Chapter 6

Transportation Models and their Applications Using GIS

Keywords: GIS in land-use modelling, Four-stage modelling, network bands, network flow

6.1 The Role of GIS in Land Use and Transport Planning

Maps have always occupied a central role in planning, and today’s digital maps provide an unlimited range of map views and printed products that enrich everyone’s understanding of existing and planned development, locations for new facilities, and accessibility provided by transport. Databases have always been desired by decision makers, and GIS have made a powerful contribution to planning by making it possible to collect, create, and manage vital data needed for many forms of planning. Query and visualization of geographic information rather than formal analysis dominate most GIS application, but in some areas, such as transport modeling, analysis is more common. GIS technology itself has been enabled by the collection of large amounts of spatial data, which has further stimulated applications. The increasing spatial resolution of available data is enlarging the quantity and quality of planning applications.

6.1.1 GIS in Land Use Planning

GIS are now commonly used to prepare and illustrate land use plans and, to a great extent, digital mapping has become principal graphics tool of the urban and regional planners. Existing land uses, zoning maps showing permitted land uses, and planned developments are routinely created and disseminated by planners both in hard copy and in digital form.

6.1.2 GIS in Transport Planning

GIS in transport planning lags behind than in land use planning but is catching up. In a sense this is more of a technology diffusion issue rather than one of solution availability. There is now well over a decade of experience in applying GIS to transportation planning. Stimulated in the USA, in particular, by the public domain tiger street and census boundary files, there are scores of different types of transportation applications of GIS that have been successful. These would
include facility and pavement inventories, emergency response systems, corridor alignment studies, project visualization, fire station location, transit planning, freight analysis, travel-demand modeling etc. GIS technology has also been granted a central role in the development of transportation information systems such as those that were mandated for congestion management and other applications.

Travel demand modeling has always been the most computerized and computer-intensive operation in transportation planning. Thus, it is not surprising that GIS are playing an increasing role in demand forecasting and in the software with which they are implemented. In fact, the use of GIS in demand modeling is now almost universally accepted.

Much of the work on GIS applications in transportation (GIS-T) has been pursued at the state or national level, and focused on issues that may not take on the same importance at the municipal or regional level, where data collection activities may be significantly less intimidating or make use of different concepts. Nevertheless, regional transportation planners are embracing GIS technology, and are now making use of it in many ways. At the same time they are making demands on GIS-T that will lead to improvements in future.

### 6.2 Transportation and Land Use Models

It is difficult to empirically isolate impacts of land use on transport and vice versa because of the multitude of concurrent changes of other factors. This poses a problem, if the likely impacts of integrated land-use and transport policies to reduce the demand for travel, are to be predicted. Based on the various relationships between land use and transportation several land use models have been constructed which actually predict results that can be used as input in a transportation model. These are called transportation / land use models (TLUM). The core foundation of TLUM involves two components. The land use component, which is based on the location of housing, industrial and commercial activities, tends to be more stable than the transportation component which is highly dynamic. See Figure - 6.1 which is a general schematic flow chart of integrated land use and transportation. Most of TLUM have been applied regionally, mainly at the urban level, as a larger scale would be prohibitively complex to model. The modeling of the
transportation components is particularly relevant and is divided in four sequential stages for the estimation of travel demand, from where movements originate, how they are allocated, what modes are used and finally what segments of the transport network are being use. To gain a better understanding of the behavior of urban areas, several operational transportation / land use models (TLUM) have been developed. These models have several uses like forecasting future urban patterns based on a set of economic assumptions or to evaluate the potential impacts of legislations pertaining to environmental standards, testing theories, policies and practices about urban systems. With this simulation model, urban theories can be evaluated and the impacts of policy measures, such as growth management and congestion pricing can be measured.

![Figure - 6.1 General Schematic Flow Chart of Integrated Land Use and Transportation](image-url)
6.2.1 Four Stage Transportation Demand Modeling

Figure – 6.2 shows the four stage travel demand modeling framework. The same is briefly described below:

- The first stage is called trip generation and deals with trip rate estimates, usually at the zonal level. The most common methods for trip generation are cross-classification (also referred to as category analysis) and multiple regression analysis. Cross-classification seeks to identify specific socioeconomic groups within the population that have common trip generation characteristics. The trip generation of a zone will thus be the outcome of its composition. Regression analysis estimates the number of trips generated by a zone (dependant variable) as a function of a series of independent variables.

- The second stage is referred to as trip distribution and deals with spatial movement patterns; the links between trip origins and destinations. The most common technique for estimating trip distribution is the gravity model. There are various forms of the gravity model and various calibration techniques as well. Cross-classification and multiple regression can also be used to estimate the number a trips a zone would attract.

- The third stage is modal split where the proportion of trips made by automobile drivers and passengers, transit, cyclists, walking etc. are estimated. Logit modeling is commonly used as it evaluates the preference of each user in terms of probability of using a specific mode for a specific origin / destination pair.

- Finally, once the spatial patterns of movements by various modes are estimated, trips are assigned to the various transport links. This is done mostly by using operations research methods aiming at minimizing travel costs or time over a transport network.

6.2.2 Components of a Transportation / Land Use System

A transportation / land use system can be divided in three subcategories of models (Figure - 6.3):

Land use models which are generally concerned about the spatial structure of macro and micro-economic components, often correlated with transportation requirements. For instance, by using a set of economic activity variables, such as population and level of consumption it becomes possible to calculate the generation and attraction of passengers and freight flows.
Spatial interactions models which are mostly concerned about the spatial distribution of movements, a function of land use (demand) and transportation infrastructure (supply). They produce flow estimates between spatial entities, symbolized by origin-destination pairs, which can be disaggregated by nature, mode and time of the day.

Transportation network models which try to evaluate how movements are allocated over a transportation network, often of several modes, notably private and public transportation. They provide traffic estimates for any given segment of a transportation network.

To provide a comprehensive modeling framework, all these models must share information to form an integrated transportation / land use model. For instance, a land use model can calculate traffic generation and attraction, which can be an input to the spatial interaction model. The origin-destination matrix provided by a spatial interaction model can be an input to traffic assignment model, resulting in simulated flows on the transportation network.

6.2.3 Major TLUM Models

There are a wide variety of TLUM, most of them developed during the quantitative revolution that transformed geography in the 1960s and 1970s. Among the best known are:
• Lowry Model. Considered to be the first transportation / land use model (1964), it links two spatial interaction components. The first calculates spatial interactions between basic employment activities and zones of residence, while the second calculates spatial interactions between service employment activities and zones of residence.

![Figure - 6.3 Components of a Transportation / Land Use System](image)

- ITLUP. The Integrated Transportation and Land Use Package is composed of a residential allocation model, an employment allocation model, and a travel demand model.
- MEPLAN. This model is a derivative of the Lowry model, since it is based on the economic base theory. It considers the two components of the transportation / land use system as markets, one market for land use and one market for transportation.
- Cellular automata. A new range of models where space is represented as a grid (raster) with set rules enforced to govern the state of a cell depending on the configuration of its adjacent cells.
The core of most transportation / land use model is some kind of regional economic forecast that predicts and assigns the location of the basic employment sector. As such, they are dependent on the reliability and accuracy of macro-economic and micro-economic forecasting. Traditionally, such forecasting tends not to be very accurate as it fails to assess the impacts of economic, social and technological changes. For instance, globalization and the emergence of global commodity chains have significantly altered the dynamics of regional economies.

Additionally, few TLUM are dealing with freight transportation. This can be explained by the fact that passengers transportation in urban areas tends to be highly regulated by governmental agencies (e.g. public transit) while freight transportation is dominantly controlled by private entities. Paradoxically, while freight related activities such as terminals and distribution centers tend to occupy a large amount of space, they do not generate a large amount of passenger traffic.

### 6.3 Typical Uses of GIS in Four Stage Transportation Modeling

#### 6.3.1 Travel Demand Forecasting in a GIS Context

Travel forecasting models are used to predict changes in travel patterns and the utilization of the transportation system in response to changes in regional development, demographics, and transportation supply. Modelling travel demand is a challenging task, but one that is required for rational planning and evaluation of transportation systems.

There are many reasons why it is valuable to have a GIS as an integral part of a travel demand forecasting package. First, GIS makes it possible for planning models to be much more accurate. For example, network distances are based on the actual shape of the road network and a correct representation of highway interchanges.

Second, the whole modelling process is more efficient. Data preparation is greatly facilitated and the database and visualization capabilities catch errors before they cause modelling problems. For all of these reasons, less staff time is needed to implement and maintain travel models.

A third important advantage of a GIS-based modelling system is the use of the GIS itself and
GIS-derived measurements directly in the modelling process. For example in TransCAD, different modelling equations can easily be derived and applied for different geographic subareas. It also brings new and much-needed capabilities for measuring geographic accessibility.

### 6.3.2 GIS Modelling Capabilities

Certain modelling capabilities are required in GIS so that they can perform modelling with respect to transportation context. It should include comprehensive tools for trip generation, trip distribution, mode split modelling, traffic assignment, and all related matrix and network processes. For example the GIS software TransCAD supports all important styles of travel demand modelling including sketch planning methods, four-step demand models, activity models, and other advanced disaggregate modelling techniques.

#### 6.3.2.1 Trip generation

The goal of trip production (Figure - 6.4 and 6.5) is to estimate the number of trips, by purpose that are produced or originate in each zone of a study area. Trip generation is performed by relating frequency of trips to the characteristics of the individuals, of the zone, and of the transportation network. The four primary tools for modelling trip production as also provided in software TransCAD are:

**Cross-Classification:** Cross-classification methods separate the population in an urban area into relatively homogenous groups based on certain socioeconomic characteristics. Then, average trip production rates per household or individual are empirically estimated for each classification.

**Regression Models:** They estimate and apply multivariable aggregate zonal models and disaggregate models at the household or individual level. They use data aggregated at the zonal level, with the average number of trips per household in the zone as the dependent variable and average zonal characteristics as the explanatory variables. The second method uses disaggregate data at the household or individual level, with the number of trips made by a household or
individual as the dependent variable and the household and personal characteristics as the explanatory variables.

**Discrete Choice Models:** Discrete choice models use disaggregate household or individual level data to estimate the probability with which any household or individual will make trips. The outcome can then be aggregated to predict the number of trips produced.

**Population Synthesis:** In addition to applying disaggregate models to expanded survey samples, synthetic populations can be generated whose trip making can be forecasted with micro-simulation.

A GIS based modeling system facilitates identifying geographic variation in trip generation and applying differential rates based upon sets of zones that combine geographic and other selection criteria. Models included with TransCAD estimate the number of trips, by purpose that are produced or originate in each zone of a study area. Similarly geographic data can be readily used in computing and incorporating accessibility measures in trip generation relationships. GIS-T approach can be used in refined treatment of special generators like parcels or larger areas which have intimate connection with network as point locations and not as zones. So their influence on trip generation can also be added.

**6.3.2.2 Trip Attraction**

The goal of Trip Attraction (Figure - 6.6) is to predict the number of trips attracted to each zone or to a particular land use. In many ways, estimating attractions is similar to estimating trip productions. Thus, cross-classification, regression, and discrete choice methods can be used to estimate the number of trips attracted to a zone.

**6.3.2.3 Trip-Balancing**

In trip generation, separate models are used to predict productions and attractions. This invariably leads to a discrepancy between the number of intraregional trips produced in an area
and the number of trips attracted to an area. To conserve trips, balancing methods are required so that the number of attractions equals the number of productions. Trip generation and attraction can be balanced flexibly to productions or attractions or a linear combination thereof.

Figure - 6.4: A Typical Trip Production Map Generated in TransCAD

Figure - 6.5: A Typical Bus Trip Production in TAZ Generated using Prism Map
6.3.2.4 Trip distribution

Trip distribution (Figure - 6.7) models are used to predict the spatial pattern of trips or other flows between origins and destinations. Models similar to those applied for trip distribution are often used to model commodity flows, retail trade, and store patronage. In conventional practice choice alternatives are tagged with the network distance between origin centroids and destination centroid for each mode. For access modes the best path can be found on the walk or drive networks and incorporated in to the model. GIS can be used to develop more precise measures of accessibility and to identify choice sets for destination and mode choice models. For example for some trip purposes destination can be limited to those within an hour from the origin.
Figure - 6.7: A Typical Trip Distribution Map Generated in TransCAD

TransCAD provides numerous tools with which to perform trip distribution, including procedures to implement growth factor methods, apply previously-calibrated gravity models, generate friction factors, and calibrate new model parameters. In addition to doubly constrained trip distribution models that ensure that the output flow matrix from trip distribution matches the input productions and attractions, it has tri-proportional models which allow for another dimension of constraints. In tri-proportional models, groups of cells in the P-A flow matrix are required to sum to specified values.

6.3.2.5 Mode Choice Modeling

Mode choice models are used to analyze and predict the choices that individuals or groups of individuals make in selecting the transportation modes that are used for particular types of trips. Typically, the goal is to predict the share or absolute number of trips made by mode (Figure –
6.8). An important objective in mode choice modelling is to predict the share of trips attracted to public transportation. GIS should provide procedures for calibrating and applying mode choice models based on multinomial and nested logit models (Figure - 6.9), as well as legacy methods, and which may be pursued at either a disaggregate or aggregate zonal level.

![Figure - 6.8: A Typical Mode Choice Model Map Generated in TransCAD](image)

### 6.3.2.6 Traffic assignment

GIS technology have ushered in a trend of using much more detailed and realistic networks in traffic assignment (Figure - 6.10) which results in more accurate measurement of distances and improvement of travel times. GIS-T can be a powerful calibration aid for traffic assignment. Map graphics that scale the widths of network segments to reflect volumes are an efficient way to examine deviation from traffic counts and spot links that clearly have incorrect flows. Various
forms of traffic assignments models which has been incorporated in GIS-T model TransCAD are:-

![Image of Nested Logit Model in TransCAD]

**Fig.6.9 Nested Logit Model in TransCAD**

- All-or-Nothing Assignment
- Incremental Assignment
- Capacity Restraint Assignment
- User Equilibrium Assignment
- Stochastic User Equilibrium Assignment
- System Optimum Assignment

Similarly, there are various advanced methods of traffic assignment that are also included in software TransCAD:

- Multi-modal toll road assignment
- Path-based assignment
- Multi-point equilibrium assignment
- Combined distribution-assignment
- Assignment with traffic signals and HCM intersection delay
- Dynamic equilibrium traffic assignment

**Figure - 6.10 Traffic Assignment on a Network**

### 6.3.2.7 Assignment Utilities

**Screenline Analysis:** Screenline analysis compares the results of trip assignment with the traffic counts on roads. More precisely, it is a process of comparing the directional sum of ground count traffic volumes across a screenline or a cordon line with the directional sum of the assigned traffic volumes across the same screenline or cordon line. Screenline analysis is a useful tool for the calibration of trip assignment models, and it can also be used for more general purposes of...
calculating flows that cross a screenline. Such exercise is also made easy through availability of GIS-based data and network.

**Subarea Focusing:** While forecasting transportation demand for a region, you may be interested in performing a more detailed investigation of traffic patterns within a subarea, such as the downtown area. To carry out subarea analysis, we can create an O-D trip table for any subarea. The reduced O-D table may be used for performing a traffic assignment on a subarea network in GIS, which may be more detailed than the regional network, or used in a traffic simulation for the subarea.

**Assignment Differences:** You can compare two flow tables to find assignment differences. The assignment differences utility creates a theme that graphically illustrates the locations and magnitudes of differences. This tool is particularly useful for analyzing the effects of changing network attributes, such as capacity, or employing different assignment techniques.

**Select Link/Zone Analysis:** You can create an origin-destination matrix file that indicates the number of trips that pass through a specified set of links or zones, sometimes referred to as critical links or critical zones. You can also create an assignment table that contains the component of flow on links that pass through a specified set of links or zones.

### 6.4 Linear and Network Models

The network model is a database model conceived as a flexible way of representing objects and their relationships. The details about database in transportation have already been discussed in earlier chapters. Typically with respect to transportation, a network is a graph in which object types are nodes and relationship types are arcs and is not restricted to being a hierarchy or lattice. The nodes represent points in space and possibly in time, and the links correspond to identifiable pieces of transport infrastructure (e.g. a section of road or railway). Directed links are referred to as arcs while undirected links are edges. A path is a sequence of distinct nodes connected in one direction by links.
6.4.1 Network routing problems

At the core of many procedures in GIS-T software are algorithms for solving network routing problems like finding shortest paths, travelling salesman problem, vehicle routing problem, network partitioning problem, arc routing problem and formation of network bands etc.

6.4.1.1 Shortest paths

They are routes over a transportation network that have the shortest distance, time, or lowest generalized cost, where the cost can be any combination of factors like distance, time or actual cost of travel. Finding shortest paths (Figure - 6.11) on a network is the principal block of many other algorithms and models.

![Figure - 6.11: Map Showing Shortest Path between Two Stations](image)

Let \( G = (V, A) \) be a network where \( A \) is the set of arcs and \( V \) the set of nodes \( N \cup \{o,d\} \). \( N \) consists of nodes that can be visited from an origin \( o \) to a destination \( d \). With each node \( i \in V \), a
time window \( \{g_i, h_i\} \) is associated. A path in \( G \) is defined as a sequence of nodes \( i_0, i_1, \ldots, i_k \) such that each arc \((i_k, i)\) belongs to \( A \). All path start at time \( g_0 \) from node \( i_0 \) and finish at \( i_k = d \) no later than \( h_d \). A path is elementary if it contains no cycles. Each arc \((i,j) \in A\) has a positive or negative cost \( c_{ij} \), and a positive duration \( t_{ij} \). Service time at node \( i \) is included in \( t_{ij} \) for all \( i \in N \). An arc \((i,j)\) in the set \( A \) is defined to be feasible only if it respects the condition 
\[ g_i + t_{ij} \leq h_j. \]

The mathematical programming formulation of the shortest path problem with time windows involves two types of variable: flow variable \( x_{ij} \) with \((i,j) \in A\) and time variables \( t_i \) with \( i \in V \).

\[
\min \sum_{i,j \in A} c_{ij} x_{ij}
\]

Such that 
\[
\sum_{j \in V} x_{ij} - \sum_{j \in V} x_{ji} = \begin{cases} 
1 & \text{if } i=0, \ 0 & \text{if } i \in N, \ -1 & \text{if } i=d 
\end{cases}
\]

\[
x_{ij} \geq 0, \text{ for } (i,j) \in A
\]

\[
x_{ij} (t_i + t_{ij} - t_j) \leq 0, \text{ for } (i,j) \in A
\]

\[
g_i \leq t_i \leq h_i, \text{ for } i \in V
\]

Here the first equation tries to minimize the total travel cost. The second and third equation are constraints that define the flow condition on network, while time window constraint appear in fourth equation and compatibility between flow and time variables is given in last equation.

### 6.4.1.2 Travelling salesman problem

The Travelling Salesman Problem (TSP) is a problem in combinatorial optimization studied in operations research and theoretical computer science (Figure - 6.12). Given a list of cities and their pair wise distances, the task is to find a shortest possible tour that visits each city exactly once. The problem was first formulated as a mathematical problem in 1930 and is one of the most intensively studied problems in optimization. It is used as a benchmark for many optimization methods. Even though the problem is computationally difficult, a large number of heuristics and exact methods are known, so that some instances with tens of thousands of cities can be solved.
With respect to transportation TSP consists of finding the low cost path over a network that visits a set of nodes from a specified starting point. The starting point for a travelling sales man problem is known as depot and the points to be visited are known as stops. The resulting path is called tour. The tour always begins and ends in a depot.

![Figure - 6.12: Map Showing Solution of TSP for a Set of Points](image)

Using integer linear programming formulation, assume a directly connected network $G= (N,A)$, where $N$ is the node set with $|N| = N$ and $A$ is the arc set defined as the Cartesian product of $N$ with itself then the travelling sales man problem is formulated as

$$
\min \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij} x_{ij}
$$

Subject to

$$\sum_{j=1}^{N} x_{ij} = 1 \quad \text{for} \ i = 1, \ldots, N$$
\[ \sum_{i=1}^{N} x_{ij} = 1 \quad \text{for } j = 1, \ldots, N \]

\[(x_{ij}) \in X\]

\[(x_{ij}) \in \{0,1\} \quad \text{for } i,j = 1, \ldots, N\]

Where \(c_{ij}\) is the length of the arc from node \(i\) to node \(j\), and the \(x_{ij}\) are the decision variables: \(x_{ij}\) is set to 1 when arc \((i,j)\) is included in the tour, and 0 otherwise. \((x_{ij}) \in X\) denotes the set of sub tour breaking constraints that restrict the feasible solutions to those consisting of a single tour. The sub tour breaking constraints can be formulated in different ways. But very intuitive formulation is

\[ \sum_{i,j \in S} x_{ij} \leq |S_A|-1 \quad S_A \subseteq A, \quad 2 \leq |S_A| \leq N-2 \]

Where \(S_A\) is some subset of \(A\) and \(|S_A|\) is the cardinality of \(S_A\). These constraints prohibit sub tours, i.e. tours in subsets with less than \(N\) nodes. Without this travelling sales man problem reduces to an assignment problem.

### 6.4.1.3 Vehicle Routing

A generalised version of travelling sales man problem is called a vehicle routing (Figure - 6.13) problem which has so many applications in transportation logistics. The problem is to route a fixed number of vehicles through a number of demand locations such that total cost of travel is minimized and vehicle capacity constraints are not violated. Characteristically there is a designated location known as depot where all the peoples have to start and end their tours. So it consists of two set of interlinked problems first, finding an optimal assignment of customer orders to vehicles. And second ascertaining which route each vehicle will follow in servicing its assigned demand in order to minimize total delivery cost. For example imagine a company that has one ware house that supplies goods to 20 retail stores in various locations. Each day truck must deliver goods from the ware house to each of the retail stores and then return to the ware house. Each truck has a fixed capacity and each retail store has some demand, the company must determine the number of trucks that are needed to meet the demand at each store and find cost efficient routes for each truck.
Each day, trucks must deliver goods from the warehouse to each of the retail stores, and then return to the warehouse. Each truck has a fixed capacity, which is a limit on the weight or volume of the goods that the truck can carry. Each retail store has some demand, which is the weight or volume of goods that must be delivered each day. In the simplest version of the vehicle routing problem, the company must determine the number of trucks that are needed to meet the demand at each store, and find cost-efficient routes for each truck.

The starting points for each route (such as the warehouse in the above example) are known as depots, and the points to be visited are known as stops. A vehicle route starts at a depots, visits one or more stops, and may or may not return to the depots. The goal of the procedure is to obtain a set of routes that minimizes the total time or distance travelled by the vehicle routing matrix.
The VRP is a well known integer programming problem which falls into the category of NP hard problems, which means that the computational effort required to solve this problem increases exponentially with the problem size. For such problems it is often desirable to obtain approximate solutions, so they can be found fast enough and are sufficiently accurate for the purpose. Usually this task is accomplished by using various heuristic methods, which rely on some insight into the problem nature.

There are various factors which make vehicle routing problem very complex, like:-

- **Multi depot problem**: Here there will be more than one warehouse and trucks can be served from any one of these warehouse.
- **Time window**: When there are restrictions in time for delivery points or for warehouse.
- **Fixed service time and variable service time**: Each stop will require an amount of time to service, which may be fixed or variable depending on the nature of demand.
- **Back haul stops**: Here vehicles may need to pick up empty containers at the end of trip.
- **Mixed pickup and delivery stops**: Each stop may have various types of pickups and deliveries, like only pickups or deliveries, or both.
- **Open ended route**: Here the route will not have the return trip from last stop to the depot.

There are many problems which could be solved by vehicle routing procedures, like:-

- Determining assignments and routes for bridge inspectors.
- Managing a messenger or pizza delivery service.
- Scheduling and routing sales personnel to potential customer site.
- Collecting solid wastes from dump sites located at office or industrial complex.

Let \( N = \{1, \ldots, N\} \) be the set of demand locations and \( k = \{1, \ldots, K\} \) be the set of available vehicles to be routed and scheduled. Consider network \( G = (V,A) \), where \( V = N \cup \{0\} \) is the set of nodes with 0 representing the depot of the vehicles and \( A = V^* V \) is the arc set that contain all the arcs \( (i,j) \) with \( i,j \in V \). \( C_{ij} \) denotes the cost of direct travel from point \( i \) to point \( j \), \( b_k \) the capacity of
vehicle \( k \), and \( a_i \) the size of the order of customer \( i \in N \) measured in the same units as vehicle capacity. Define the flow variable \( Y_{ik} \) as 0-1 variable equal to 1 if the order from customer \( i \) is delivered by vehicle \( k \), and 0 otherwise, and \( y_k: (y_{0k},...,y_{nk}) \). Then the vehicle routing problem can be formulated as the following non-linear generalized assignment problem.

\[
\min \sum_{k=1}^{K} f(y_k) \\
\text{Subject to}
\]

\[
\sum_{k=1}^{K} a_i y_{ik} \leq b_k, \text{ for } k = 1,\ldots,K,
\]

\[
\sum_{k=1}^{K} y_{ik} = (k \text{ if } i = 0 \text{ or } 1 \text{ if } i = 1,\ldots,N),
\]

\[
Y_{ik} \in \{0,1\} \text{ for } i = 0,1,\ldots,N; \ k = 1,\ldots,K.
\]

Here last three equations are the constraints and guarantee that each route begins and ends at the depot \((i=0)\), that each customer is serviced by some vehicle and that load assigned to the vehicle is within its capacity. \( f(y_k) \) represents the cost of an optimal travelling sales man problem.

### 6.4.1.4 Arc Routing

In arc routing problems (Figure - 6.14), the GIS-T user is attempting to find routes which will allow for an optimal (or at least an efficient) transversal of a set of arcs in the transportation network. Arc routing problems (ARP) consist of determining a least cost traversal of some arcs or edges of a graph, subject to a variety of constraints. Applications include bus service and any residential delivery, pick-up, or monitoring systems such as mail delivery, solid waste collection, or meter reading, respectively. In an arc routing problem people or vehicles are dispatched from one or more depots to traverse a set of service links. The result of arc routing problem is a set of one or more routes that covers all the set of service links with a minimum amount of dead heading. Deadheading is the distance from the point at which service is completed back to the bus depot, mail sorting plant, or other base facility.
Real world variations of arc routing problems include:

- Certain links may require no service because they perhaps lack houses
- Service is required on only one side of a street
- Multiple passes may be required by street cleaning or snow ploughing vehicles.

![Arc Routing Image](image)

**Figure - 6.14: Arc Routing**

### 6.4.1.5 Network Partitioning and clustering

It can be used to create service districts of networks based on accessibility so that each node or link is assigned to the closest or least cost service locations (Figure - 6.15). Network partitioning is used to perform drive-time analysis, or evaluate possible least cost facility locations. When you perform network partitioning, you can also calculate the network distance or travel time from specific locations.Partitioning problems involve creating of groups of features in a layer based on proximity or measures of similarity. The partitioning procedures in GIS-T software TransCAD support applications in service territory alignment, sales and marketing, political redistricting, and many other disciplines. Some examples of partitioning are:
You need to design legislative districts within a state. Each district is composed of a number of Census blocks and you need to balance the voting age population of each one.

You need to group retail sites into sets of equal demand so that each grouping can be serviced from a single supply centre. After determining an appropriate grouping you will assign each retail centre to a supply centre and run a routing procedure.

You need to develop marketing regions for a large company. You want the number of stores in each region to be about the same.

There are two procedures that can be used for these types of problems, regional partitioning and clustering. Regional partitioning will be used when you want to create compact and balanced areas that are composed of smaller geographic areas. We use clustering when you want to create groupings of features in a point or area layer based on the distance or travel cost between them, with or without capacity restriction.

There are also some differences between the two procedures:

<table>
<thead>
<tr>
<th><strong>Partitioning</strong></th>
<th><strong>Clustering</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Used only on area features</td>
<td>Used on point or area features</td>
</tr>
<tr>
<td>Specify seed for each district</td>
<td>Does not require to specify seeds</td>
</tr>
<tr>
<td>Creates balanced groups with no capacity restriction</td>
<td>Creates balanced group with a capacity restriction</td>
</tr>
<tr>
<td>Always creates contiguous groups</td>
<td>May create groups that are not contiguous</td>
</tr>
</tbody>
</table>

The partitioning model attempts to produce districts that are contiguous, compact and balanced. Contiguous means that all the zones that make up the district are adjacent or connected to each other. To use regional partitioning procedure we need to:

- Open or create a map containing the area layer to beportioned
- Create or open an adjacency matrix file that contains information on spatial relationship between the zones.
- Create a selection set of seed zones.
The primary output from the regional planning procedure is an assignment table contains the original zone IDs and the district to which each zone is assigned. The table is joined to the zone layer and can be displayed in a data view.

Clustering is the grouping of features in a layer based on proximity. The goal of clustering is to produce groupings that are as compact as possible, where there may also be limits on the size of each other. Some examples of clustering problems are:

- Assigning customers to sales people. Since each sale person has to travel from one customer site to another, we want each group of customers to be compact. There are also limits on the number of customers each sales person can handle.
- Creating groups of users of a telecommunication service.
- Managing a fleet of moving vans that pick up and deliver household goods.

![Network Partitioning](image)

**Figure - 6.15: Network Partitioning**
6.4.1.6 Network Bands

A network band (Figure - 6.16) encloses an area in which all links or nodes on a network are within a certain impedance, or value limit, of an origin. Creating network bands is useful, for example, for finding the distance from one or more origins along links in a network that can be covered within a certain amount of time, or for finding the number of locations within a certain distance of one or more origins. TransCAD creates bands by creating points along the network at which a certain value that you set is reached, and then joining those points to draw the border of each band.

![Network Bands](image)

Figure - 6.16: Network Bands

6.4.1.7 Facility Location Models

Facility location models are used to identify good location for warehouses, hospitals, retail stores, manufacturing facilities, and other types of facilities. In general, the goal in locating such
facilities is either to provide a high level of service to minimize operating costs, or to maximize profits.

Some examples of facility location problems are:

- Determining the best location for a new branch of public library. The goal is to provide the best overall level of access to city residents.
- Determining the best possible location for a new police station. The goal is to reduce the maximum distance a patrol car needs to travel from the station to a resident’s home.

The goal of a facility location problem may be to determine the number of facilities that are required to guarantee a prescribed level of service. The objective is to locate one or more facilities. The locations for these facilities are chosen from a set of candidate locations. In a regional warehouse location problem, for example, we may have identified half a dozen parcels that we can acquire for a new facility; in a nationwide location problem we may have chosen 25 metropolitan areas as possible facility sites. Typically, there is also set of existing facilities to be considered in evaluating new locations.

There may be fixed cost associated with locating or operating a facility at each candidate location. This cost can include land acquisition costs, overhead costs, and other expenses associated with candidate location. Each facility serves a number of clients. In some cases the clients are individuals or households, while in other cases the clients are stores or manufacturing facilities served by the facility. For each combination of facility and a client, there is a measure known as the cost of serving that client from that facility. The costs of service are stored in a matrix known as the cost matrix. When we use the facility location procedure to maximize profit, the cost matrix is replaced by profit matrix that indicates the profit that results from serving each other client from each existing and candidate facility.

To solve facility location problem, we must choose the objective, which could be to minimize costs, maximize profits or one of several other options,

In general the goal of a facility location problem is one of the following:-
### Goal | What it means
---|---
Minimize average cost of service | Provide the best overall service to the clients without worrying about whether service to any particular client is much worse than the average.
Minimize highest cost of service | Provide the best possible service to the client who is farthest away from the set of facilities.
Minimize lowest cost of service | Place the facilities that are as far as possible from the nearest client.
Maximize profit | Choose locations to increase the difference between revenue and cost.

The procedures works in two stages:

- It identifies a set of initial facility locations using a greedy heuristic.
- It attempts to improve on the initial set of locations by swapping candidates with chosen facilities on a pair-wise basis until no improvement can be made.

The greedy heuristic chooses the next best location by evaluating all the candidates and selecting the one that best achieves the desired objective. When we chose to maximize profit, there should generally be at least one candidate facility with a positive fixed cost. Otherwise, the solution will be to locate a new facility at each location.

**Exercise**
1. Explain 4-stage travel demand modeling process.
2. What are land use models? Which are the different types of transport land use models?
3. Explain the various applications of GIS in travel demand modeling.
4. Explain the travelling sales man problem and vehicle routing problem. Explain the various complexities involved in vehicle routing problem?

**Assignments**
1. In a digitized map of any city with point data (bus stops, land marks etc) and road network data try to find the shortest path between any two points.
2. Try creating a network band with respect to an origin point using TransCAD or any other GIS software.