportation, logistic, telecommunications and production–distribution systems. The interested reader can consult the surveys of [44,47,2]. These problems are formulated as multicommodity network flow problems and can deal with large networks, which are generally modeled as graphs. Some interesting examples of techniques that have been developed to solve the DNDP are the *branch-and-bound* (see [4,17]), the *modified quasi-optimization* heuristic (see [52,13]), the *Lagrangian relaxation* (see [20]) or heuristic algorithms such as *simulated annealing, genetic algorithms, etc.* (see [15,40]).

The HAO is a microscopic highway route design problem and a continuous location model, whose input data are the highway endpoints. The inputs are used to calculate the alignment that minimizes a certain combination of costs and requirements, such as construction costs (right-of-way, pavement and earthwork costs), user costs (travel time, vehicle operating and accident costs), environmental costs (noise, air pollution and wetland loss), design constraints (horizontal alignment, vertical alignment and cross-section) and geographical constraints. The costs and constraints involved in HAO problems are analyzed in detail in [32,35]. There are various studies dealing with HAO problems and most of them are solved by means of genetic algorithms and the help of geographic information systems (GIS) [26–28,23,24]. Authors have improved sequentially these problems, for example, [29] added to previous work the maintenance costs, which has been traditionally ignored in the past. Refs. [41,42] developed methods for locally optimizing intersections within HAO problems. Ref. [25] considered the traffic demand in the optimization problem. Although these models have acquired a high level of sophistication they all assume that the highway endpoints and the demand are already known. In addition, due to the high computational cost they are unable to optimize large networks.

There are many mathematical models in the existing literature that have been developed for optimizing three-dimensional (3D) alignments (see, for example [7,8,22,24,30,31,33–38]), from which most of them deal with the HAO problem.

Recently, [38] proposed a bi-level method that incorporates to the HAO problems the demand, the route location and all the costs above mentioned. The problem of this work is that it only locates optimally the connection of two highway corridors. Ref. [1] proposes a demand-based approach to provide a set of potential corridors. The problem is formulated as a continuous location model which seeks a set of optimal corridors with respect to the demand of potential users while satisfying budget constraints. This work is a microscopic problem that allows locating of a highway corridor without considering the existing network.

Table 1
Comparison of DNDP, HAO, a problem solved in [38] and our CNDP*.

	DNDP	**HAO Problem**	[38] **Problem**	**Our CNDP***
Scope	Macroscopic highway network planning	Microscopic highway network planning	Microscopic highway network planning	Macroscopic highway network planning
Objective	Find a network configuration that minimizes network travel cost (normally, travel time cost)	Find actual highway alignment that minimize costs associated with road construction	Find highway alternatives that best improve the existing roadway (construction and travel time costs)	Find new highway corridors that best improve the existing roadway (construction and travel time costs)
Input	Conceptual road network	Highway endpoints	Two road network corridors	Towns coordinates
	Travel demand		Travel demand (i.e. OD matrix)	Travel demand (i.e. OD matrix)
		Spatial information of the study area	Spatial information the study area	Spatial information the study area
		Geometric data associated with highway design	Geometric data associated with highway design	
Output	Conceptual road network alignment	Optimized 3D highway alignment	Optimized 3D highway alignment	Several possible corridors (defined by their endpoints)
	Network travel cost		Network travel cost	Network travel cost
		Detailed total cost	Detailed total cost	Detailed total cost
		Environmental impact summary	Environmental impact summary	Environmental impact summary
Advantage	Can reflect drivers' route choice behavior from a traffic assignment process		Can reflect drivers' route choice behavior from a traffic assignment process	Can reflect drivers' route choice behavior from a traffic assignment process
		Can work in continuous search space	Can work in continuous search space	Can work in continuous search space
		Can exploit massive amounts of information in a GIS	Can exploit massive amounts of information in a GIS	Can exploit massive amounts of information in a GIS
	Can deal with large networks			Can deal with large networks
		Can generate realistic 3D alignments	Can generate realistic 3D alignments	
	Gives a conceptual network frame			Gives a conceptual network frame
Disadvantage	Cannot consider detailed highway costs and constraints associated with highway construction	Cannot reflect route choice behavior of the network drivers for different highway alternatives		
		Has great computational burden for a large network	Has great computational burden for a large network	
	Cannot generate realistic 3D alignments			Cannot generate realistic 3D alignments

Source: [35,38].