TRANUS: Integrated Land Use and Transport Modeling System

This document presents a general description of the TRANUS Integrated Land Use and Transport Modeling system. Emphasis is made on conceptual aspects, described in certain detail. This document is intended to those who wish to obtain an overview of the TRANUS model and its purposes and capabilities, particularly new or potential users.

The following topics are treated in the sections that follow:

- Purpose and range of applications
- Theoretical basis of the TRANUS system
- Main components of the modeling system
- Activities location and land use
- Activities-transport interface
- The transport system
- The evaluation procedure
- Operative characteristics and user interface

For a detailed description of specific aspects of the system, the following additional documents are available:

- Mathematical and algorithmic description of the Tranus system
- Operation of the Graphical Interface of Tranus
- Operation of the Programs of the Tranus system
- Tranus Tutorial

These documents are available from Modelistica's Internet site (www.modelistica.com), where additional material is available, such as utilities, articles, and so on. From the site it is also possible to download and install the software free of charge.

Purpose and scope of applications

Tranus simulates the location of activities in space, land use, the real estate market and the transportation system. It may be applied to urban or regional scales. It is specially designed for the simulation of the probable effects of projects and policies of different kinds in cities and regions, and to evaluate the effects from economic, financial and environmental points of view.

The most worthy characteristic of the TRANUS system is the way in which all components of the urban or regional system are closely integrated, such as the location of activities, land use and the transport system. These elements are related to each other in an explicit way, according to a theory that was developed for this purpose. In this way the movements of people or freight are explained as the results of the economic and spatial interactions between activities, the transport system and the real estate market. In turn, the accessibility that results from the transport system influences the location and interaction between activities, also affecting land rent. Economic evaluation is also part of the integrated modeling and theoretical formulation, providing the necessary tools for the analysis of policies and projects.

With a system of this kind it is possible to evaluate the effects of transport projects and policies on the location of activities and land use. It is also possible to assess the effects of urban regulations or housing projects on the transport system. Even if it is in integrated land use and transport projects and policies where the TRANUS system yields it maximum value, the system may be used also as a stand-alone transport model, especially to evaluate the short-term effects of transport projects.

The integrated nature of the model also makes possible the estimation of origin-destination matrices for several traveler types, modes and trip purposes. It is well-known that the use of households surveys to estimate such matrices is a vary costly procedure, and even with a relatively large sample size, it is virtually impossible to guarantee reliable results. With TRANUS it is possible to use a small sample to calibrate the integrated model of land use and transport, resulting in a set of reliable trip matrices at a reasonable cost and time.

In terms of the scale of applications, the TRANUS system may be applied to:

- Detailed urban areas
- Metropolitan areas
- Metropolitan regions
- Regions, states or provinces
- National level
- Regions made of several countries

The modeling system is able to represent the movements of both passengers and freight, and public and private modes, all in a single and common network with different vehicle types competing for road space. In the case of urban applications it is common to give more importance to the movements of passengers, including freight exogenously to represent its contribution to congestion. In the case of regional or national applications usually both passengers and freight are represented endogenously and with similar importance. In such applications it is also common to make full use of the input-output structure of the activities and land use model to make an explicit representation of the spatial economics involved, also evaluating the combined effects with the multimodal regional network.

The range of projects and policies that the model is able to represent is particularly wide. Land use policies may be combined with transport projects of different types and evaluated in combination. The following list is indicative of the range of policies that have actually been represented in many applications:

- Urban development plans
- Land use controls
- Impact of specific urban projects, such as industries, residential estates or shopping centers
- Regional development plans
- Housing plans or incentives
- Environmental protection plans, or protection to special areas
- New roads or improvements to existing roads
- Reorganization of the public transport system (new routes, fares, etc.)
- Exclusive Busways and integrated networks (Bus Rapid Transit)
- Mass transport systems (metros, light rail, etc.)
- Highways with tolls, urban or interurban
- HOV lanes
- Restrictions to automobile use
- Pricing policies, such as fuel taxes or parking fares

- Park-and-ride
- Selective road pricing or congestion pricing
- Rehabilitation of highways
- Road maintenance policies
- Railway projects or improvements to the existing rail network
- New port facilities or relocation of existing ones
- Relocation of freight and passengers airports

Tranus has been applied in a large number of studies in cities and regions of very different socioeconomic and cultural contexts, such as Latin America, USA, Europe and Japan. It is also used as a tool for postgraduate teaching in many universities around the world.

TRANUS was developed since 1982 for personal computers, and in this sense it pioneered the area, being the first transport model to become available for PCs. Today, with the increasing availability of computers, this early start became a clear advantage, because it required a strict discipline in the programming of the code. With the introduction of the Windows operating environment, the world of personal computers changed drastically, and TRANUS took advantage of the new facilities, becoming the first model of its kind to have a graphical interface in Windows. Nowadays the system makes full advantage of the interaction with other software, especially word processors, spreadsheets, geographic information systems (GIS) and traffic models.

Tranus is developed and maintained by Modelistica, that also supplies support and consulting services. New improved versions of the software are produced continually. The name TRANUS is protected by copyright. As from 2005 Modelistica has liberated the licence, making it available completely free. The code is also available to facilitate collaboration with other institutions, universities and companies acting under an open source arrangement.

Theoretical basis of the TRANUS system

Important theoretical advances have been made in the area of activity location-interaction and the transport system in the last few decades. Many have been formal theories based on quantitative methods to improve the understanding of urban and regional systems. The literature is vast, so that only the most important work is mentioned here, especially those related to the development of the TRANUS system. Figure 1 shows the 'family tree' of TRANUS in the form of the main schools or theoretical approaches.

The origins of spatial analysis go back as far as Von Thünen in 1826, whose work initiated the school of spatial microeconomics. From this starting point the work of Wingo and Alonso in 1964 developed the theoretical foundations to a great extent. More recent work of Mills and Anas are also relevant. From this school TRANUS adopted the main concepts of spatial economics, location, land use, and the generation of land rent.

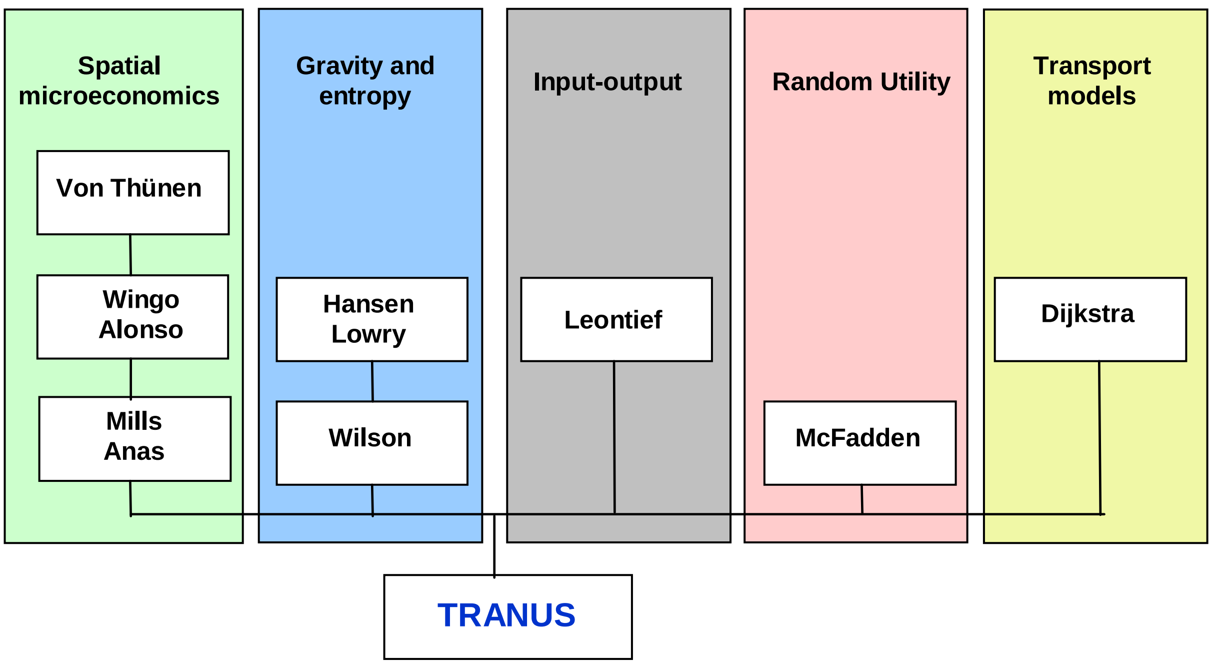
The second line of thought is known as gravity and entropy models. The first developments go back to the 1930s, but the work of Hansen (1959) and Lowry (1964) are considered as the first in this area of research. The first generation of gravity models was followed by the important work of Wilson (1970), who not only introduced maximum entropy principles to derive a set of spatial models, but also showed the way towards integrated land use and transport models. Wilson showed that the urban/regional and transport systems can be represented with a single comprehensive and consistent theory. This principle and the spatial interaction approach form an important component of the Tranus system.

The third line is represented by the important work of Leontief in 1936 on the input-output accounting framework. TRANUS owes much to this concept, since it includes a complete input-output model to represent the economy of a spatial system and the formation of prices. In TRANUS the original input-output model has been greatly extended and generalized, and the spatial dimension has been added and integrated with the transport system.

TRANUS is also embedded in the influential school of discrete choice models and random utility theory, leaded by the work of McFadden in 1975. Even if a general model was proposed and several areas of interest have been pursued, most authors of this school concentrate on the modal choice problem in transportation. In TRANUS the discrete choice approach is applied to all components of the urban/regional and transport system, from trip generation to mode choice, path choice, location choice, land use choice, and others. Rigorously speaking, TRANUS is a long chain of linked discrete choice models. The modeling system offers several choices of discrete choice models, from the standard logit model to scaled utilities and the new powit model proposed by Galvez.

Finally the family tree includes a branch for conventional transport models, from which TRANUS has drawn heavily, such as graph theory, queuing theory, and others, including minimum path search as originally proposed by Dijkstra in the 1950s.

Figure 1: The famliy tree of the TRANUS system



A unique characteristic of TRANUS is that it keeps total theoretical consistency throughout the decision chain, using the same discrete choice model in all cases, including modal split and assignment or path choice. In fact, assignment and modal split may be combined in a single procedure. TRANUS is the only model available that uses a probabilistic logit model for assignment. This fact makes it consistent with the theory and is subject to calibration through stated preference surveys. Discrete-choice assignment has shown to be far superior to the conventional equilibrium assignment model. This not only makes it more flexible and realistic, but also allows for intermodality and a consistent way to estimate the benefits or consumers' surplus right from the assignment.

It is worth noting that the transport model in TRANUS allows for a very detailed representation of the public transport system. This is not very surprising, since the model was entirely developed in Latin America, where the public mode is of paramount importance. The model is capable of representing large mass transit systems with many modes and possible integrated fares, route-by-route simulations, including non-motorized modes, informal modes, demand/supply equilibrium through variable waiting times, a supply model that adjusts frequencies, detailed statistics and indicators, GIS-type representation of the networks, and many other capabilities. It is probably the most advanced public transport model available today.

The theoretical background of the TRANUS system may be found in De la Barra: *Integrated Land Use and Transport Modelling*, Cambridge University Press, 1989. Based on this theoretical development, Modelistica has pursued a continuous research and development process. A detailed mathematical formulation of the model is available, as well as considerable documentation on the operation of the model, sample databases and tutorials.

Main components of the modeling system

The following sections describe the general structure of the land use and transport model. This is followed by sections describing each component in more detail: location and interaction between activities, the interface module, the transport model and the evaluation procedure.

General structure of the model

The main components of the integrated land use and transport model are shown in Figure 2. The two main subsystems are presented: activities and transport. Within each subsystem a distinction is made between demand and supply elements that interact to generate a state of equilibrium.

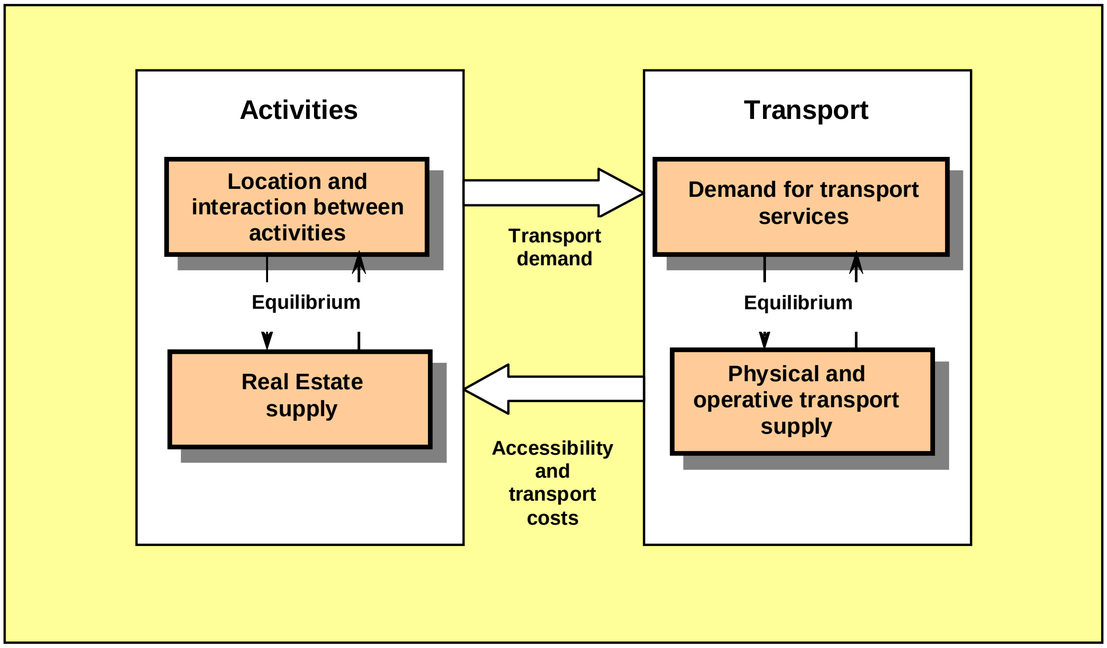
The location and interaction of activities represent the demand side in the activities subsystem. Activities such as industries or households locate in specific places and interact with other activities to perform their functions. Activities also require land and floorspace in order to perform their functions. Such spaces are provided by developers in the real estate market, thus representing the supply side. The interaction between these two elements must lead to a state of equilibrium. If demand for space is greater than supply in a specific place, land rent will increase to reduce demand. Consequently, land rents or real estate prices are the variable elements that lead the system to a state of equilibrium.

In turn, the interaction between activities generate travel requirements. In the transport subsystem demand is represented by the need for travel, that may take the form of people traveling to their places of work or services, or goods that are produced in one place and consumed in another. A distinction must be made between the physical supply and the operative supply. The physical supply is made of roads, railways, maritime routes or any other relevant component. The operative supply is made of a set of transport operators that supply transport services, such as bus companies, truck companies, airlines, or even automobiles and pedestrians. The operative supply uses the physical supply to perform its functions.

Demand/supply equilibrium in the transport subsystem is achieved in two ways: prices and time. If demand becomes greater than supply for a particular service, the price of the service may increase, but it is mainly the travel time that increases to achieve equilibrium. For instance, if the number of boarding passengers for a bus service is greater than the spare capacity of the service, waiting time will increase. Similarly, if the number of vehicles along a road gets close to the capacity of the road, congestion is generated, thus increasing travel times. In other words, time is an important component in the demand/supply equilibrium in the transport system.

The result of such equilibrium is synthesized in the concept of accessibility. It is the friction imposed by the transport system that inhibits the interaction between activities. Consequently, accessibility feeds back into the activities system, affecting the location and interaction between activities and the prices in the real estate market. Because it is a cost function, accessibility may also be called *transport disutility*.

Figure 2: Main elements of the land use-transport system



As may be seen, activities and transport are conceived as fully interrelated components with mutual dependencies. The interaction between activities gives rise to travel demand, and transport equilibrium, in turn, affects activity location and interaction and the real estate system.

The two main components, land use and transport, relate to each other in a dynamic way through time as shown in Figure 3, on the basis of discrete intervals *t1, t2, t3*, and so on. In this scheme, the interaction between activities in space generates *functional flows*, from which travel demand is derived. Demand is assigned to transport supply in the same time period. Transport demand/supply equilibrium determines accessibility between locations and influence economic flows. This feedback, however, does not occur in the same time period, but after a *time-lag* has elapsed. Consequently, accessibility in period *t1* affects the distribution of flows in time period *t2*. As there are several inertia elements in the location of activities, changes in the transport system may take several time periods to fully consolidate.

In this way, a change in the transport system, such as a new highway or a mass transit system, will have an immediate or short term effect in travel demand, but will only affect economic flows in the following time period. Changes in the activities system, such as increments in the production of some sectors or a new supply of buildings and land, will have an immediate effect on the transport system.

Figure 3: Dynamic relationships between activities and transport

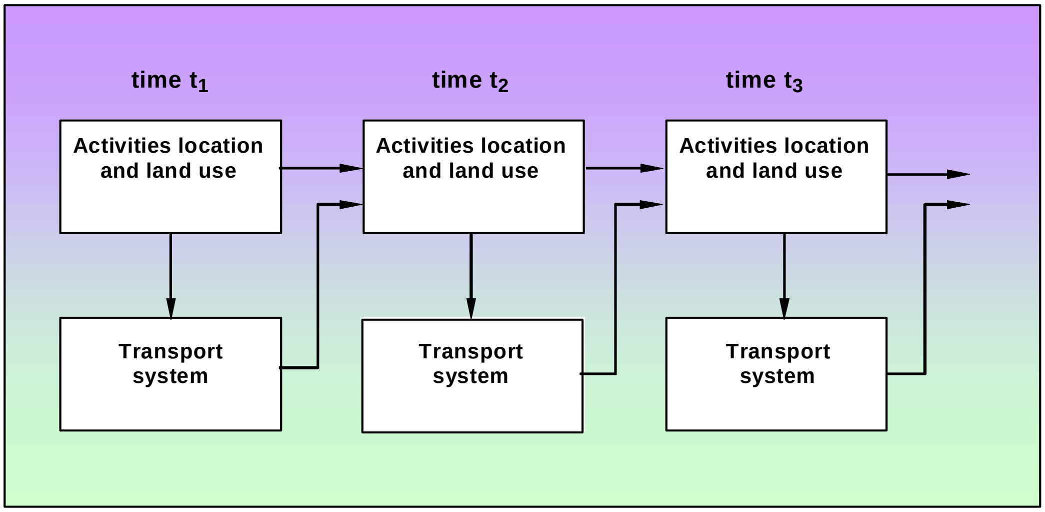


Figure 4 shows the main stages in the calculation sequence of the modeling process. The description begins with the activities system. As will be described later, the first stage is the location of final demand or *exogenous production*, followed by the location and interaction of induced production. One all activities have been located, the model checks for the demand/supply conditions in each location, especially land and floorspace. If demand is not equal to supply, prices are adjusted accordingly, thus initiating an iterative process until equilibrium is reached. At the end the land use model outputs the location of activities, consumption of space and land rents. The model also outputs a set of origin-destination matrices with the economic flows by activity sector. These matrices are an input to the transport model.

Transport related calculations begin with a procedure called *multipath search*. The model reads the data on the transport network, transport services supply, and a number of additional parameters such as fares, operating costs, values of time, preferences, and so on. On this basis the model estimates several paths or *travel options* for each origin-destination pair. Each path is a combination between physical links, modes and transport services or routes.

The next stage in the series of calculations is the estimation of transport costs and disutilities for each intermodal travel option or path. The number of trips is calculated as a function of the economic flows and an elastic function of transport disutilities. The number of trips thus generated may be split by mode, but this is an optional procedure because the multimodal assignment may do this. The purpose of multimodal assignment is to distribute travel demand among the several travel options or paths. The result is the number of person trips or freight assigned in each possible combination of physical link and route, as well as the number of vehicles.

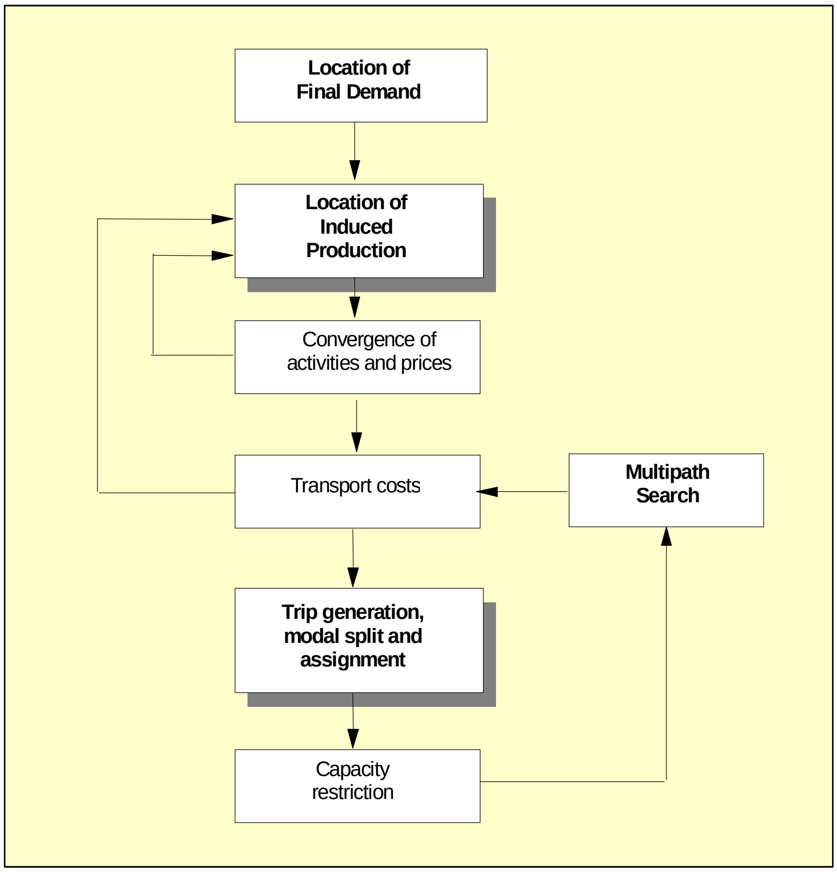
The final stage is capacity restriction, in which travel times are adjusted according to the relationship between demand and supply. As will be explained later on, in TRANUS this is a relatively complex procedure representing several phenomena. As the number of vehicles in a link gets close to capacity, speeds are reduced, increasing travel time. A point may be reached in which queues are formed, generating delays not only in the congested link, but also spreading congestion upstream into incoming links. It is worth noting that congestion affects all vehicles sharing a link, such as passenger cars, trucks or transit vehicles.

Capacity restriction is also applied to boarding passengers of public transport services. If the number of passengers gets close to the capacity of a specific route, the model increases waiting times, making the route less attractive in the following iteration. The model also calculates the time taken by transit vehicles at stops, as a function of the number of boarding or alighting passengers.

Congestion and waiting time change the transport costs and disutilities that were calculated at the beginning. For this reason the calculation sequence returns to calculation of costs, repeating trip generation, (modal split) and assignment, generating an iterative process that ends when the system reaches equilibrium.

In the following sections these processes are described in further detail.

Figure 4: Sequence of calculations in the TRANUS system



Activities location and land use

The activities generation and location model is an input-output model with production and consumption relationships, built into a very general and flexible structure. On this basis it is possible to develop a complex model to represent the economic and social system, or a simplified model with only a few elements interacting with each other. The complexity of the model depends on the purpose of the application, of available resources and availability of information.

The classical structure of the input-output model, with final demand, intermediate demand and primary inputs, is taken as a starting point. Final demand is the final destination of production, usually including private consumption, government consumption, exports and investment. The economic system must produce the quantities required from each sector, and for this purpose intermediate inputs are required. In turn, these intermediate inputs also require further inputs, thus forming a long chain of production and consumption. Apart from intermediate inputs, primary inputs are required, usually in the form of salaries, profits taxes, and imports.

The sum of all final demand and intermediate demand is equal to total production in the economic system. The sum of all intermediate inputs plus primary inputs is also equal to total production.

In TRANUS the basic concepts of the original input-output model have been generalized and given a spatial dimension. The concept of *sectors* is more general than in the traditional definition, because it may represent the classic sectors in which the economy is divided (agriculture, manufacturing, government, services, etc.), as well as population groups, and land and floorspace, all of which are part of the economic system. The number and types of sectors are defined according to the requirements of each application. The units in which each sector is represented is also a function of the purpose of the application, and may be monetary units, jobs, households, m2, Ha, or any convenient unit. Such flexibility makes it possible to apply the model to a large variety of cases, and to urban or regional levels.

An important distinction is made between *transportable* and *non-transportable* sectors. The main difference is that transportable sectors may be produced and consumed in different places, while non-transportable sectors may be consumed only where they are produced. The demand for coal by a steel industry, for example, may be satisfied by production of coal in many regions. The most typical non-transportable sectors are land or buildings that must be consumed wherever they happen to be. As a consequence, transportable sectors generate flows, whether movements of goods, services or people. For such movements to became possible, transport facilities must be available, adding transportation costs to production. Non-transportable sectors do not generate flows and do not consume transport.

The activities model also distinguishes between *internal* and *external* zones. Internal zones make up the study area, within which all interactions take place. External zones are used to represent economic relations between the study area and other areas outside it limits, especially imports and exports. These usually take the form of production, but it could be people as well, for example, people working within the study area and living outside. External zones may be defined only for the purpose of representing external trips to and from the study area, or even through traffic.

A number of characteristics are associated with each sector and zone. These are:

- **Exogenous Production:** Production not generated by internal consumption, equivalent to final demand in the classical input-output model. The location of this production does not depend on other elements of the study area, consequently may be given to the model, or may be assigned through spatial distribution functions.
- **Induced Production:** Production generated within the study area, to be consumed by internal or external sectors. The growth and location of induced production is determined by the sectors that demand it.
- **Exogenous demand:** Demand in addition to that demanded by the system. Exogenous demand is allocated to zones together with induced demand. Growth is distributed with an incremental model.
- **Induced Demand:** Production demanded by final or intermediate demand.
- **Exports:** Exogenous demand located in external zones.
- **Imports:** Production demanded by internal zones that is satisfied by production outside the study area. Imports compete with internal production, although may be limited by contraints.
- **Production Constraints:** Total production (exogenous + induced) may be limited in specific sectors and zones. There may be minimum constraint or maximum constraint or both.
- **Consumption Cost:** It is the unit cost of a sector in the consumption zone (CIF). Depends on the production price or cost in the production zone, and the unit cost of transport from the production zone to the consumption zone.
- **Production Cost:** The unit cost of production of a sector in a zone in the production zone (FOB). It is a function of the consumption cost of all of its inputs plus value added.

- **Equilibrium Price:** The unit price of a sector and zone with constraints. If there are no constraints, the price is equal to the production cost. If there is a maximum production constraint, and demand is greater than the maximum, the price is increased, generating an excess profit to the producers or scarcity rent. If demand is less than the minimum constraint on production, the price is reduced, possibly generating a loss to producers.
- **Value Added:** The cost to production in addition to the consumption cost of its inputs. Usually includes remunerations to capital and labor, and taxes.

Demand and distribution of production

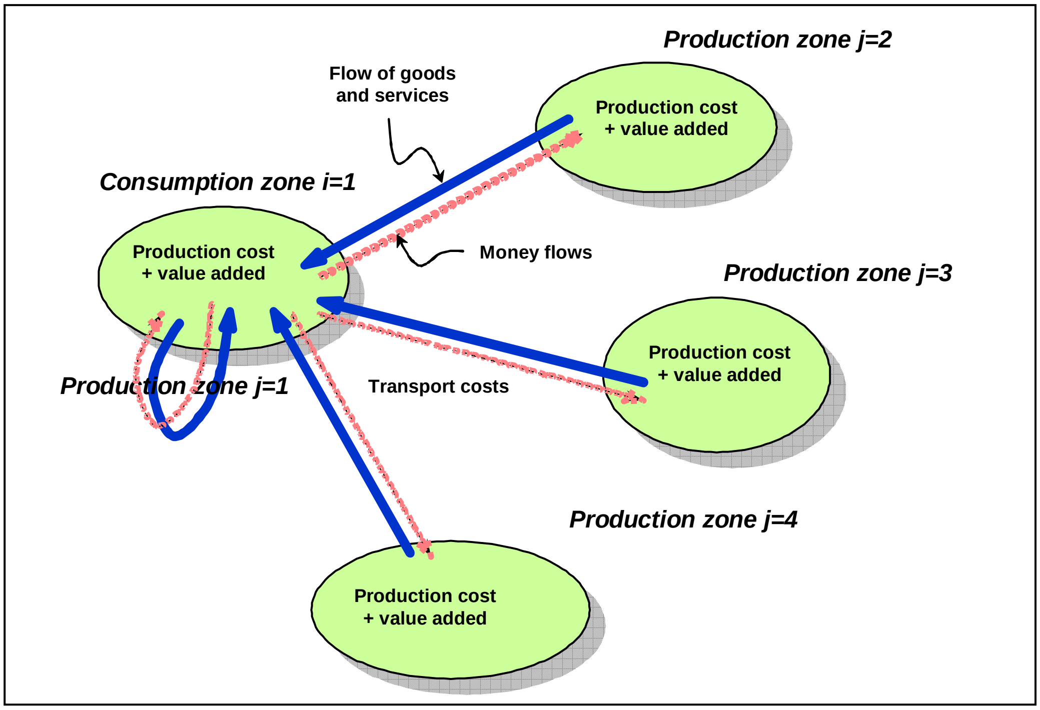
In principle, every sector requires inputs from other sectors. Part of total production goes to intermediate demand and part goes directly to final demand (internal or external). Given certain amounts of final demand in specific sectors and zones, the model determines the amounts of induced production required through *demand functions*, and allocates them to production zones through a spatial distribution or *location choice* model. In turn, allocated induced production requires further inputs, generating a production-consumption chain.

Each link in the chain represents economic and spatial flows, giving rise to functional flows when production and consumption take place in different zones. In some cases the production of non-transportable goods are demanded (such as land), giving rise to an economic transaction without flows. Each sector may require inputs of different types. For instance, manufacturing industry may require raw materials, workforce and other transportable goods, and may also require non-transportable buildings and land.

As shown in Figure 5, a transaction involves a consumption zone and several production zones, and the consumption zone may also be a production zone. The model distributes purchases from the consumption zone to the production zone with a discrete choice model. In the figure, blue arrows show the way production moves, and red arrows show the way the money goes. Some production zones may be external, in which case the flow will result in imports. The result of a transaction will be several flows from different production zones to the consumption zone. The model also keeps track of the cost of the transactions. In each transaction the following costs are computed:

- Production cost in the production zone (PC)
- Value added in the production cost (VA)
- Transport cost from the production zone to the consumption zone (TC)
- Consumption cost in the consumption zone (PC+VA+TC)

Figure 5: Production and consumption relationships

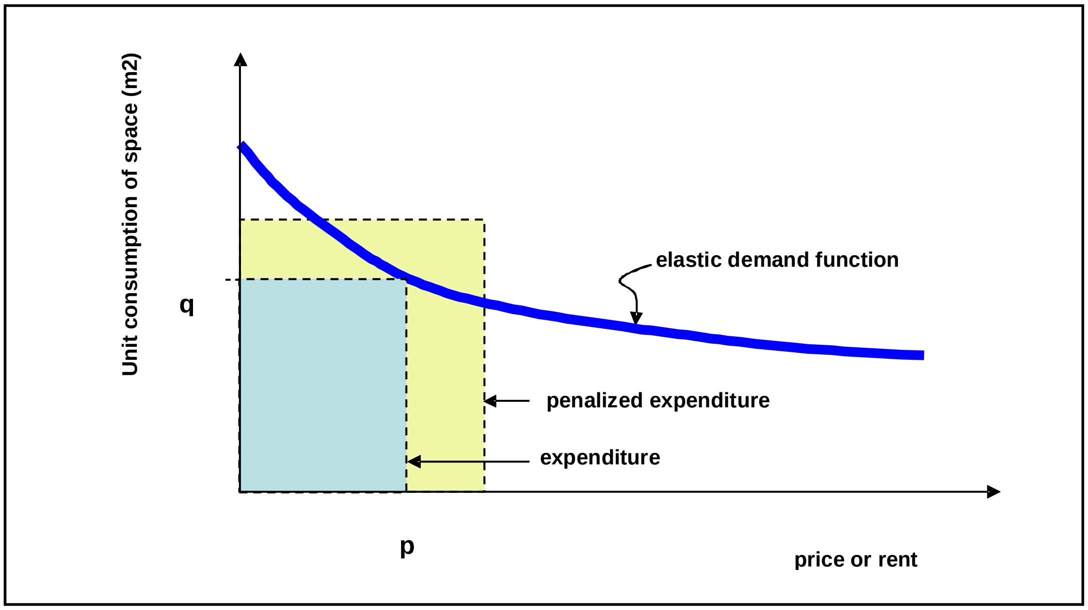


The spatial distribution from a consumption zone to the production zones is made with a discrete choice model logit or powit. The demand function in the model includes the consumption cost as well as transport disutility between zones. It is also possible to include attractors, that may be other variables or zonal values to represent non-modeled elements (for instance, environmental factors, urban regulations, etc.).

Once all demand has been assigned to production zones, the model checks for possible production constraints. For example, if in a zone more land of a certain type is consumed than is available, the model increases the price accordingly. Consequently this type of land will be less attractive in the next iteration. In the case of land and other constrained non-transportable sector, demand functions become elastic, as shown in Figure 6. In this example the elastic demand function related the amount of land consumed by unit of production to the price of land. If the price is *p*, the amount consumed will be *q*. The amount consumed multiplied by the price represents expenditure, the shaded area in the diagram.

If in a zone there are several types of land, the model takes them as alternative or substitutes. In this case a second discrete choice model is applied to distribute land consumption among the different types of land. The demand function includes penalized expenditure. Expenditure for each type of land in a zone is multiplied by factors making it bigger or smaller (as shown) depending on preferences. For example, low-income households may prefer high-density residential land, while high-income households may show opposite preferences.

Figure 6: Example of an elastic demand function for land



For very simple applications, the above description of the model may sound too complex. The intention here was to describe the potential of the modeling system. Most of these elements are optional, they are possibilities open to the model builder, and may be used if the data and resources are available. The model allows for very simple configurations, but offers the tools and capabilities to build rich and complex models as well.

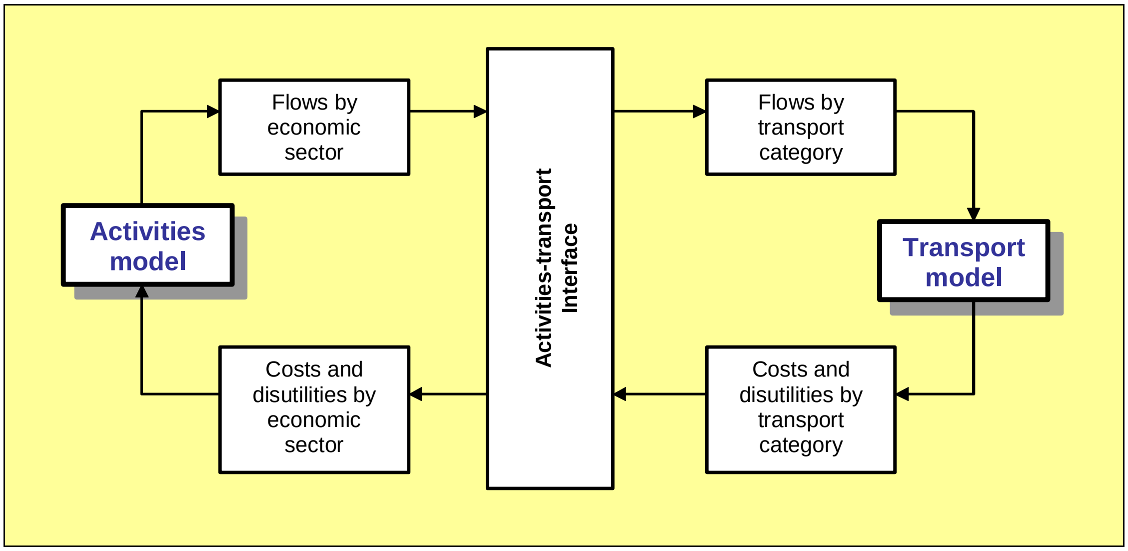
Activities-transport interface

The process of location and interaction between activities generates a set of matrices of flows, one for each transportable sector. These matrices form the basis for the calculation of trips by the transport model. But before they are fed in, it is convenient to perform a number of transformations to these matrices. This is the purpose of the activities-transport interface, as described in Figure 7. Several transformations can be made, such as:

- Formation of transport categories from flows by economic categories, according to fixed proportions. For example, flows generated by a manufacturing sector may generate heavy and light freight.
- Conversion of production units, since different units may be used in the activities model re the transport model. For example, in some applications production may be represented in monetary units, while freight may be in Tons. This is called value-to-volume transformation.
- Conversion of time units. For example production in the activities model may be represented in monthly or even yearly units, while freight in the transport model may be in daily units or even peak-hour.
- Change in the direction of flows. Economic flows go from the consumption zone to the production zone. This may be reversed in the transport model, or may be it is more convenient to have them both ways, as is the case of commuters on a daily basis.
- Addition of exogenous trips, such as external trips, through traffic or any other. The interface adds these to those generated endogenously by the model. It is also possible to have all transport demand specified exogenously for short term projections for a transport-only model.

These are transformations that are performed in the activities-to-transport direction. In the opposite direction some transformations are also necessary on the matrices of costs and transport disutilities. In general the transformations are the same but are applied in reverse. In the example above, manufacturing industry generated heavy and light freight; the transport model will calculate costs and disutilities for both heavy and light freight, so that a weighted average is required to estimate costs and disutility for the manufacturing sector.

Figure 7: Activities - Transport Interface



The transport system

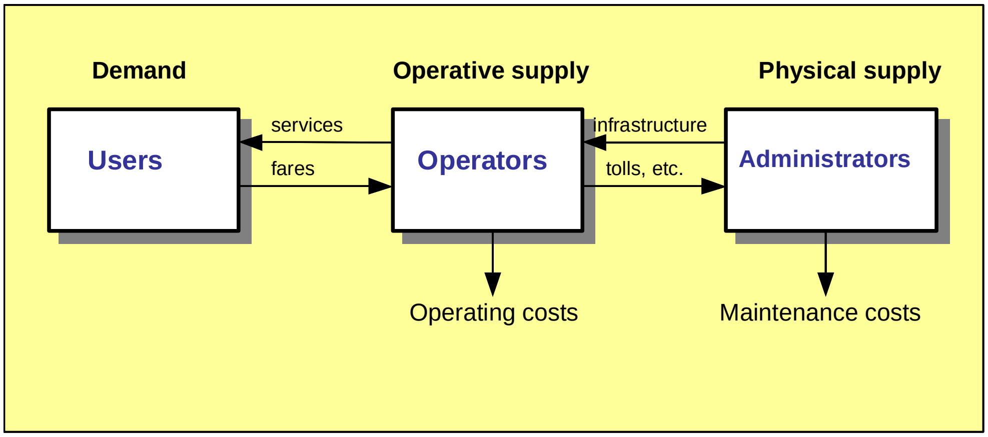
The activities-transport interface produces a set of matrices of flows or potential travel demand, as well as possible exogenous trips. From these, the transport model estimates the number of trips (trip generation), modal split, and assigns demand to supply.

As was mentioned, the main components of the transport system are demand, operative supply and physical supply. Demand is the need for travel, whether passengers or freight. Operative supply is represented by the different transportation services available, such as cars, bus routes, trucks, railway and even pedestrians. Physical supply is the infrastructure that makes transport possible, such as roads, railways, cycleways, maritime routes, etc.

Figure 8 shows the main economic relationships that take place between the various agents that the model keeps track constantly. **Users** demand transport services to operators, and pay tariffs. **Operators** charge users, and in turn have to pay operating costs, and in some cases may have to pay tolls for the use of the infrastructure. **Administrators** may charge the operators, and have to pay maintenance costs.

The above scheme may have some peculiarities. For example, a car driver is both user and operator at the same time. In many cases railways and metros are both operators and administrators. Pedestrians are both users and operators, but do not have operating costs or tariffs. Even so, the transport model applies the same accounting system to all entities alike.

Figure 8: Economic relationships in the transport system

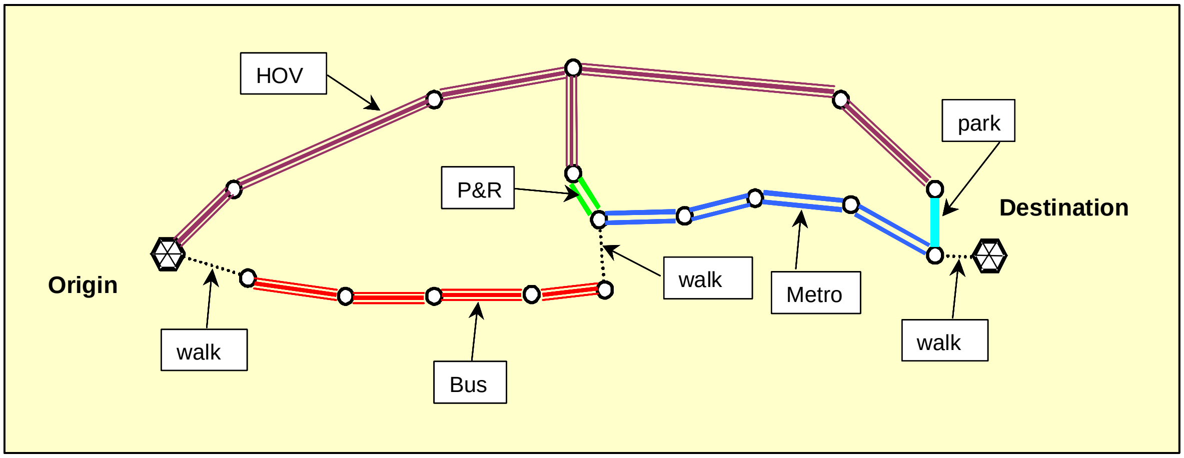


The first task in the transport model is the search for paths that connect each origin zone to each destination zone by *transport mode*. Transport modes, in turn, may be formed by several *transport operators*. The main difference between modes and operators is that travelers may chose to travel by one mode or another, and then they may choose to travel on several operators within a mode, making transfers. The modeler has plenty of flexibility in the definition of modes and operators. In an urban application, it is common to define a single mode for passengers, and then define many operators such as single-occupant cars, multiple-occupant cars, walk, cycle, buses, minibuses, metro, etc. In urban applications with very complex public transport systems it may be more convenient to define a private and a public mode and then have several public operators. In this case travelers will not be able to transfer from private to public modes. In regional applications it is common to have a passenger mode, light goods and heavy goods. Light trucks may be the single operator of the light goods mode, but the heavy goods mode may have heavy trucks, rail, ships, etc. In the later case heavy goods may transfer, say from trucks to rail and then get shipped. In the case of transit operators, several routes may be defined with specific itineraries, frequencies and stops.

A *path* is a combination of physical links and operators or routes, and represent a *travel option*. Links are part of the network, represented in the form of a directional graph. Each link in the graph has several characteristics, such as link type, length, capacity, transit routes and turn prohibitions or delays. Link types define a number of common characteristics for a set of links, such as free flow speeds by operator, flow-delay functions, equivalent car units (pcu) possible tolls, maintenance cost functions and the *administrator* in charge of the link. There may be several paths that have an identical sequence of physical links but with different operators and routes. Whenever there is a transfer, the model calculates possible transfer tariffs and waiting times.

Tranus uses a unique method called *multidimensional path search*. For each origin-destination pair and mode, the method finds several paths representing travel options. Path search is performed on a single multimodal network, avoiding the coding of separate networks for each mode. Paths are selected from all elements that make up generalized cost, including monetary cost, travel time, waiting time, and possible preferences. The method also allows for delays in links and turns. Worth noting is the possibility to represent integrated tariffs between transit operators, such as feeder buses and metro, or maybe park-and-ride with rail. It is also possible to specify different transit fares for special travelers, like school trips or elders. Figure 9 shows an example of multimodal paths connecting an origin to a destination. It also helps to explain why in Tranus modal split and assignment may be fully integrated. Note that one option in the example is to travel by high-occupancy vehicle (automobile with two or more passengers) to a park-and-ride facility, and then to the metro.

Figure 9: Example of a set of multimodal paths connecting an origin to a destination



Another technique that is unique to Tranus is called *dual graph*. For all internal calculations, the model builds a dual graph from the original conventional graph, in which the original links are transformed into the nodes of the dual, and the dual links represent turning movements. This procedure makes it very easy to specify prohibited turns without the need to expand the nodes, and with totally reliable results. The dual graph technique is also used to represent transfers between transit routes. The dual graph technique is completely transparent to the modeler, because when the calculations are finished, results are transformed back into the original representation.

Finally, *overlapping control* is a technique that solves the well-known problem of attribute correlation among competing paths. The model keeps track of the degree of coincidence between paths, selecting only those that represent really distinct options. In this way the search method does not 'get lost' in small, less relevant, links. The method also allows for the hierarchical ordering of link types, such as express roads, arterial roads, locals, and so on. The method guarantees that if the network is symmetrical, the resulting paths will also be symmetrical.

Once path search is finished, the transport model begins the iterative process with the calculation of costs and disutilities. Three types pf costs are calculated: monetary cost, generalized cost and composite cost. Monetary cost is what the traveler, whether passenger or freight, pays for the trip. Generalized cost is what the traveler perceives as a cost, and includes the monetary cost, the value of travel and waiting time and possible preferences. Composite cost is the perceived cost of the population of decision makers, also known in the literature as maximum perceived disutility, or log-sum in the logit formulation. Monetary costs are calculated at a path level, mode level and at the trip generation level. Composite costs are calculated at mode and generation levels. These highest level is stored and fed towards the activities model.

Once costs are calculated, the model estimates trip generation, modal split (if applicable) and assignment. Trip generation takes the matrices of flows generated by the activities model and transformed by the interface module, and applies an elastic function with respect to travel disutility. This means that if there is an improvement in the transport system, the number of trips increases, particularly those that benefit the most with the improvement. Each transport demand category will have different parameters for the trip generation function, particularly different elasticities. In this way the trip generation module transforms the matrices of flows into actual matrices of trips for a particular period of time, such as peak hour or total day.

Elasticity in trip generation is very important for evaluation, because it means that *induced demand* is taken into account in the consumers' surplus. It also produces more realistic results. At peak hour, for instance, work trips may have a low degree of elasticity, given the compulsive nature of the trips, while trips to services may be postponed to off-peak periods if there is too much congestion. The model also compares the number of trips that would be generated if there was no congestion to those that are actually generated under congested conditions.

The difference is called *repressed demand* and is reported by the model, since it enables to estimate the economic cost of congestion in the study area, usually a surprisingly high figure.

Note that, because trip generation is applied to the matrices of flows, the results are matrices of trips. This completely avoids the need for a trip distribution procedure as in conventional transport models.

The next step in the sequence of calculations is the distribution of trips among competing modes. As was mentioned, this is optional because the multimodal assignment procedure can perform modal split as well. In some cases, however, the modeler may choose to separate trips by mode before going to the assignment stage, for instance, divide trips into public and private modes. If chosen, modal split is performed by applying a logit/powit model to the matrices of trips by demand category that resulted from the trip generation procedure. The utility function is the travel disutility by mode, in turn the composite cost derived from the path choice model. Of course each category may be split into modes that are available to the category. For example, passenger categories may be divided into public and private modes, while freight categories may be divided into light and heavy goods.

Trips by mode and demand category are then assigned to the network with a logit/powit path choice model. For each origin-destination pair, the path search algorithm selected a number of paths, each path representing a travel option. The model calculates the probability that trips of a certain category traveling from the origin to the destination will choose each path. The utility function of the model is the generalized cost of traveling along each path. This means that different categories may choose a same set of paths in different proportions. For instance, high-income travelers may prefer paths with private car instead of transit, or in general paths that even if they are more costly take less time. A good example is a choice of a fast highway with tolls and a normal slower road. In this case high-income travelers may prefer the toll highway, and maybe high valued freight traveling in small trucks will also prefer the toll highway. In all cases it does not mean that these categories do not use the slower/cheaper alternative; it only means that the proportions will be smaller.

This is one of the many advantages of probabilistic discrete choice assignment. If the network is not congested, as is usually the case in intercity conditions, each travel option receives a proportion of demand. In equilibrium assignment models, if the network is not congested, all traffic goes to the apparently shortest path, producing unrealistic results. Furthermore, the use of logit models means that each travel category will attribute value to characteristics of each travel option, such as monetary cost, travel time, convenience, and so on. There is, therefore, a direct relation between the behavior of the decision makers and the utility function of the model, and the parameters of the utility function may be estimated with statistical methods such as maximum likelihood or other. In turn, these methods are based on surveys, whether revealed or stated preferences, with the possibility of estimating the level of confidence. By contrast, the conventional equilibrium assignment model is not behavioral in this sense and cannot be estimated.

The final step in the iterative sequence is *capacity constraint*. In Tranus this involves several processes:

- As the flow of vehicles on a link increases, the speed along the link is reduced. This is done by applying flow-delay functions to each vehicle type. All vehicles are subject to delay, such as cars, buses, trucks, but not non-motorized modes (e.g. pedestrians).
- Beyond a certain point, delays in a link may spread up-stream in the network, slowing down vehicles in in-coming links, thus propagating queues.
- Turn-delays may be included at intersections.
- As the number of passengers boarding a public transport service increases and gets close to the capacity of the service, waiting time is increased
- Stop times in public transport services increases as the number of boarding or alighting passengers also increases, whichever is the greatest
- As the number of boarding passengers increases in a certain route, the operator may decide to increase the capacity by increasing the frequency. This is estimated by applying a supply model that takes into account the demand profile of the route, current and expected income and a parameter. Minimum and maximum frequencies are applied to each route.

At the end of each iteration, the degree of convergence is estimated by comparing in each link the difference in flows and the difference in speed between the current iteration and the preceding one. The worst case must be less than a specified convergence criteria for the process to stop, otherwise iterations continue until a maximum number of iterations is reached. At the end of each iteration the convergence indicators are displayed on-screen.

The evaluation procedure

The Tranus model estimates all the indicators or inputs required to perform socioeconomic, financial and environmental evaluation. Such indicators are completely embedded in the models and consequently keep total consistency with the simulations. Indicators are calculated both in the activities model and the transport model, and are differentiated by the socioeconomic agent involved, such as producers, households by income, land developers, travelers by category, transport operators, toll roads operators, government maintenance, and so on. For each of these agents, costs and benefits are calculated. In the case of suppliers of land or transport services, evaluation takes into account only monetary elements, but in the case of consumers, non-monetary elements are also included, such as preference for land, values of time, convenience of transport supply and others.

In the case of transport, the evaluation procedure has proved particularly useful to evaluate the effects of toll roads, enabling a complete analysis of the socioeconomic consequences on the various traveler categories, the economic effects on operators, and the financial effects of each possible concessionaire, including income split by who pays, and maintenance costs split by who causes the damage. In the case of complex integrated public transport systems, the model also provides very detailed results, estimating operating costs at a link level for all vehicle types and fares collected, also split by traveler category. Matrices of transfers between operators of the integrated system are particularly useful to calculate the transfer of money from one operator to another, an important component in the financial evaluation of integrated networks. Maps may be produced to represent benefits by zone of, say, a proposed metro line.

The results are reported by the model for each simulation period and scenario. If, say, the land use model represents a period of a month, then all economic indicators will be in monthly terms. Similarly, if the transport model simulated a peak period of two hours, then all costs and benefits are reported for the two-hour period. Tables of this kind may be produced for each scenario. In Tranus a scenario is a combination of year and policy, such as *'year 2020 with proposed rail service'*. In this way the analyst is able to compile a rich and vast set of indicators to evaluate the effects of proposed policies and projects.

For environmental evaluation, the activities and land use model provides a substantial part of land-related effects. Of interest are the expansion of urban areas by type and location depending, perhaps, on a transport related project or based on urban regulations. This not only makes it possible to asses the amounts of sensitive land that will be affected with one policy or another, but also allows the economic effects involved. For example a policy of urban expansion constraint, limiting the amount of land that may be consumed in the future, may result in an increase of the price of land, thus affecting the consumers' surplus of land consumers. In other words, it is possible to calculate the economic implications of an urban master plan. It is also worth pointing out that, because the model is capable of simulating the consumption of building areas by type, it is also possible to estimate fuel consumption and emissions produced by the built environment.

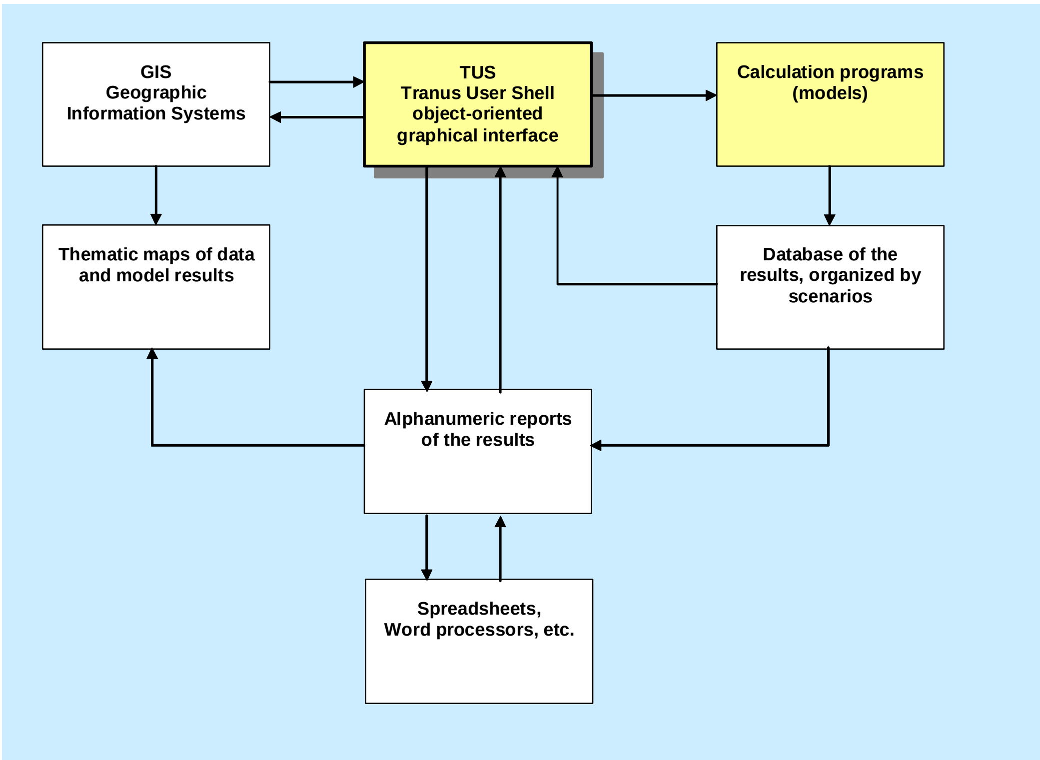
In the case of transport, environmental evaluation concentrates on emissions and energy consumption. These may be very detailed by vehicle type at a link level. It is also possible to estimate emissions by socioeconomic category, to estimate which category is most responsible for high levels of emissions.

Operative characteristics and user interface

The TRANUS system is programmed to run on standard PCs operating under Windows 98 onwards, preferably XP. Depending on the size of the application, fast machines with good RAM are most convenient. All programs and documentation may be downloaded free from www.modelistica.com or www.tranus.com. Installation of the software is a very simple process that takes less than 5 minutes. The programs are dimensioned for large applications.

TRANUS is composed of a number of programs and modules linked to each other. Figure 10 presents the main components of the operating structure of the modeling system. These are briefly described in the following paragraphs.

Figure 10: Operative components of the TRANUS system



TUS (Tranus User Shell)

This is one of the most remarkable features of the Tranus system, providing great flexibility and ease of use. It is the main component with which the model user interacts to perform most functions, like setting up a database, importing/exporting data to and from other applications, running the models, presenting maps with data and results of the simulations and producing numeric reports. The main features of the interface are:

- **Windows-based interface** with familiar-looking menus and icons to perform most tasks. All graphics are vector-based and may be copied to other Windows applications via the clipboard. Numeric data may be copied to and from a spreadsheet.
- **Object-oriented database.** Elements such as links, routes, zones, etc. are objects of the database that keep strict functional relationships with other objects. This facilitates the building of a database and makes the result fully consistent.
- **Representation of scenarios.** All year/policy combinations in a project are represented in a single consistent database. Scenarios are organized in the form of a tree. Each data object in the database is related to a scenario. Scenarios are logically linked to each other in the tree. For example, if a change is made in, say, year 2010-B, the change is automatically *'inherited'* by all depending branches down the scenario tree, such as 2015-B, 2020-B... Data may be copied and pasted to other branches. Color codes facilitate the identification of changes. At all times it is possible to navigate the database along

scenarios, and the changes are automatically shown on-screen. This is a great time-saving feature of the interface, it is very easy to operate and avoids many errors.

- **Data validation on-the-fly.** As soon as an error or inconsistent data is entered to the database a color code and a balloon message is produced. A validation report may be produced at any time.
- **Unlimited undo and safety backups.**
- **Extensive context-sensitive Help support** in English and Spanish.
- **Complete graphical network editing tools.** Create nodes and links interactively, Split links and merge links, define routes and many other facilities.
- **Geographical coordinates** (usually UTM) are used to locate nodes and calculate link lengths.
- **Background digital maps** with layers and geographical coordinates may be read-in in DXF format. The whole network may be coded over the imported maps with the network editing tools.
- **Import/export utilities** are provided to bring in all network-related data, including nodes, links and transit routes from other models or GIS databases. Similarly all network data already in the Tranus database may be exported to text comma-delimited files.
- **Run menu**, to run the required simulations for any scenario
- **Maps with the results of the transport model** are automatically generated in a variety of formats
- **Menu-driven generation of numeric tables with results** based on queries that may be stored. An area of the network may also be defined to produce selective tables.
- **MIF formatted maps** may be produced to generate maps that may be read in MapInfo.

Figure 11 shows the graphical interface of TRANUS (TUS). The typical menus at the top are accompanied by a second taskbar with icons to perform the most common tasks, a third taskbar with color palettes, and a status bar at the bottom. Then, to the right, the *network views* are displayed, and to the left, the *scenario tree* is shown. 'Navigating' the scenario tree changes the network view automatically. Several windows may be opened simultaneously.

Figure 12 presents a network view that has been copied to this document, showing assigned vehicles to the network with bandwidth proportional to volumes and a color code to distinguish different types of vehicles.

Figure 13 shows a map with the level of service in each link in the network, according to HCM standards represented in color codes.

Figure 14 shows an image of the interface that has been copied to this document in which a network has been coded directly over a GIS map imported as background. The network was entirely coded with the network editing tools provided by the Tranus interface. Color codes represent link types, and bandwidth is proportional to the capacity of each link.

Figure 15 shows a number of transit routes displayed over a digital map with actual UTM coordinates. For clarity, each route is shown offset with respect to the street center line.

Figure 11: Graphical interface of the TRANUS system

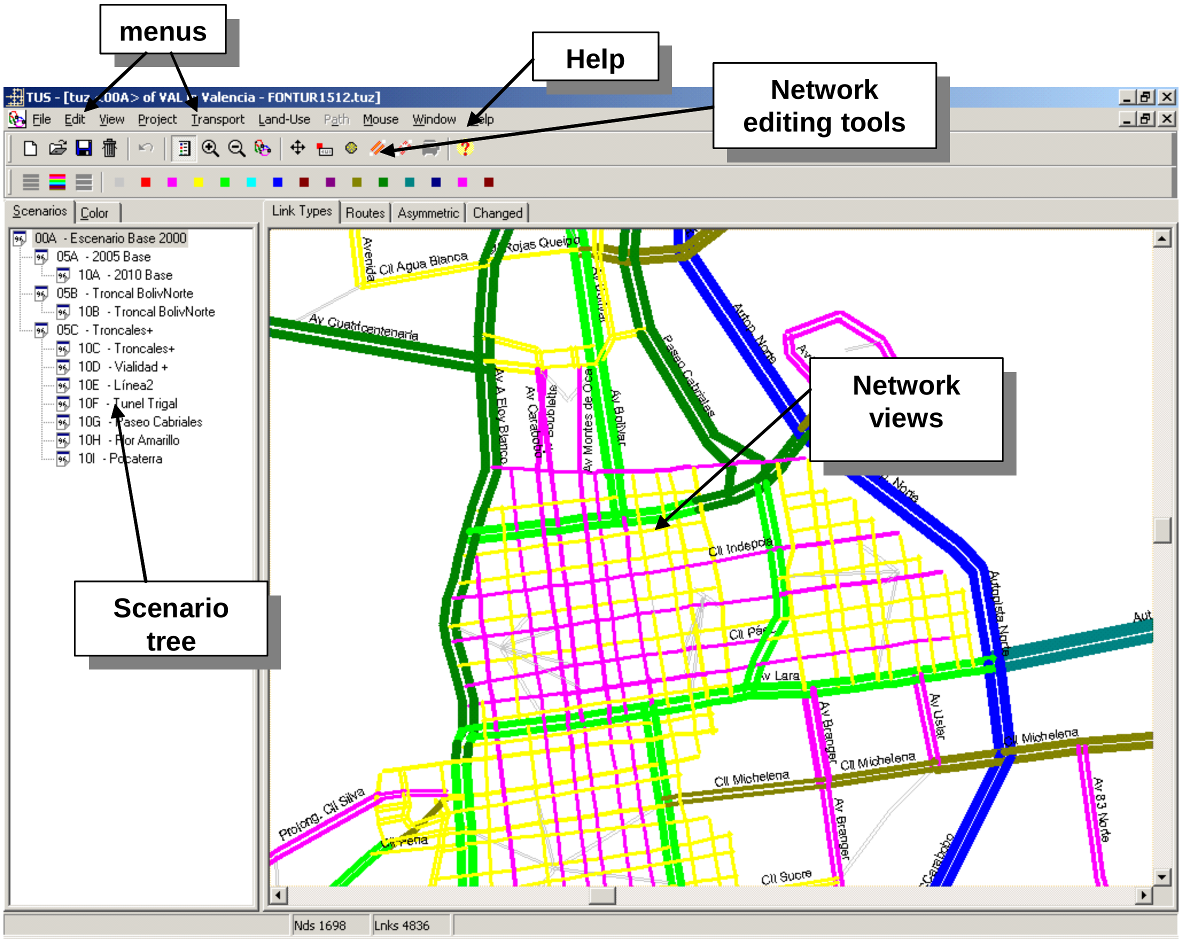


Figure 12: Assigned vehicles (red = cars, green = transit)

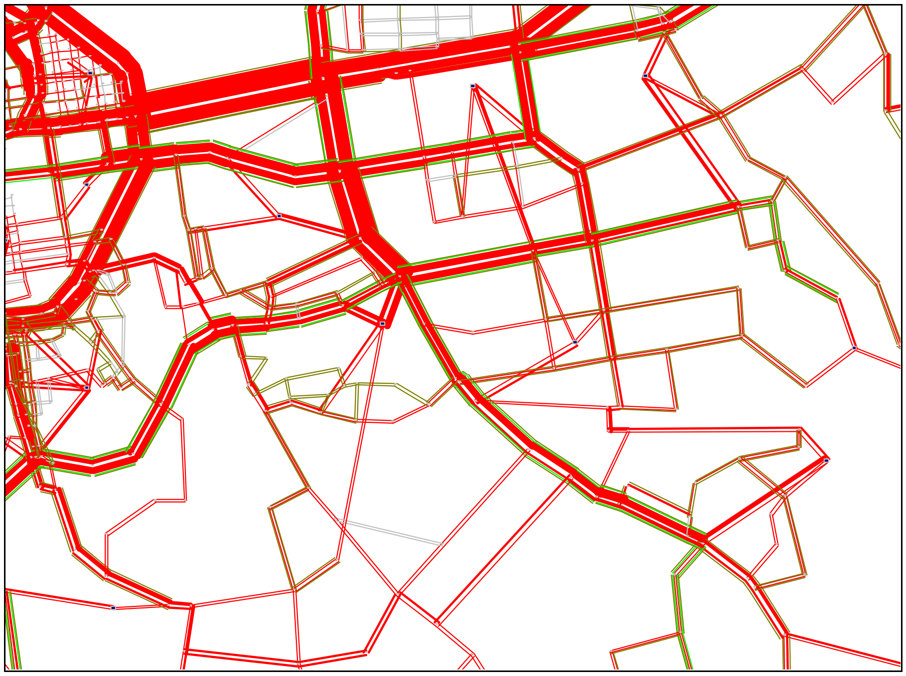


Figure 13: Level of service map

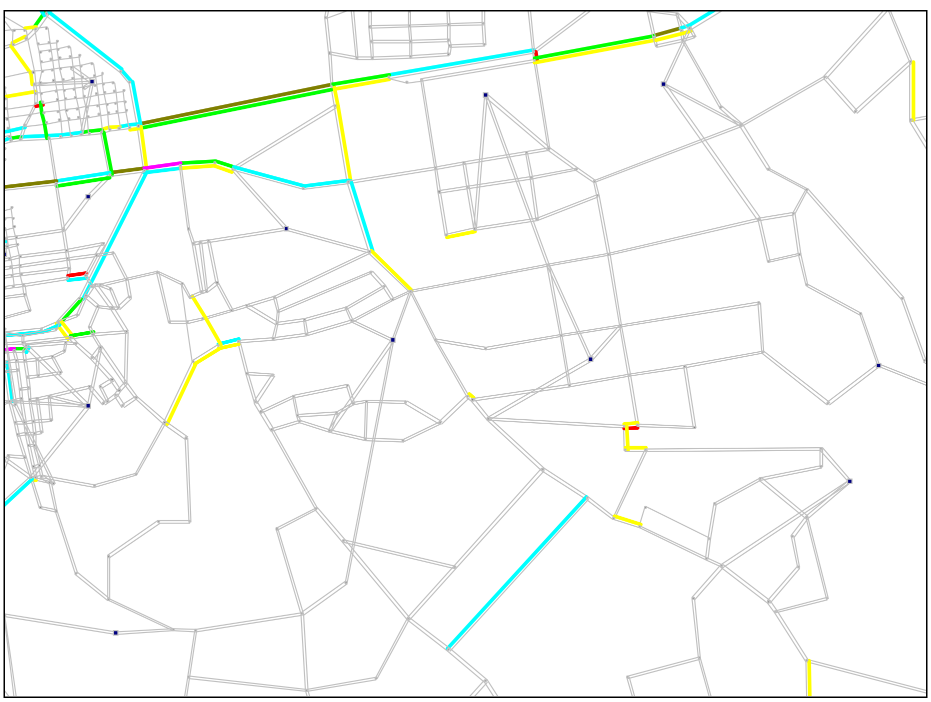


Figure 14: Example of a network coded directly over a GIS background imported into the TRANUS interface

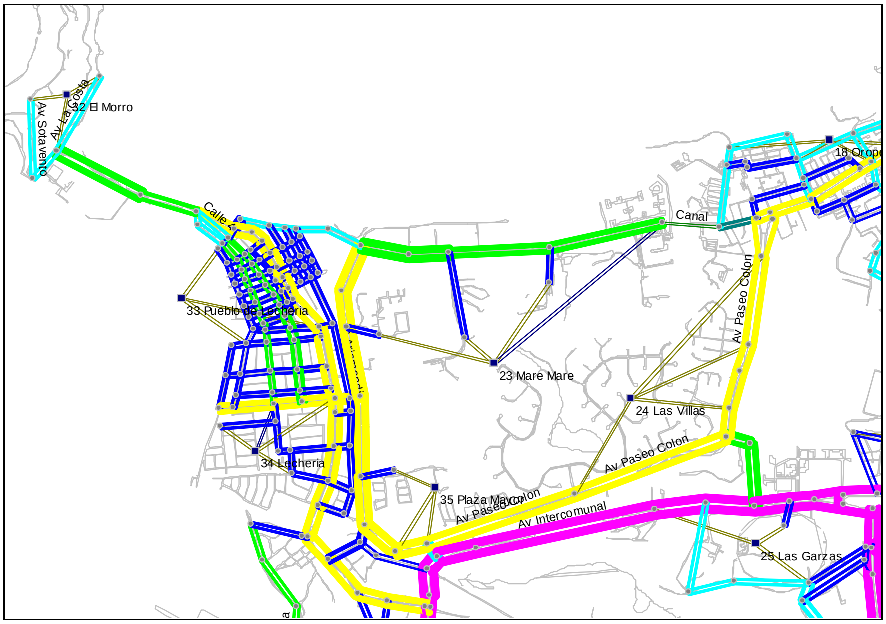
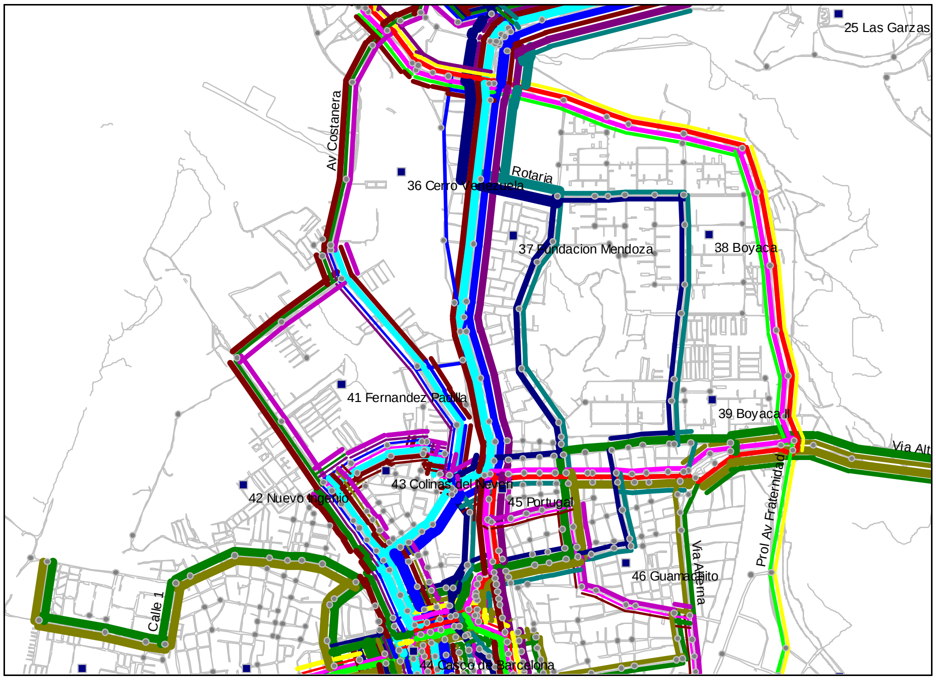


Figure 15: Presentation of transit routes



Model Programs

A set of programs that perform all modeling-related calculations, such as activities location and land use, path search, assignment, and others. The programs may be run directly from menu-driven commands in the interface with the possibility of storing long run sequences, or from the Windows Commands window, either individually or through long batch files. In general, the model programs require minimum user intervention.

Report generating programs

A set of programs that consult the results in the database and generate reports in a large variety of formats and options. The most common reports are tables with the results of activities location and land use, assignment results at a link level, O-D matrices of trips, costs or disutilities, transport indicators, and many other. Some special reports are O-D matrices of consumers' surplus comparing two scenarios, O-D matrices of trips that use one or more links, distribution of vehicle-km by speed class, O-D matrices of trips that make *n* or more transfers, and so on. New options are added continuously. The reports may be generated directly from the interface through menu-driven options, obtaining Excel-ready XML files. Alternatively reports may be generated from the commands window.

7/27/2007