Travel Time Calculation With GIS in Rail Station Location Optimization

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by

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Abstract

In recent years GIS has been extensively applied in solving transportation and logistics problems. Working directly with GIS maps allows precise calculation of several key parameters in transportation problems involving optimization, such as travel time. In this research we use ArcView Spatial Analyst with ant algorithm to optimize station locations along rail transit lines. The genetic algorithms perform optimal search and are coded in C. Travel times are calculated from centroids of residential locations to proposed rail stations using actual road network. An example study is presented.

Introduction

The station location problem along a transit line (Figure 1) is a challenging problem. The positions of stations can be determined based on a lot of parameters such as, the user cost, right-of-way cost, construction cost etc. From the user's perspective the travel time to the station from home is the most important deciding factor as the freeways and arterial streets are heavily congested during rush hours. The in-vehicle travel time is less significant compared to the time taken to arrive at the station since additional stations may only add up a few minutes to the in-vehicle travel time. So, a good candidate location will be the one with higher degree of accessibility.

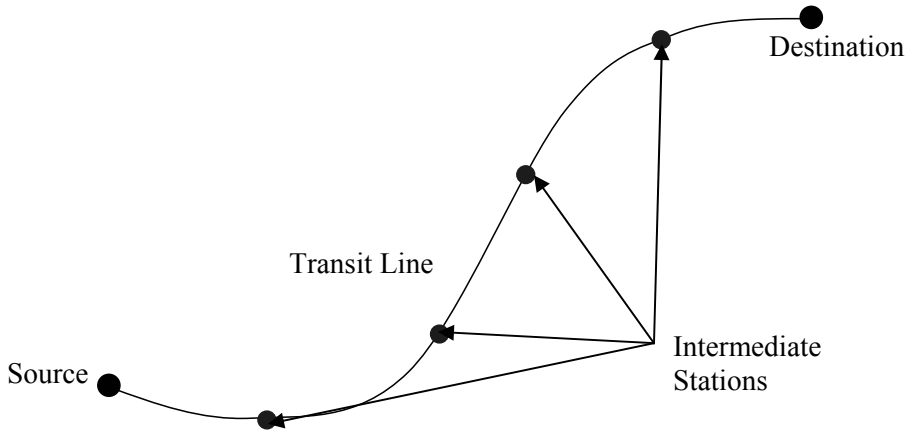

Figure 1. Station Location Problem

The problem can be described as an optimization problem where the alignment of the transit line between two points, e.g., source and destination are given (Figure1). The positions of the intermediate stations are to be determined optimally. Though the problem is associated with various factors governing the final locations of the stations, the travel time cost can be identified as the predominant component to decide the optimal solution. The aim is to model the problem based on the travel time cost. The objective of the present study is to determine how to calculate the travel time cost which can be computed

in the optimization algorithm developed to solve the problem. The Geographic Information System (GIS) is an emergent tool used to analyze the spatial data functionally for various transportation problems. Network Analyst, an extension of ArcView GIS, which is used to calculate the travel time cost, is integrated with the optimization algorithm to obtain the optimal location of a station.

Literature Review

The problem of station location has been approached by many researchers. Vuchic and Newell (*1*) tried to solve the problem by minimizing the travel time. They solved the problem analytically using dynamic programming. They oversimplified the problem by assuming various factors, such as the transit line was considered to be linear and the population distribution to be uniform etc. The methodology lacked the involvement of real time parameters.

Jha and Schonfeld (*2,3,4*) and Jong, et al. (*5*) developed an optimization model for highway alignment using genetic algorithm integrated with GIS. The GIS was used to compute the geographic sensitive costs, such as right-of-way costs, earthwork costs, environmental costs etc. and was integrated to a 'C' program coded for genetic algorithm. The model could be followed for the problem of locating transit stations as it could produce efficient results considering real GIS database.

Guo and Poling (*6*) used GIS and GPS to calculate network travel time. They integrated GIS database with the field data regarding position and speed collected by GPS for travel route selection. They defined link topology to develop control nodes by extracting information from the base map. Then the linear positions of the nodes were generated by Dynamic Segmentation using ARC/INFO. These measures were used to calculate the length of the links for two given points which resulted in to the travel time calculation of the selected route. This method was expensive as it was highly dependent on the GPS data and GPS units were expensive to purchase or rent.

Horner (*7*) developed a GIS-based methodology to locate urban rail terminals. He used the network drive time and park-and-ride facilities for the potential ridership for the rail in order to identify the locations of the terminals. It included the route network layer with the link length attribute. Once the travel speed data was assigned to the link, it calculated the travel time cost for the links in the network. But, this methodology did not include the automated shortest route calculation for the network.

The integration of an optimization algorithm with GIS seems very promising in determining the optimum location of transit stations using the real-life travel time data calculated by GIS.

Proposed Methodology

The section describes the proposed methodology which consists of the formulation of the problem, mechanism of Ant Algorithm for the particular problem and the calculation of the travel time using ArcView GIS. The problem of station location is formulated as an optimization problem to minimize the total cost of locating the station. Ant Algorithm is used as the optimization tool. GIS is used to obtain the travel time data. The GIS database is integrated with the optimization algorithm to find out the optimal solution.

A brief discussion on the formulation of the problem and the application of Ant Algorithm has been included in the description in order to emphasize the relevance of the travel time calculation in the algorithm.

Formulation of the problem:

The objective function for the station location problem can be formulates as:

Total cost (TC) = user cost (UC) + operator cost (OC) + capital cost (CC)+ other costs (OC) (including the environmental factors and geographical factors)

where,

operator cost = unit operator cost(UOC) × [vehicle travel time (t_v) + standing time (t_s) + time loss in acceleration-deceleration (t_{loss})]

user cost = unit travel cost(UTC) × total travel time

where,

total travel time = access time (t_a) + waiting time (t_w) + in-vehicle travel time (t_i)

Mathematically, the objective function (total cost) can be formulated as

$$TC(D_1, D_2, ..., D_N) = \sum_{k=1}^{N} TC(D_k) = \sum_{k=1}^{N} \left[\sum_{i=1}^{R} UC(D_k, P_i) + OC(D_k) + CC(D_k) + OC(D_k) \right] \quad \ldots\ldots(1)$$

Where, $D_k = k^{th}$ station along the rail transit line (see, Figure 1)
P_i = centroid of ith area

Application of Ant Algorithm to solve the problem:

The total cost is minimized using Ant Algorithm. The solution search space is discretized as Ant Algorithm is mainly effective for the discrete optimization problems (*8)*. Ant algorithm works on the principle of food collection behavior of a group of ants. The selection of the path depends stochastically on the amount of pheromone trail present in the path. For the station location problem, let us assume that there will be *i* possible locations for the first station to be positioned and *m* ants travel *i* different paths. It chooses the location to go to with a probability that is an inverse function of the total cost and of the amount of trail present on the connecting edge. Finally, the ants end up selecting the option with the least cost and we obtain the best location for the first station.

Calculation of travel time:

This subsection describes the method to calculate the passenger access time (t_a) as it plays the most important role in the total cost calculation. The average access time of the passengers from the centroid of the areas to different points on the transit line is computed using GIS. The study area is divided in different segments based on the number of major cities present in the area. Let the centroid of the first area is located at P_1. The average access times to various points on the line from P_1 are given by T_1, T_2 etc. Similarly, that from P_2 be U_1, U_2 etc. The corresponding access time values T_1, T_2 and U_1, U_2 are calculated by Network Analyst extension of ArcView GIS. Let the passenger demand distribution for these two areas be $p_1(x)$ and $p_2(x)$, respectively. So, if there are R such areas, then for the ith area let the travel time be $V_1, V_2..V_k$ and the passenger demand for i^{th} area will be $p_i(x)$. For i such areas and N stations, the total access time of the passengers can be written as,

$$t_a = \int_0^{L_1} \sum_{j=1}^{N-1} (T_k + T_j) \cdot p_1(x)dx + \int_{L_1}^{L_1+L_2} \sum_{j=1}^{N-1} (U_k + U_j) \cdot p_2(x)dx + ... + \int_{L_1+L_2+..L_{i-1}}^{L} \sum_{j=1}^{N-1} (V_k + V_j) \cdot p_i(x) \quad \text{…….. (2)}$$

where, $L_1, L_2 ... L_n$ are the lengths in which the transit line is divided depending on the number of segments in which the study area is divided. Number of such segments will depend on the population density and attractiveness to the rail transit mode by potential users. The model users will have a better sense of the number of areas to be segments based on a survey of the study area.

The travel time is calculated using Network analyst of ArcView GIS. The results obtained from the network analyst can be integrated with the optimization algorithm coded in 'C'. The calculation of the shortest path is a built-in feature in the software of the Network Analyst. The alignment of the transit line is already given for the problem. Now the travel time from the CBD (P) to the possible station (S) has to be computed in the formulation of the total cost in order to optimize the station locations.

The road grid network within the study area has to be built (Figure 2). The travel time for the shortest path from the CBD to the nearest node in the network to the possible station is calculated. The origin, which is the centroid of the population area and the destination, which is the nearest node to the possible station are given as the input on the network. Network Analyst solver calculates the travel time for the optimum path using shortest path algorithm using the network solver (Figure 3). This travel time is computed in the Equation 2 to obtain the total access time.

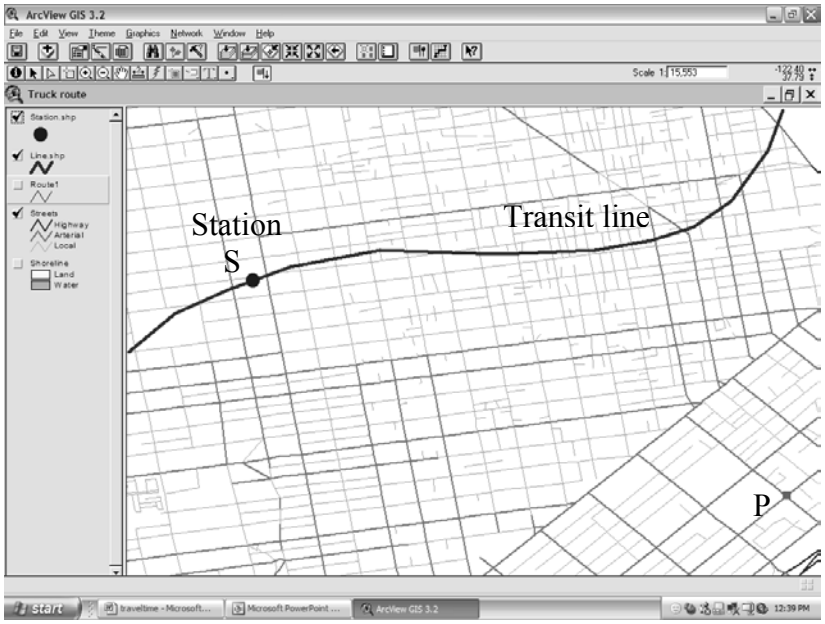

Figure 2. Road network for the study area

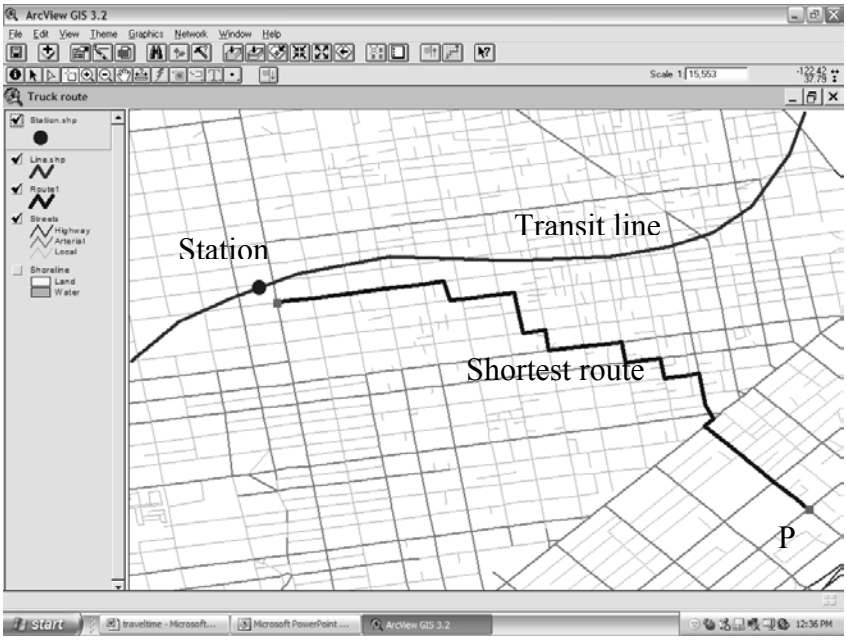

Figure 3. The shortest route from CBD to the possible station

Example Case study

The proposed methodology has been applied on a small hypothetical problem shown below. The origin, destination and the alignment of the transit line are given. The objective is to locate a station optimally between these two points along the transit line. Suppose a transit line of length L is aligned between A and B. From the population density data from GIS we get that there are two major cities or the localities present in our study area. So, we divide our study area in two different segments. The first segment is assumed to be extended for L_1 distance and the second area to L_2 distance. The problem has been designed as a discrete optimization problem and Ant Algorithm is found to be very efficient for such problems (*8*). The 4 possible stations are assumed to be positioned at the integer distances on the transit line (Figure 4). Ant Algorithm integrated with GIS has been developed to find out the best one among these four locations. The potential ridership is assumed to act from the centroid of the two segments represented by P_1 and P_2, respectively.

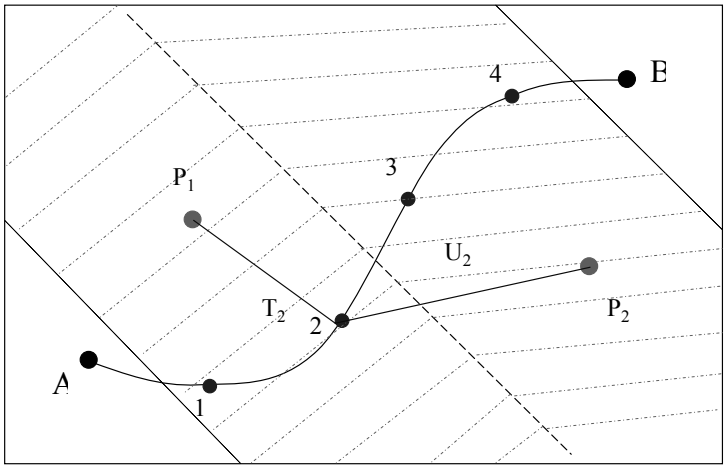

Figure 4. Example case study

The travel times along the shortest paths for all the possible stations are calculated using Network Analyst. The route network has been developed for this purpose (Figure 5). The Ant Algorithm is applied by formulating it as a cost minimization problem. The best location obtained is position 3 (Figure 6) based on the minimum travel time cost.

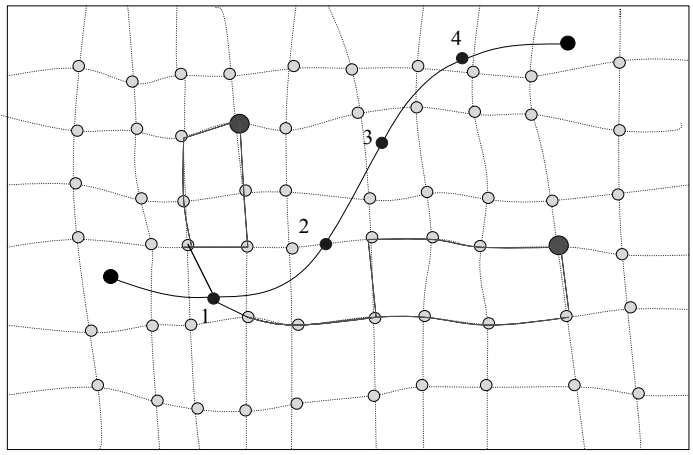

Figure 5. Development of the route network theme to use Network Analyst

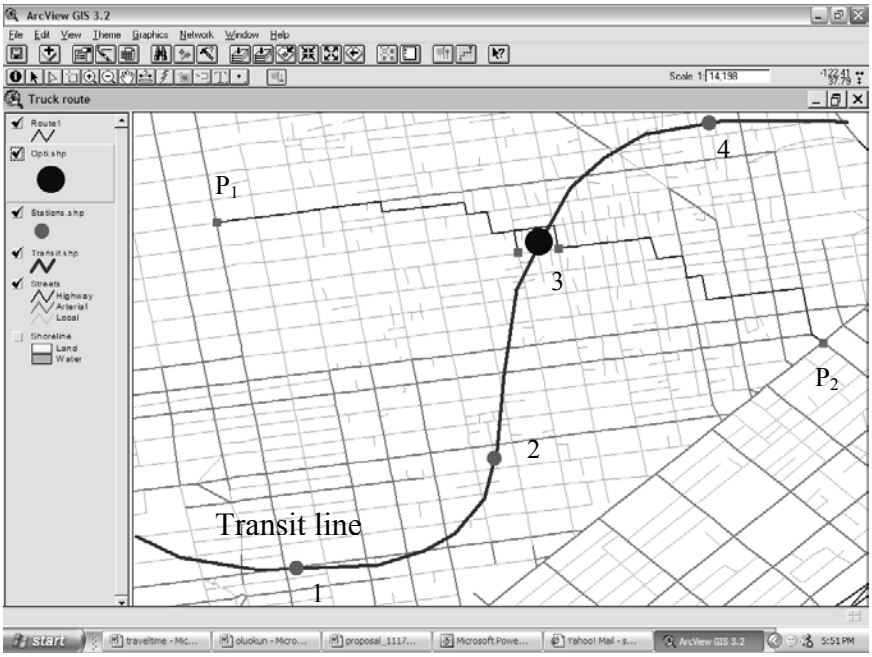

Figure 6. Optimal location of a station

Conclusion

The result of this study shows that an efficient mechanism can be developed to solve the rail transit station location problem by integrating an optimization algorithm with GIS.

Network Analyst is found to be very efficient to calculate the travel times for the shortest routes between two points. The performance of the algorithm depends on various factors, such as, the accuracy in modeling the route network and in calculating the travel time cost etc. The intensive the route network is, the better the solution will be. Integration of GIS makes the algorithm slower but gives better results as the algorithm computes the real travel time data.

Acknowledgement

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