DETERMING CORDONS AND SCREEN LINES FOR ORIGIN-DESTINATION TRIP STUDIES

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Abstract: Conventionally, establishment of cordon and screen lines for traffic volume studies is purely subjective, relying much on the political jurisdictions, natural boundaries or man-made barriers. Two considerations are generally made in setting cordon and screen lines: obtaining as much and representative traffic information as possible and saving subsequent manpower requirement in data collection. This paper makes a first attempt to develop a systematic way for selection of cordon and screen lines for a given study area and road network. We formulate an integer programming model to choose the optimal locations of a given number of survey stations to intercept as many O-D pairs as possible, we then develop a procedure with the proposed model to determine the minimum number of survey stations to intercept all O-D pairs. The model and algorithm are illustrated with numerical examples.

Key Words: traffic survey, location theory, integer programming, optimization

1. INTRODUCTION

An origin-destination (O-D) matrix and other traffic census information such as average annual daily traffic, seasonal, monthly and daily variation coefficients as well as total vehicle-kilometer are essential for efficient traffic planning, design, control and management. Generally, the quality of the estimated O-D matrices and other traffic census information greatly depend on the number and locations of traffic counting/survey points in the network as well as errors in input data (Lam and Lo, 1990; Yang *et al.*, 1991; Yang and Zhou, 1998). There have been extensive studies and applications for estimation of O-D matrices from traffic counts or roadside survey data (Yang *et al.*, 1992 & 1994; Yang, 1995) and development and evaluation of annual traffic census program (Faghri and Chakroborty, 1994).

Traffic survey station for obtaining O-D data: The origin-destination survey is to identify where and when trips begin and end. It is important, yet time consuming and expensive step and the prime source of the transportation studies such as future travel demand forecasting. Either home interviews or roadside interviews can be carried out to establish O-D travel pattern satisfactorily. The resulting matrix obtained through roadside interview with appropriate sampling rate will be a reasonable sample of the true pattern and it can be factored up to the observed control totals (directional flows of vehicles at each observation point).

Traffic counting station for annual traffic census: In nearly every large city, comprehensive traffic counting program is implemented and annual traffic census is published. In Hong Kong, regular traffic counts were initialized in 1961. In 1970, the traffic census covered the entire territory. With gradual developments in the sub-sequential years, a comprehensive system was established. In 1998, there are in total 96 core stations, which provide traffic counts continuously collected by automatic traffic recorders, and 63 permanent coverage stations located at cordon/screen lines. Daily and hourly directional flows are obtained at each of the station, thereby providing estimate of vehicle-kilometers of travel, annual average daily traffic, and seasonal, monthly and daily variations. These area or citywide volume studies provides basic information for transportation analyses and forecasting, as well as for facility design, monitoring and operations.

For either annual traffic census or O-D matrix estimation, traffic counting or sampling survey is generally carried out at cordons or screen lines for data collection. When information is required on traffic movement within an area, such as the central business district of a city, an imaginary closed loop called a cordon is selected to enclose the study area. The area enclosed within this loop is defined as the cordon area. The intersection of each street crossing the cordon line is taken as a count or survey station. Normally, a cordon area is divided into up to hundreds of zones. To obtain information of traffic movements from zones to zones, the study area is divided into large sections by setting imaginary screen lines. Traffic counts or O-D interview surveys are then taken at each point where a road crosses the screen line. Collection of data at these screen line stations at regular interval facilitates the detection of variations in the traffic volume and traffic flow direction due to changes in the land-use pattern of the area. Conventionally, setting of a cordon or screen line is purely subjective, depending much on the political jurisdictions, census area boundaries, and natural boundaries or man-made barriers, such as rivers or railway trucks. There exists, however, no systematic way for selection of cordon and screen lines for a given study area and network.

This paper proposes to develop a mathematical model for choosing the cordon and screen lines in a network with a given prior or reference O-D pattern. For a given limited number of survey stations, we consider how to determine their locations to intercept as many O-D pairs as possible. We then determine the minimum number of survey stations required intercepting all O-D pairs to save on subsequent interview requirements. In the next section, we formulate the problem of locating a given number of survey stations as an integer-programming problem embodying a shortest path algorithm. In Section 3, we propose a bisection algorithm based on the proposed model to determine the minimum number of survey station required for intercepting all O-D pairs. In Section 4, we present two numerical examples to illustrate the application of the methods. General conclusions are presented in Section 6.

2. MODEL FORMULATION

2.1 Locating A Given Number Of Survey Links To Intercept Maximum O-D Pairs

Consider a directed road network G (N, A) where N is the set of nodes and A is the set of directed links in the network. Let W be the set of origin-destination (O-D) pairs with nonzero traffic demand and q_w be the traffic demand (veh/hr) between O-D pair $w \in W$. Let r_w and s_w be the origin and destination of O-D pair $w \in W$.
We define that the network is connected if there exists at least one directed simple path (a path that contains no repeated arcs and no repeated nodes) between each O-D pair $w \in W$ starting at node r_w and ending at node s_w.

Now, we introduce the integer location decision variable: $z_a = (0,1)$, $z_a = 1$ if a counting or survey station is located on link a, and 0 otherwise, $\mathbf{z}$ denotes the corresponding location vector with element z_a. Let t_a be a *virtual* travel time on link $a \in A$. For the sake of our model formulation, we suppose t_a is a function of z_a and is simply defined as

$$t_a(z_a) = z_a, \forall a \in A \tag{1}$$

Since each link has no negative travel time, we can use an appropriate shortest path algorithm to find the shortest path and its travel time from each origin r_w to each destination s_w, $w \in W$, with limited number of iterations. Let u_w be the shortest travel time between O-D pair $w \in W$ determined by an appropriate shortest algorithm. Clearly, u_w is a function of the integer decision variable $\mathbf{z} = (\ldots, z_a, \ldots)$, and we can easily understand that if $u_w(\mathbf{z}) > 0$ then the shortest path includes at least one counting link. In view of the definition of link travel time function, we can easily understand that if $u_w(\mathbf{z}) > 0$ the origin r_w and destination s_w for O-D pair $w \in W$ is separated by at least one cordon or screen line. Otherwise, there exists one shorter path with zero travel time from r_w to s_w that does not include any counting link or does not cross the cordon/screen line**.

Because our objective is to select a subset of counting or survey links that constitute one or more screen lines to separate as many O-D pairs as possible, the problem of interest can be formulated below:

$$\text{Maximize } f(\mathbf{z}) = \sum_{w \in W} \delta(u_w(\mathbf{z})) \tag{2}$$

subject to

** Note that we should distinguish the cordon or screen line considered here and the traditional cut in network theory. A cut is a partition of the node set N into two parts, S and $\overline{S} = N - S$. Each cut defines a set of links consisting of those links that have one endpoint (either starting or ending point) in S and another endpoint in $\overline{S}$. A source-terminal cut is defined with respect to distinguished nodes r and s and is a cut $[S, \overline{S}]$ satisfying the property that $r \in S$ and $s \in \overline{S}$. In contrast, a screen line here is established with respect to the availability of path not crossing a screen line. Thus the latter depends on which node is the origin and may not necessarily divide the network in to two disjoint parts.

$$\sum_{a\in A} z_a \le l \tag{3}$$

$$z_a = 0,1,\ a \in A \tag{4}$$

where $\delta(u)=1$ if $u>0$ and 0 if $u=0$, l is a predetermined number of survey links according to resource availability for survey. It is evident that $f(\mathbf{z})$ is the total number of O-D pairs that are separated by at least one screen line for given $\mathbf{z}=(\ldots,z_a,\ldots)$, double counting effect is not taken into account in the objective function. The integer maximization procedure embodies a shortest path calculation (calculation of u_w) as an internal procedure. Note that one can interpret the proposed model as a max-min problem because the shortest path problem in a network can be formulated as a linear programming problem (Bertsekas, 1998).

2.2 Determining The Minimum Number of Survey Links Required for Intercepting O-D Pairs

If, for a given l, the maximum value $f(\mathbf{z}^*)$ associated with the optimal solution vector $\mathbf{z}^*$ is less than the number m of the O-D pairs in the network, there remain $m-f(\mathbf{z}^*)$ O-D pairs that are not intercepted by the screen lines. In this case, we may be interested to determine the minimum number of counting links required for intercepting all O-D pairs in a road network.

There are two possible ways to determine the minimum number and the location of the survey links: Forward gradual addition method or backward gradual reduction method.

Suppose we have two predetermined numbers of survey links, l^l and l^u where $l^l < l^u \le n$ and n is the number of links in the network. Suppose $f^{(l)}$ and $f^{(u)}$ are the optimal objective function values of the integer programming problem (2)-(4) when the prescribed numbers of survey stations are l^l and l^u, respectively. If $f^{(l)} < f^{(u)} = m$, then we can conclude that l^l and l^u are the lower and upper bounds of the minimum number, $l^{\min}$ of links required for intercepting all O-D pairs: $l^l < l^{\min} \le l^u$.

Forward gradual addition method. We first set an initial number $l=l^l$, then we increase the number of counting points one by one and solve the problem (2)-(4) to get the corresponding objective values. This process should be repeated until there is no more increase in the objective value or until $f^{(l)}=m$. At this point, the minimum number of survey links is obtained for intercepting all O-D pairs.

Backward gradual reduction method. We first set an initial number $l=l^u$. Then we reduce the number of survey links one by one and solve the problem (2)-(4) to get the corresponding objective values. This process should be repeated until the objective function value starts to decrease if there is a further reduction. At this point, the minimum number of survey links is obtained for intercepting all O-D pairs.

Note that for implementation of either method, addition or reduction of a single link may not alter the objective function because it may be not enough to create one additional effective screen line to intercept a new O-D pair. To save computational requirement, one can combine the two methods with variable number of link additions or reductions. For example, one can add more than one link at each iteration of the gradual forward addition methods. Once we

Recalling the proposed bi-level mathematical programming problems, it is non-convex and hence might be difficult to achieve the global optimum. At this point, probability based optimization methods are applicable to solve the proposed problem and achieve a near optimum solution instead of the global optimum.

In order to solve the problem described in (2)-(4), it must be represented as a GAs problem for which the GA operators can be applied.

Generally, GAs consist of two approaches: binary and continuous. The binary approach uses bits of zeros and ones to represent a gene, while the continuous approach uses a real number to code each gene without the quantize of the solution parameters. By considering the characteristic of this problem, the binary parameter approach is applied in this model. Thus, whether there is a survey station on the link or not is the decision variable.

Z_a=1, a link with survey station;

Z_a=0, otherwise

By combining all these genes, each chromosome then stores the information about the survey stations' establishment in the network. Based on the constraints, the total sum of survey stations is fixed as l. And the length of chromosome is equivalent with the number of links in the network. As a result, its length grows quickly with the network size.

Apart from these parameters, population size, crossover probability, mutation probability, and iteration also play important roles in GAs.

Population size is the number of chromosomes in one generation. Determining a good population size involves a tradeoff. A large population size would allow a better sampling of the feasible region but would obviously increase the computational time for each generation. The fitness function C_n^k for chromosome *n* at the *kth* generation is defined as:

$$C_n^k = \sum_{w \in W} \delta(U_w(Z)) \tag{5}$$

$$\delta(u)=1, u>0;$$

$$\delta(u)=0, \text{otherwise}.$$

Where u_w denotes the shortest travel time between O-D pair $w \in W$, which is determined by an appropriate shortest path algorithm. By summing up all the $\delta(u)$, we can subsequently get the fitness value of the current generation, which equals to the number of OD pairs to be intercepted.

The fitness value describes the quality of the solution at the current iteration. The higher this value, the better is the solution. In this model, when the iteration approaches the given maximum number or the fitness value equals to the total O-D pairs in the network, the algorithm can be stopped.

GAs apply three distinct operations: selection (reproduction), crossover, and mutation to generate new generations.

Selection is the process to choose two parents to produce two off springs. It is the first way a genetic algorithm explores the feasible solutions. This is called exploration because the genetic algorithm makes use of the bit combination, which is already presented in the chromosomes.

There are many selection methods, such as pairing from top to bottom, and reproducing according to the proportion to the fitness of each parent chromosome. In order to explore more feasible areas, we apply the following method in this model, which pairs the chromosome in population sequence. As a result, the structure of the best chromosome in the current iteration may be destroyed by such pairing method. Based on this point, we add a procedure after calculating the fitness value of the new generation. If the maximum fitness of the new generation is smaller than the one of previous generation, then the best chromosome will replace the worst one in the current generation. The application of this procedure ensures the best chromosome to be kept in the population.

The crossover operation provides a mechanism for the algorithm to jump out of a local optimum by searching other regions at random once a while. It is done at the string level by selecting two strings using the aforementioned method. The crossover points between each pair are randomly selected and their genes are swapped at the crossover points. This process includes two types of techniques: one site crossover and two-site crossover. A two-site crossover method is applied in the proposed model.

Random mutations also alter a small percentage of the bits in the list of chromosome. It can introduce traits not in the original population. It is usually performed with a low probability called mutation probability to change a "1" to "0" or visa versa.

In summary, the detailed algorithmic steps are described as follows:

Step 1: Generate the initial populations. Set *Generation*=1;
Step 2: Calculate U_w of each population in current generation by using an appropriate shortest path algorithm.
Step 3: Calculate C_n^k, find the maximum C_n^k; Keep the maximum C_n^k (in previous generation) if current maximum value is smaller than it.
Step 4: Perform three distinct operators: selection; crossover; mutation.
Step 5: Replace and generate new generation. If Generation is equal to *MG* (the number of maximum generation) or the maximum fitness value is equal to *M* (the number of O-D pairs), program finishes. Otherwise, *Generation* = *Generation*+*1* and return to step 2.

4. A NUMERICAL EXAMPLE

In this section, we will apply the proposed algorithm to the examples and report the computational results. All the analysis is based on 2 different size networks.

4.1 A Small Size Network Example

Now we present a small example shown in Figure 1 to explain the above procedures. The detailed input information is described as follows:

$$N=\{1,2,3,4,5,6,7,8,9\},\ A=\{1,2,3,4,5,6,7,8,9,10,11,12\}$$
$$NO=\{1,4\},\ ND=\{6,8,9\}$$
$$W=\{1\text{-}6,1\text{-}8,1\text{-}9,4\text{-}6,4\text{-}8,4\text{-}9\},\ M=6,\ L=12$$

NO and ND are the sets of origins and destinations respectively.

As we have mentioned, the aims of the proposed algorithms are to choose the optimal locations for a given number of survey stations to intercept as many O-D pairs as possible and to determine the minimum number and locations of survey stations required for intercepting all the O-D pairs. The proposed GAs method conjunction with the forward gradual addition method is applied to calculate the maximum number of intercepted O-D pairs as well as their corresponding optimal locations (See Figure 1). It can be seen that when the number of survey stations l equals to 2, the fitness value of Equation (5) is 3, which is smaller than the value of total O-D pairs $M=6$ in the network. Subsequently l increases to 3, the corresponding fitness value changes to 6, which indicates that all the O-D pairs have been intercepted by this kind of establishment (See Figure 1). In the case of l=4, the corresponding result remains which implies that even adding more counting spots in the network, we can't go further. Thus, the programming stopped.

Finally, the screen lines of each scenario are formulated by crossing all the links with survey stations as shown in Figure 1. The figure indicates that the studied area has been correspondingly divided into two separated areas by each screen line. This phenomenon matches well with the aforementioned cut theory (Chen, 1990; Daskin, 1995). For instance, in the case l=3, any flow from origins to destinations must pass through screen line 3. Actually, screen line 3 can be called cut set as it cuts the whole network into two components from the original one component). Therefore, all the O-D trips in the network can be captured.

4.2 A Large-Scale Network Example

However, due to the network size and the homogeneous directions from origins to destinations the example discussed in Section 4.1 has its limitation to show the generality of the proposed algorithm. Therefore, we apply it to the Sioux Falls network shown in Figure 2. This network consists of 24 nodes, 76 links and 182 O-D pairs. Clearly, it is much more complex than the example discussed in Section 3.

The applied algorithms are almost the same with those used before. Moreover, after obtaining the number of O-D pairs to be intercepted under different scenario, the minimum number of stations to intercept all O-D pairs will be solved by a bisection algorithm employing the proposed GAs.

Before the algorithm's application, we should determine the parameters:

- Population size: 400
- Maximum number of generation: 500
- Crossover probability: 0.6
- Mutation probability: 0.05

In the first step, the proposed algorithm is applied to choose the optimal locations for a given number of survey stations to intercept as many O-D pairs as possible.

The programming is conducted under different scenario. Here we give detail explanation to the result in case of l=20. The optimal station locations obtained from the calculation are shown in Figure 2. With this set of counting links, the fitness value, i.e. the number of O-D pairs to be intercepted, equals to 129, which is about 71% over 182, the number of total O-D pairs in the network.

In contrast with the aforementioned example, in this case the formulation of screen lines is not unique which is closely related to the complexity of the adopted network. The selected survey stations constitute two or more screen lines in the study area for traffic in one direction. For instance, one of the screen lines can be formulated by crossing link 37->38->42->71->46->67->59->61->56->60, which can cut the whole network into two separate parts.

Results of other situations are shown in Figure 3. It can be observed that the ratio of intercepted O-D pairs to the total O-D pairs in the network progressively verge to 1 with increasing number of survey stations. It indicates that the more stations in the network, the more O-D pairs to be cut, while the marginal effect is decreasing.

In the second step, the proposed algorithm should give the solution to determine the minimum number of survey stations to intercept all the O-D pairs for a given network. As mentioned in Section 3, a bisection algorithm combining the proposed GAs can solve this problem. In order to let GAs explore more areas and finally get the most optimal solution, the population size has been increased to 900. The main steps of the algorithms can be summarized as follows:

Step 1: Set $k=0$; Given $l^{l(k)}=38$ (half of the total links) and $l^{u(k)}=76$ (total number of links), set;

Step 2: Let $l^{(k)}=\text{int}\left(l^{l(k)}+l^{u(k)}\right)/2$, apply the algorithms mentioned in Section 3.2 to obtain $f^{\left(l^{(k)}\right)}$.

Step 3: If $f^{\left(l^{(k)}\right)}=m$ and $l^{l^{(k)}}=l^{u^{(k)}}=l^{(k)}$, go to Step 4; otherwise, form new interval $\left[l^{l^{(k+1)}},l^{u^{(k+1)}}\right]=\left[l^{l(k)},l^{(k)}+1\right]$. If $f^{\left(l^{(k)}\right)}<m$, $\left[l^{l^{(k+1)}},l^{u^{(k+1)}}\right]=\left[l^{(k)}+1,l^{u^{(k)}}\right]$, $k=k+1$ and go to Step 2.

Step 4: $l^{(\min)}=l^{(k)}$, algorithms finish.

The corresponding minimum number obtained form the aforementioned algorithm is 51. The optimal locations of survey stations, which intercept all the O-D pairs in the network are illustrated in Figure 2. Referring to Figure 2, it can be observed that the screen line is not unique. For example, screen line which pass through link 3->1->11->9->->31->10->34->40->41->44->46->67->63->68->62->64 formulates a cutest by dividing the whole network into two separate parts. By crossing link in such a sequence: 34->40->28->43->57->45>63->68->62->64->39->74->34, a cordon line can be formulated which ultimately makes the whole network into two rings.

4.3 Flow-Capturing Analysis under User-Equilibrium Traffic Assignment

All above discussion is based on an imaginary travel time without considering real traffic flows. In this subsection, we apply UE traffic assignment on the network to test whether the optimal locations provided by the proposed model can collect valuable traffic flow information.

The travel time on the used paths of each O-D pair is assumed to be same under UE condition. It means that for a certain O-D pair there exists a number of shortest paths. In this case, we are interested in whether the trip between a certain origin and a destination is totally observed by the survey stations. In other words, if the entire path flows on different shortest paths of a certain O-D pair can be observed by the survey stations, we can say that this O-D trip has been totally captured. Calculation results of different scenarios are shown in Figure 3 (Series 2). Although there are some slight difference between some values of Series 1 and Series 2, they illustrate the increasing trends, which imply that with more survey stations establishing in the network, more and more O-D pairs can be intercepted by the counting links.

Furthermore, we consider how many path trips can be observed by a certain setting. It is an important indicator to show how effectively the proposed model works. Table 1 lists the ratios of the observed trips over the total under different scenarios. It can be concluded that the observed flows dramatically increase with the number of survey stations. However, in the latter situations many flows are counted repeatedly.

All above calculation is based on a low congestion level. Furthermore, three different congestion levels are considered to test the proposed model's performance:

- Low congestion level: 1.o demand per O-D pairs
- Medium congestion level: 1.5 demand per O-D pair
- High congestion level: double demand per O-D pair

The net flow mentioned in Figure 4 is defined as the sum of path flows on the used paths of each O-D pair. This indicator can eliminate the influence of double counting and thus provide less bias assessment to the proposed algorithm. From the figure, we can clearly see that the three curves (Series 1-3) almost coincide with each other especially when more and more counting links are set up in the network. It agrees with the basic assumption that the number of intercepted O-D pairs is not associated with the O-D demand, but purely depending on the network topology. Thus, it can be concluded that the proposed model can be applied in the real network with different congestion level.

Based on the numerical example results, the performance of the proposed GAs has been illustrated to be promising.

5. CONCLUSIONS

This paper examined the problem of how to set cordons and screen lines in a study area for traffic volume study. Two problems are examined: how to locate a given number of survey or counting stations to intercept as many O-D pairs as possible and how to determine the minimum number of stations to intercept all O-D pairs. The former problem is formulated as an integer programming problem and solved using a genetic algorithm, whereas the latter is solved by a bisection algorithm employing the proposed integer-programming model. The proposed model and algorithm are demonstrated with numerical examples and shown to be useful for practical applications to save resource requirement for effective and efficient traffic survey study.

The fundamental futures: It requires the network topology and O-D pairs, making no explicit reference to some existing available O-D matrix and behavioral assumptions on road users and traffic assignment models are not required.

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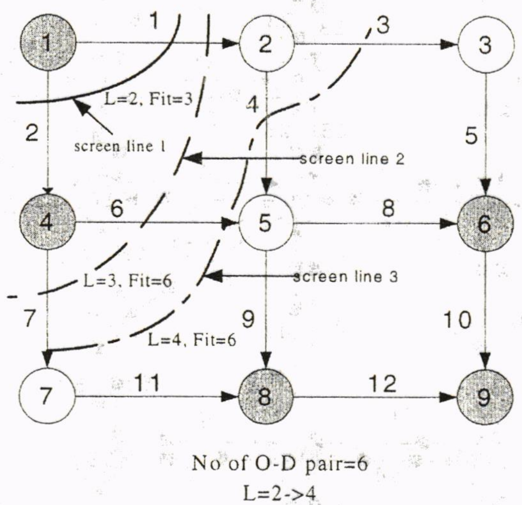

Figure1. A Small Network for The Numerical Example

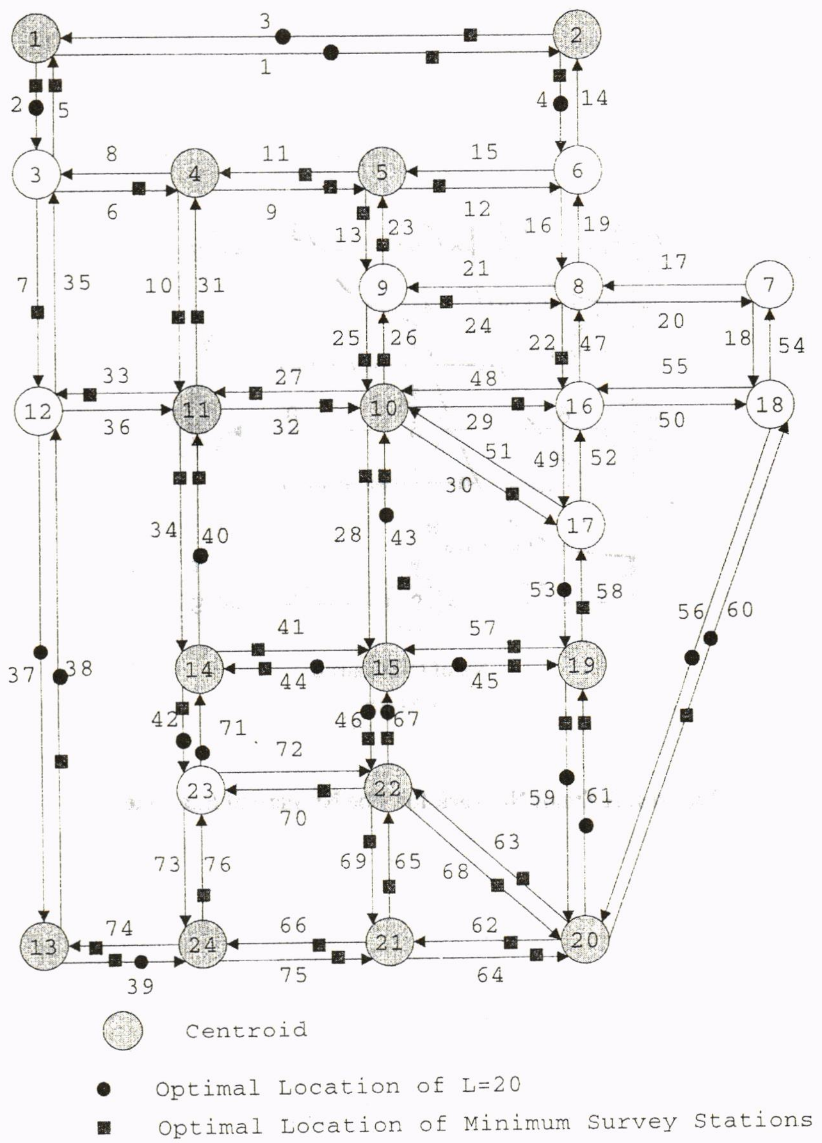

Figure 2. A larger road network for the numerical example

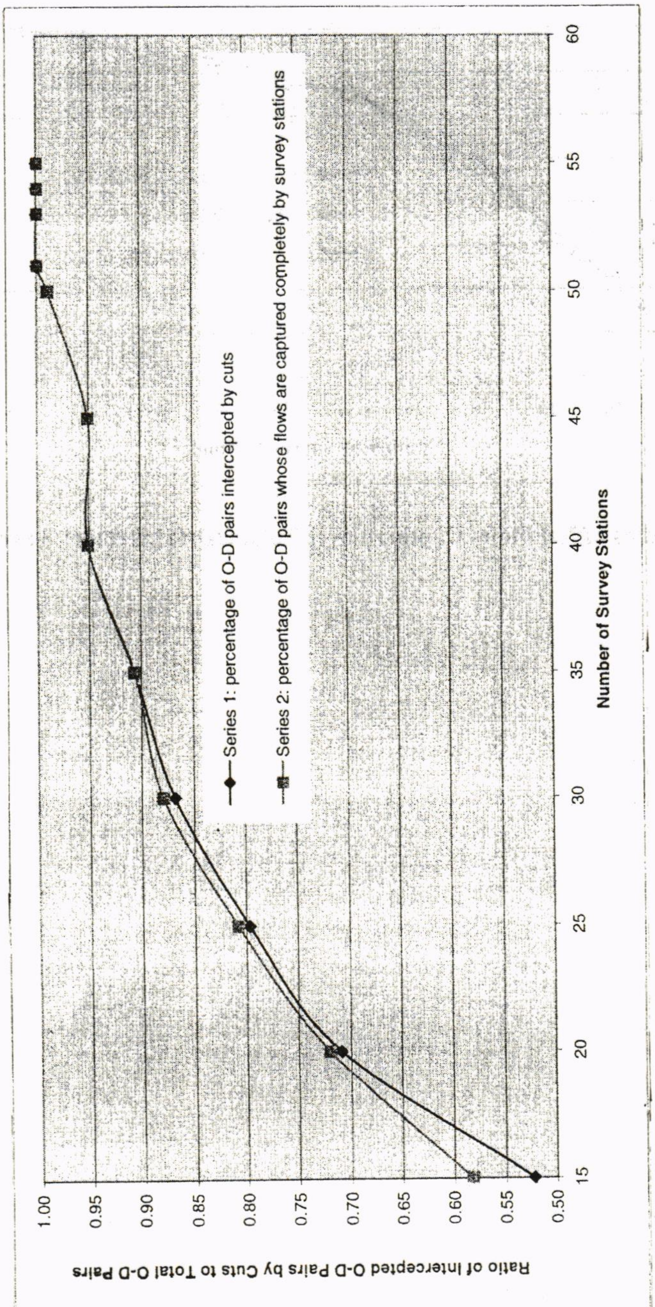

Figure 3. Maximum intercepted OD Pairs with Different Survey Station Settings

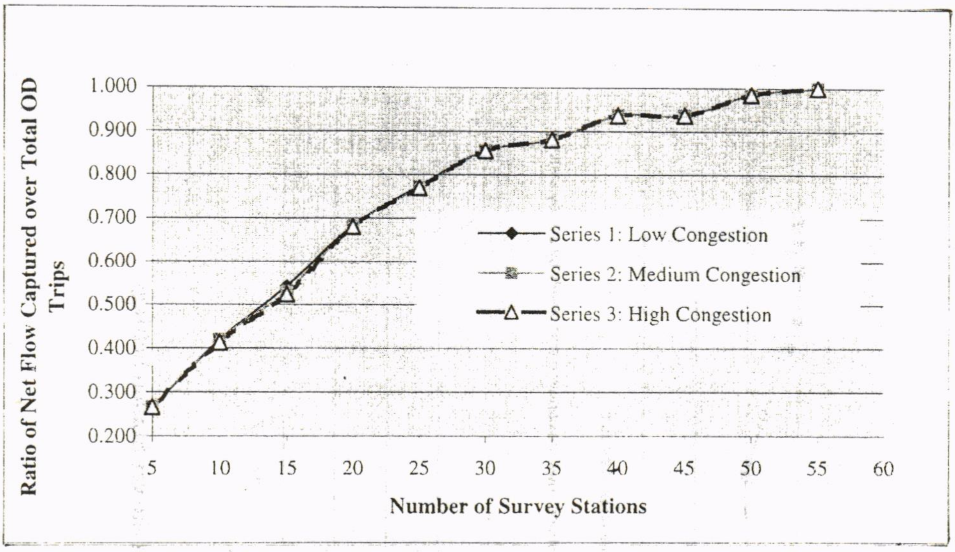

Figure 4. Ratios of Net Flows Captured over Total OD Trips under 3 Scenarios

Table 1. Percentage of Observed Path Flows (Grouped by Counting Times) over Total O-D Trips

No of Survey Station	Percentage of Observed Path Flows over Total OD Trips					
	>=1*	>=2	>=3	>=4	>=5	>=6
5	26.67	1.69				
10	41.87	4.05	0.33			
15	54.28	8.83				
20	68.21	16.42	2.92	0.33		
25	77.38	28.15	7.07	1.15		
30	85.61	32.10	6.86	1.25		
35	88.16	44.08	11.46	0.97		
40	93.64	51.80	16.55	1.51		
45	93.72	62.09	29.73	7.37	0.43	
50	98.51	65.23	26.80	6.90	0.46	
55	100.00	69.78	37.66	14.42	2.92	0.43

Note:' >=1' means that the counted time of the flows on the used paths under UE assignment