MASTER THESIS AT:

KUNGLIGA TEKNISKA HÖGSKOLAN, STOCKHOLM

IN PARTNERSHIP WITH:

BELO HORIZONTE, BRAZIL

CONSTRUCTION AND CALIBRATION OF A LAND-USE AND TRANSPORT INTERACTION MODEL OF A BRAZILIAN CITY

APPLICATION TO SIMULATE THE IMPACTS OF A LARGE PUBLIC INTERVENTION ON THE DEMAND FOR TRANSPORT AT THE METROPOLITAN SCALE

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ABSTRACT

Land use and transport interaction models have been developed for several decades, as cities got increasingly large, interconnected and as people's mobility within metropolitan areas increased. Starting from the fundamental idea that daily trips are generated by people's activities, land use and transport models are able to generate trips and to forecast land use evolution. On the other hand, transport planners use origin-destination surveys as a central tool for planning urban transportation systems. These surveys, which take the form of matrices, are costly to produce and above all hardly projectable into the future.

This master thesis research consisted in building and calibrating a land use and transport model for the city of Belo Horizonte, Brazil, using the software TRANUS. A method has then been suggested to produce future origin-destination (OD) matrices from socio-economic forecast for different development scenarios. The methodology was implemented to assess the impact of a large urban project on transport demand at the metropolitan scale.

ACKNOWLEDGEMENTS

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List of Abbreviations

AH (2001)	*Áreas Homogêneas*: geographic division of the RMBH used for the 2001-2002 origin-destination inquiry (1003 units). Every AH is an aggregation of in average 3 census sectors (SC). Used in this work as a base for TRANUS model zoning.
BH	*Belo Horizonte*
BRT	*Bus Rapid Transit*
CEPAC	*Certificados de Potencial Adicional Construtivo* (Certificates of Additional Building Potential)
LUTI	*Land-Use and Transport Interaction*
MG	*Minas Gerais*: Brazilian state whose capital is Belo Horizonte
OD matrix	Matrix informing the number of trips per *Origin-Destination* couple within a given area and for a certain period of time (e.g. day or peak hour)
OUC	*Operação Urbana Consorciada* (Concerted Urban Operation)
SC	*Setor Censitário*: census sector, geographic division of the RMBH used for the census (in average 5000 inhabitants per SC).
RMBH	*Região Metropolitana de Belo Horizonte* (Metropolitan Area of Belo Horizonte)
SMAPU	*Secretaria Municipal Adjunta de Planejamento Urbano* (author of BH master plan and responsible for the OUC project)
VIURBS	*Programa de Estruturação Viária de Belo Horizonte* (Road Structuration Programme of Belo Horizonte)

INTRODUCTION

After a year spent at KTH studying urban planning and transport engineering, I had the opportunity to do a six-month internship in a transport engineering firm located in Belo Horizonte, Brazil: Grupo Tectran / Relígio. The team is specialised in transport and urban planning, and is developing innovative methods to take better into account the interaction between transport and urban development in their projects.

This master thesis results from my work during this internship. My task was to develop further a methodology for modelling land use and transport interaction that could be implemented for medium-term projects (3 months to one year). The model was developed in order to simulate a specific project, which added to the challenge. The timeframe for such a task was very short, which lead to some important simplifications, but this report proves that it is possible to calibrate a LUTI model in a short time with small resources, but by making important concessions on the model's accuracy.

The research was part of a large urban project (*Operação Urbana Consorciada)* initiated by Belo Horizonte municipality. Grupo Tectran was in charge with coordinating the realisation of an impact study of the project. My participation dealt with the interface between transport and land use so to assess the impact of the urban project on the surroundings in terms of transport flows and at a larger, metropolitan scale on transport demand.

My research aims at evaluating the impact that the concentration of activities and inhabitants planned by the municipality in this centrally-located area may have on the amount of trips realised in the whole metropolitan area. Ideally, this re-location of dwellings, workplaces and services would result in a decrease of the transport demand at the larger scale.

The first part consists of a short review of the theoretical background of LUTI models and transport demand modelling. The model building and calibration are detailed in the second part, trying to emphasize the particular choices that were made to build and calibrate Belo Horizonte's model.

THEORETICAL BACKGROUND

THEORY OF LAND-USE AND TRANSPORT INTERACTION MODELLING

Land use and transport interaction – or LUTI – models have been developed and implemented in various cities in the whole world since the 1950s (Southworth, 1995), initially in the USA. They got a broader diffusion with the development of computing techniques, and gained interest with the rapid urban sprawl that has happened for some decades in Third World countries (De la Barra, 1989). They are very complex models inheriting characteristics from several theories in various disciplines, such as spatial micro-economics, transport models, space-time geography (see Figure 1).

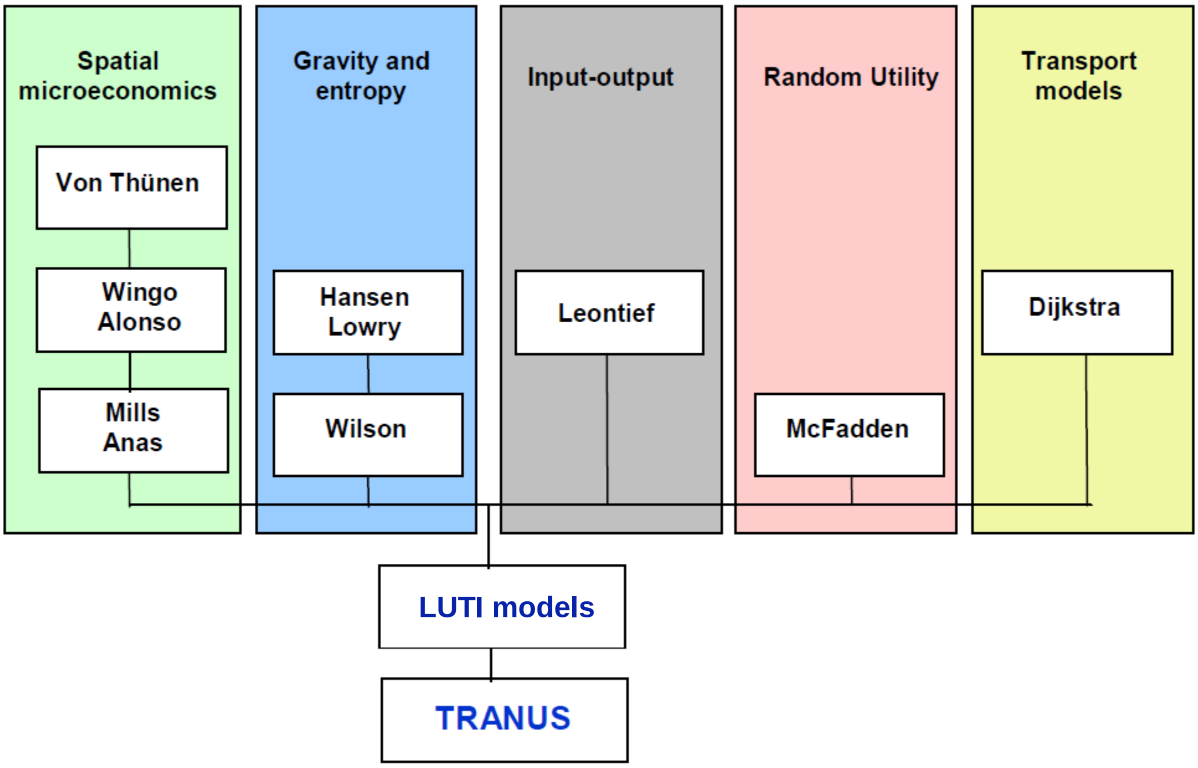

FIGURE 1: THE FAMILY TREE OF LUTI MODELS AND THE TRANUS SYSTEM
ADAPTED FROM MODELÍSTICA, 2007

These models are based on the idea that transport costs and activity location are closely related.

The influence of transport costs on land use was first identified by Von Thünen in his isolated-state agricultural production location model (1826): land owners rent it out at the maximum price farmers can afford and farmers try to maximise their revenue by renting cheaper land and reducing their transport costs by getting closer to the city centre where the market is located. In a modern urban context (see Wingo, 1965 and Alonso, 1964 *in* De la Barra, 1989), families would try to live as close as possible to their daily activities (e.g. work, school, shops, services), and firms would try to locate as close as possible to the services and to their clients. This competition results in an increase in the land prices of centrally-located areas, which tends to push households and activities to the outskirts of the city. In the equilibrium that is reached between these two opposite effects, the most profitable activities and the richest households tend either to concentrate in the city centres or to occupy larger areas, while the less profitable activities and the poorest households tend either to concentrate in the outskirts or to occupy very limited area (maximisation of the utility within a given budget). People might desire to live in culturally attractive urban environments or would prefer to live far from the city's nuisance (proximity to other social groups, violence, pollution, etc.), which can lead to an opposite organisation of the population's location (e.g. European vs. American cities). Land-use regulation can also modify these trends.

On the other hand, transport is directly influenced by activity location, which creates the need for travelling. In LUTI models, travel generation is articulated to traffic assignment, following the structure of a traditional four-step transport model:

1. Activities generate travels by identifying the zones that either produce or attract trips;
2. The trips are distributed in an OD matrix that puts together origin and destination zones;
3. For each OD couple, one or a combination of the available transport modes (e.g. walking, private car, bus, train) is chosen, depending on their relative generalized cost for the traveller;
4. The trips are assigned to the transport network.

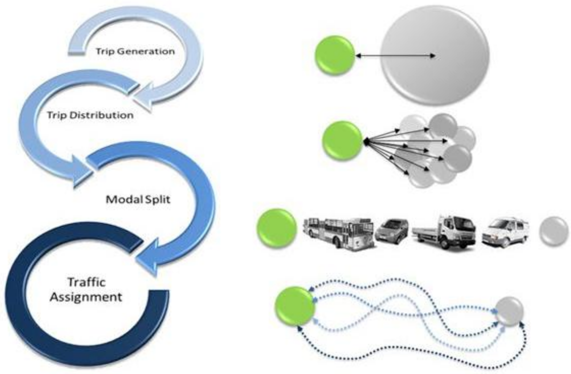

FIGURE 2: FOUR-STEP TRANSPORT MODEL
ADAPTED FROM THE DOCUMENTATION OF AIMSUN 8

Few complete and operational transport models were developed that are able to forecast transport demand (generation, distribution) apart from realising modal split and traffic assignment. Such models are most of the time based on probabilistic calculation of travel demand, so their calibration requires a large amount of work, often several months, by modellers with several years of practice. Most of these models were built at a national scale and were calibrated for this specific context, so they are hardly usable in other contexts. They are often exploited by the public planning authority, although they might be available for use by other actors. An example is the Swedish national transport demand model: Sampers (Lundqvist and Mattsson, 2001). This model is based on households' location and their probability to travel at every time in the day, but not on a proper activity model. Such activity-based transport models were suggested for Stockholm's region (Algers et al., 2005).

However, no such model has yet been developed in Brazil, neither at the national level nor at state level. As far as we know, no commercial software is able to model transport demand: existing software (e.g. TransCAD, Visum) realise only modal split and traffic assignment and take OD matrices as an input, so the trip generation and distribution has to be informed by the modeller.

LUTI models provide a solution to simulate trip generation, for instance in the case of future scenarios forecasting. Many limitations of these models have been highlighted in the literature, one of the most cited being the extensive indictment against large-scale urban models (LSUMs) written by Lee (1975), who criticised particularly the lack of transparency of these models (black boxes), their pretention to comprehensiveness that made it almost impossible to use for strategic, definite issues (general purpose) and their unclear intent (command-and-control), critiques that he could confirm twenty years later, these remaining largely unanswered by the modelling community (Lee, 1994):

> "Most formal models, including LSUMs, are too inflexible for strategic planning. They require too much information, they produce too much information that is not needed for any particular problem, and they shed too little light on the reasons for strategic choices."

Southworth (1995) concluded after a comparative study led in the beginning of the 1990s that "as detailed forecasting tools, none of the current models [were] entirely acceptable". However, the increasing availability of good socio-economic data and the database-processing capacities provided by informatics let us hope that LUTI models can be used as forecasting and decision support tools (SDSS: Spatial Decision Support Systems). The national scale models cited previously have been proving this by the accuracy of their results.

Various frameworks were developed for modelling land use and transport interaction, such as:

- TRANUS, developed since 1982 by the Venezuelan researcher Tomás de la Barra and maintained by the consulting firm Modelística;
- MOLAND, developed since 1998 by the European research project TRANSLAND, initiated by the European Commission. It performs well in modelling land use change by testing a large sample of policies, and was designed for the European context (see Wegener, 2004 and Koomen, 2007);
- UrbanSIM, including micro-simulation (Waddell, 2002);
- A generic city for studying the impact of road pricing on both location and transport (Eliasson and Mattsson, 2001);
- LandScapes, developed for Stockholm's region (Jonsson, 2008);
- Etc.

Our choice went to TRANUS, of which some of the team members already had an experience. This software appeared to provide solutions to our need and it had the big advantage to be open source so available for free, user-friendly thanks to its interface and quite well-documented: all our questions could find answers on a forum (Modelística, TRANUS Forum) with a very active community. This forum, created by TRANUS developers, also gave the opportunity to contribute to improving TRANUS and the understanding of its dynamics.

TRANUS

TRANUS is "an integrated land use and transport modelling system" (Modelística, 2007) based on geographically localised land uses whose relationships (input-output consumption relationships) generate travels. Traffic is assigned in the transport network and travel costs are fed back into the activity model, as shown in Figure 3. Model building methodology is developed further in the report.

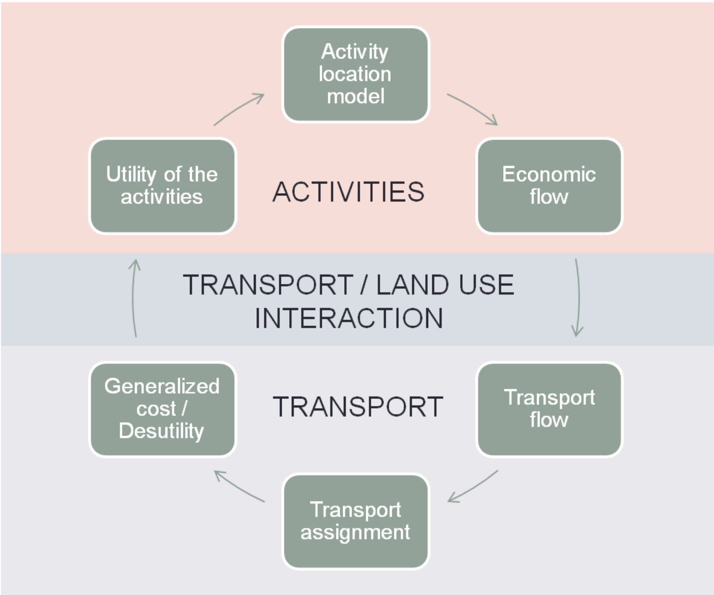

FIGURE 3: BASIC PRINCIPLE OF THE SOFTWARE TRANUS

TRANUS can be implemented at a wide scale range, from urban districts to regions composed of different countries. It has also a wide range of actually implemented applications, some of these being (Modelística, 2007):

- Urban or regional planning: development plans, housing or environmental protection plans, land use controls
- Impact studies of specific urban projects (e.g. industries, residential estates, shopping centers)
- Transport planning: new roads or improvements to existing roads, exclusive busways and integrated networks (Bus Rapid Transit), mass transport systems (metros, light rail), etc.
- Transport pricing: public transport fares, highways with tolls, fuel taxes, parking fares, congestion pricing, etc.
- Restrictions to automobile use, HOV lanes, park-and-ride
- Road maintenance policies
- Freight: new port facilities, location of freight airports, freight transport scheduling

Construction and Calibration of the model

This methodology aims at building and calibrating a land-use and transport model able to produce OD matrices of passengers' trips. These matrices will make it possible to compare different scenarios on the basis of the amount of demand for transport, the modal split and the loading of the road and railway network.

The model dynamics are initially calibrated with a base scenario (2010), which is built with present socio-economic data. Generated trips are assigned to the current transport network, and the results can be compared with existing statistics (traffic counting and OD surveys).

Subsequently, demographic forecasting is realised for different future scenarios. On this basis, economic activity forecasts are fed into the model, which enables to simulate trip generation for all scenarios.

The outcomes of this study should be future OD matrices for the different scenarios that will have been defined, and their analysis through network loading maps

MODELLING AREA AND ZONING

Belo Horizonte (**BH**) is the capital city of the state of Minas Gerais (**MG**), in South-Eastern Brazil (see Figure 4). Belo Horizonte had around 2.5 million inhabitants in 2010, which corresponds to half the population of its metropolitan area: *Região Metropolitana de Belo Horizonte* (**RMBH**), 5 million inhabitants (Estado de Minas Gerais, 2010). The RMBH is composed of 34 municipalities and is economically polarised by the city of Belo Horizonte.

Belo Horizonte was created from zero in 1897: the initial city was built following a very regular plan by Aarão Reis, which nowadays constitutes the economic centre of Belo Horizonte: the city was planned to take 100 years to reach 100,000 inhabitants, so the initial plan was quickly insufficient. Indeed, Belo Horizonte had an important development from the 1920s, reinforced in the 1940s-50s with an industrial development under the impulse of it Mayor, Juscelino Kubitschek. The urbanisation has reached Belo Horizonte's administrative limits (331 km^2), so most of the demographic growth is now happening in the surrounding municipalities.

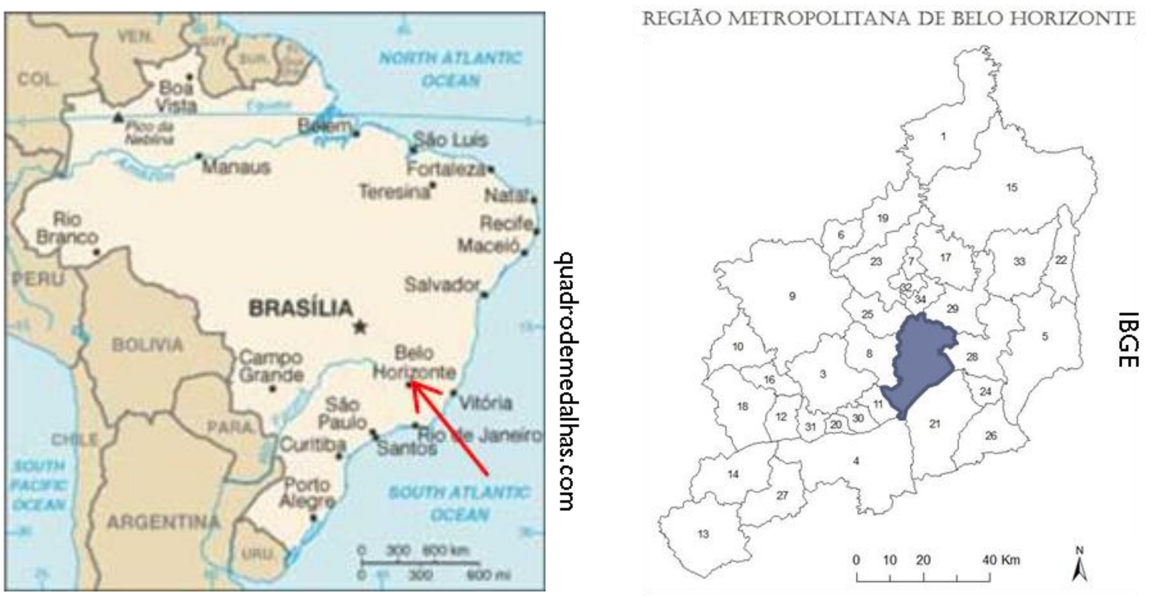

FIGURE 4: LOCATION OF BELO HORIZONTE AND ITS METROPOLITAN AREA

The modelling area should be larger than the area where the projects or policies that are going to be studied later are implemented. The focus in Belo Horizonte's model is on daily passengers' trips, which lead us to choose the metropolitan scale and to model the *Região Metropolitana de Belo Horizonte* (**RMBH**, metropolitan area of Belo Horizonte). Indeed, the economic interactions between the different municipalities are very strong and most daily passengers' trips are realised within the RMBH.

The model is composed of 84 zones, 72 of which within the city of Belo Horizonte and 12 being composed by one or several other municipalities (see Figure 5). Every zone is an aggregation of several *Áreas homogêneas* (**AH**), a geographic division of the RMBH used for the 2001-2002 origin-destination inquiry (1003 units). These *Áreas homogêneas* are also composed of census sectors, the *Setores censitários* (**SC**), in average 3 SC per AH.

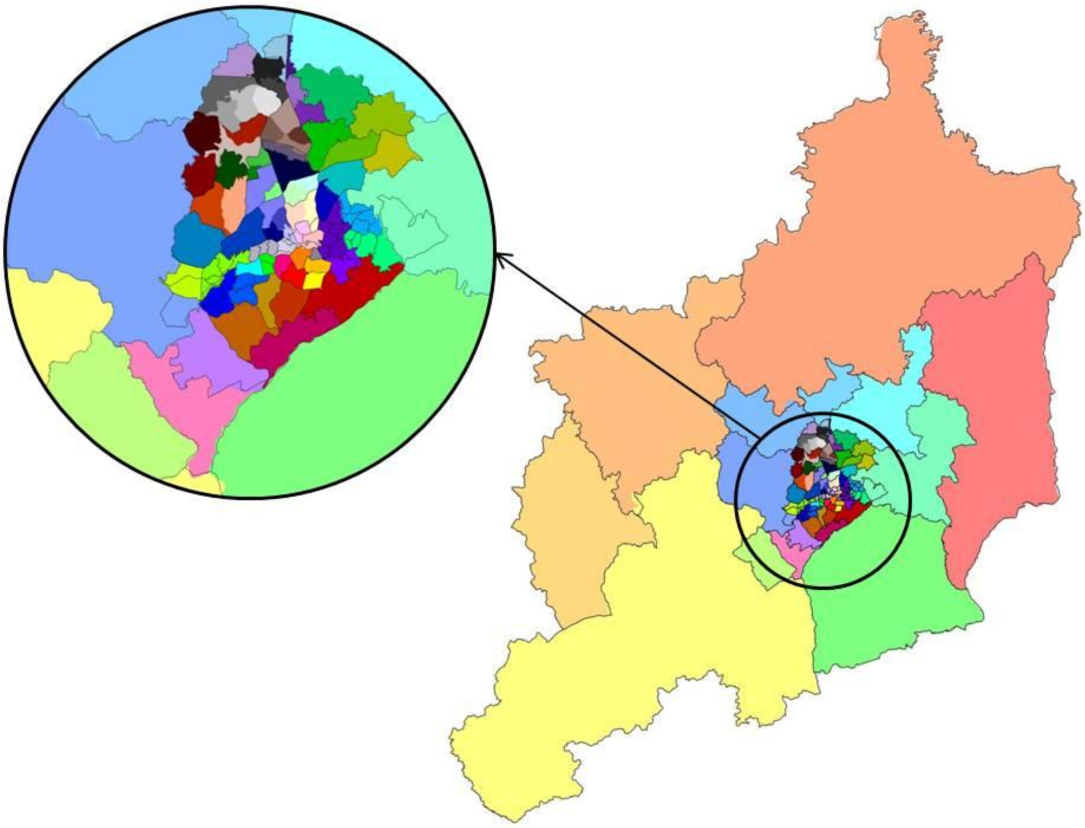

FIGURE 5: MODELLING AREA AND ZONING (ZOOM ON THE CITY OF BELO HORIZONTE)

The choice of zones takes into account various factors, which requires a very good knowledge of the modelling area, as mentioned by Nguyen-Luong (2008):

- Availability of information at a disaggregated level: in our case, traffic survey information is collected at the AH level and demographic information at the SC level, so they can be easily aggregated to TRANUS zones level
- trip distribution: TRANUS doesn't model internal trips, so the zones should be small enough not to exclude motorised trips, for example;
- amount of population and activities (smaller zones in the denser areas);
- quality of population and activities (try to identify zones whose socio-economic profile is well-characterised, either predominantly residential, commercial or industrial for instance; large facilities can be isolated, etc.);
- main transport infrastructures: they should be used to define zones limits. Each zone produces and attracts trips that are distributed in the transport axes.

In the case of Belo Horizonte's model, the zoning was made to fit a specific case study, which will be described further later in this report. We started with a zoning that was used to simulate another project realised by Tectran with TRANUS. Along the corridor composed by Presidente Antônio Carlos and Dom Pedro Primeiro avenues (around 10km from the city centre to the North), the zones were split in order to get a very good level of detail, while the zones located further away were aggregated (for other city districts and most particularly for the other municipalities), so the total number of zones was not too important, which would have slowed down the model running. The two zonings appear on Figure 5, with thin black lines for the former zoning and different colours for the new one, developed for this research.

In TRANUS, the zones are represented by one centroid each. The centroids concentrate all population, activities and floor space of the zone, so their location is chosen to correspond to the gravity centres of the zone from this perspective. They are linked to the transport network and all the travels generated (or attracted) by the zone are geographically starting from (or going to) the centroid.

It is possible in TRANUS to define external zones that are located outside the modelling area but generate trips to it and attract trips from it. However, no external trips were considered in Belo Horizonte's model because, according to the 2001-2002 origin-destination survey realized for the RMBH, 98.1% of daily trips to or from this metropolis are made within it (FJP, 2003). Considering the city of Belo Horizonte, 71.5% of daily trips within the RMBH were made between the central city and one of the 33 other municipalities, showing how much Belo Horizonte polarises the economic activity in this area.

ACTIVITY MODEL

DEFINITION OF ACTIVITY, POPULATION AND LAND SECTORS

TRANUS is based on various *sectors* corresponding for instance to dwellings, workplaces, land, or any product, either transportable (such as service-related jobs) or not transportable (floor space and land). Each zone of the simulation area is occupied by a certain amount of units from each sector: one unit corresponds to one workplace for economic activity sectors, to one household for household sectors and to one square metre for floor space sector. Relationships between the different sectors are established through consumption matrices (input/output). Transportable sectors can be consumed in another location than they are produced. One or various sectors have to be exogenously fixed, thus initiating the land-use and transport feedback cycle.

Belo Horizonte's model works with nine sectors (see Table 1 and Figure 6). They correspond to the available data and describe well the activities that mostly generate travels in the inhabitants' daily life. These sectors already existed in the model that was initially built by Tectran team, without getting to be used.

Type	Sector	Elasticity	Exogenous?
ECONOMIC ACTIVITIES	Education	0,8	
	Government	0	Exogenous
	Industry	0	Exogenous
	Health	0,7	
	Services	0,8	
HOUSEHOLDS	Lower income households	0,6	
	Medium income households	0,7	
	Higher income households	0,8	
FLOOR SPACE	Floor space	0	

TABLE 1: DEFINITION OF TRANUS SECTORS

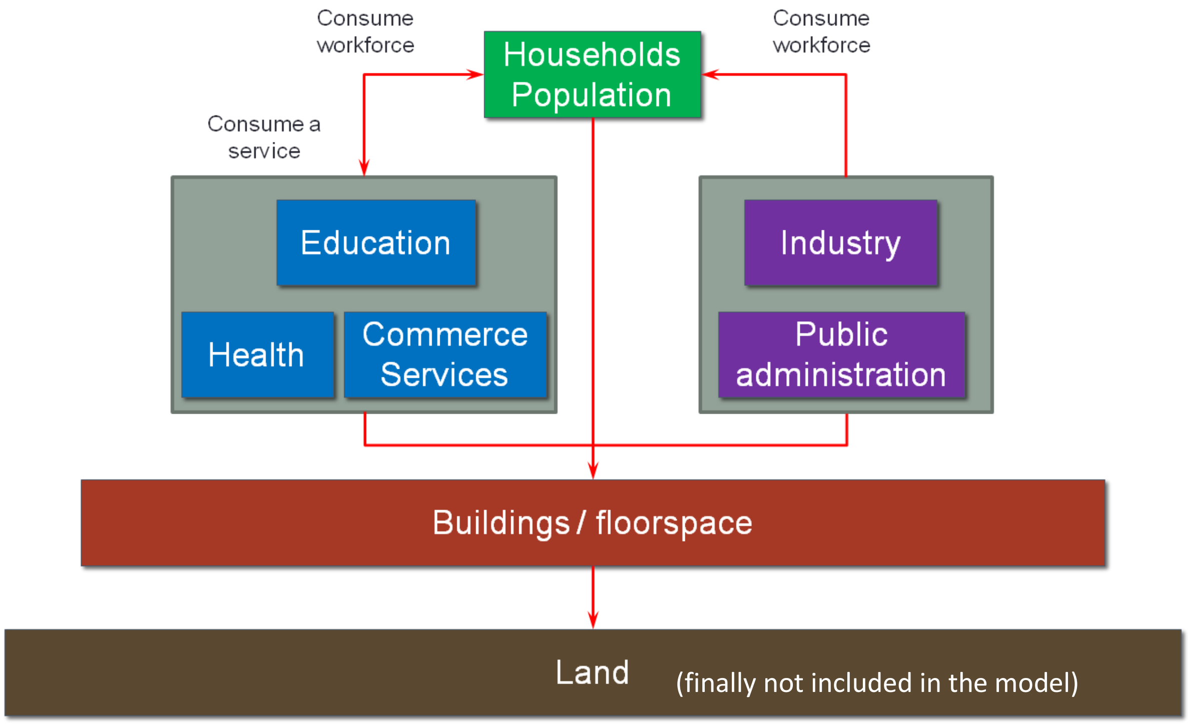

FIGURE 6: BELO HORIZONTE'S MODEL SECTORS AND THEIR INPUT/OUTPUT RELATIONSHIPS

The particular case of floor space and land sectors

In the case of models aiming to forecast activity location, floor space and land sectors are essential, as they are at the base of activity prices formation. Location choices then result from the integration of the generalised cost of transport to activity costs, including land, floor space, workforce and other intermediary goods.

It is interesting to notice that density patterns and urban sprawling directly stem from the formation of land rent: in buildings, land price is divided by the number of stories, which enables to attenuate the differences in location prices by building more floor space in the most attractive areas. This is an important reason for having a floor space sector in TRANUS.

However, concerning transport demand forecasting, TRANUS might be used only for its trip generation model, then land and floor space are not necessary. An example is the methodology suggested by Dos Santos to produce origin-destination matrices from secondary economic data, in the case of freight transportation (Dos Santos, 2013).

Land sectors are defined depending on their use, as this is the case in the Oregon model (Parsons Brinckerhoff Quade & Douglas, Inc., 1999) and in the Swindon model (Modelística, 2011). The Swindon model also includes floor space sectors. These generally correspond to building typologies, possibly taking into the account the predominant use (e.g. row houses).

Optimally, there should be different land and floor space sectors, with possible substitutes (for instance, services generally consume office floor space, but in case of penury they might consume residential floor space, and vice versa), as De la Barra mentioned on TRANUS forum:

> "In our experience using only floor space does not work so well. The main price differentials are in land mostly." (De la Barra, 2012/07/31).

At an early stage of Belo Horizonte's model development, I and my colleagues at Tectran discussed whether we should split floor space into three specific floor space sectors:

- Residential floor space, consumed mainly by households;
- Commercial floor space, consumed mainly by Government, Industry and Services;
- Education and Health floor space: characterised by their zero cost, as these activities location is considered to be planned and not to be the result of competition on land market with other uses.

Whether Government sector consumes floor space from the second or the third category could be discussed, but this choice was not so important, as Government sector is exogenous and with zero elasticity, so it will be produced independently on its production cost.

These three floor space sectors were coherent with the use that we planned to make of the model. Indeed, the Master Plan of the urban project that is described further determines how much residential on the one hand, commercial on the other hand, additional floor space will be enabled through the selling of CEPAC.

However, due to the lack of available data, we were not able to dimension these three sectors, so only one floor space sector remained. For the same reason, the model doesn't include any land sector. The consequences are that activities and households cannot choose substitutes and that the cost structure might not be as realistic as with both land and floor space sectors.

Households per income classes

The households were classified in three sectors depending on their income (see Table 2). The cutting points between income classes correspond to the definition adopted by the government (Grosner et al., 2012), which fixed at 291 R$/month/capita the threshold between working and middle class, and 1,019 R$/month/capita the threshold between middle and upper class. In order to make this definition compatible with the census data, we took cutting points that are simple fractions of the minimum salary (510 R$/month when the data were collected in 2010).

	Lower rent HH (working class)	Medium rent HH (middle class)	Higher rent HH (upper class)
Minimum salaries per capita	Less than ½	Between ½ and 2	More than 2
Income per capita (2010)	< 255 R$/month	255 to 1,020 R$/month	> 1,020 R$/month
Federal definition (2012)	< 291 R$/month	291 to 1,019 R$/month	> 1,019 R$/month
Proportion in BH (adapted from the census: IBGE, 2011)	15%	60%	25%

TABLE 2: DEFINITION OF INCOME CLASSES

In Belo Horizonte, the middle class according to this definition represents 60% of the population, which is more than the national figure (which only went over 50% in 2012). Indeed, the inequalities are less important in Belo Horizonte (Gini index = 42, data from IBGE, 2003) than in Brazil (Gini index = 58.8%, data from the World Bank, 2003).

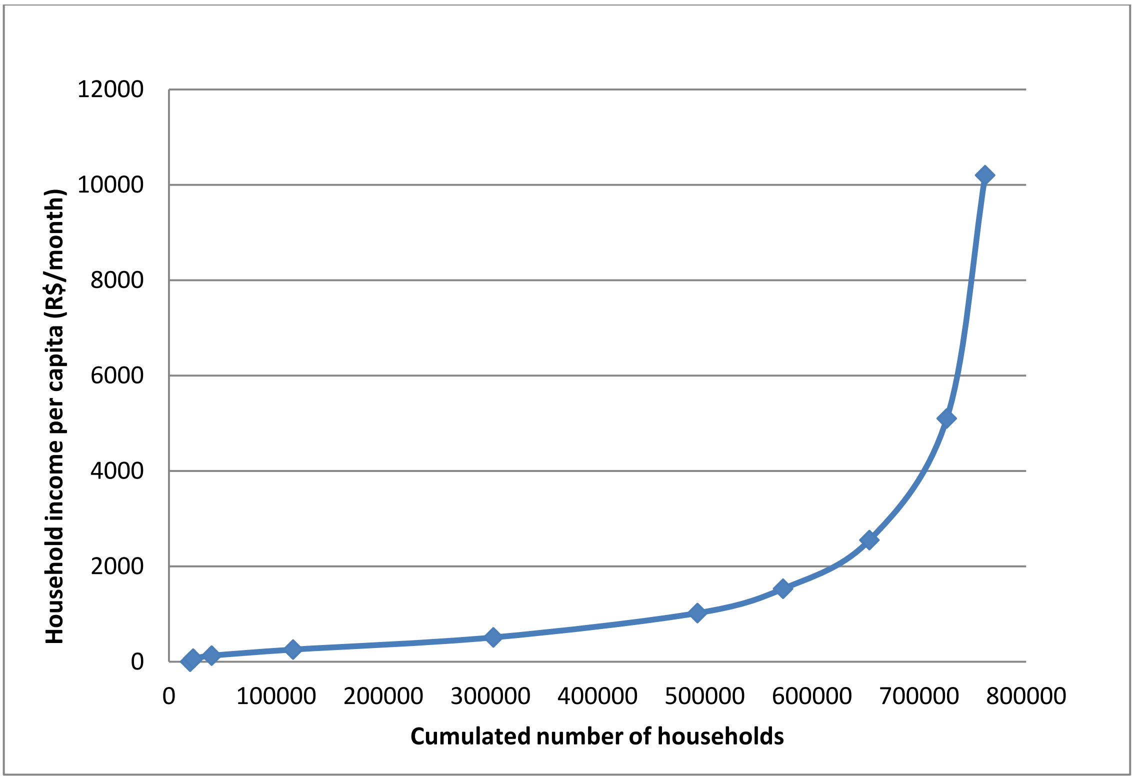

FIGURE 7: HOUSEHOLD INCOME PER CAPITA IN BELO HORIZONTE
SOURCE: CENSUS (IBGE, 2011)

ECONOMIC DATA COLLECTION

The amount of units of every sector (called Economic data in TRANUS) are collected either by own measurements and surveys or preferably from external reliable sources, for instance from governmental surveys or other academic studies. Concerning population or households, one excellent source is the census, which is realised periodically on a very large sample. Concerning economic activities, tax files can be very helpful if they are available (it depends on the country). In the case of Belo Horizonte's model, the following databases were used (Table 3, sources are public bodies referenced by their initials).

Database	Author, year	Use
PNAD (*Pesquisa Nacional por Amostra de Domicílios*)	IBGE, 2011	Household sectors (national census)
CNAE (*Classificação Nacional de Atividades Econômicas*)	MTE, 2010b	Classification of economic activities. Aggregation to 5 sectors in BH's model: Industry, Commerce and services, Administration, Education, Health
CMC (*Cadastro Municipal de Contribuintes de Tributos Mobiliários*)	PBH/SMAPU, 2010	Economic activity sectors Floor space sector (tax file registering all formal economic activities realised on the municipal territory)
RAIS (*Relação Anual de Informações Sociais*)	MTE, 2010a	Inter-sector coefficients
Cadastro Central de Empresas	IBGE, 2010	Economic activity sectors.

TABLE 3: DATABASES USED FOR BELO HORIZONTE'S MODEL

Concerning land and floor space, if no proper data is available, a good method is to measure the built area with the help of any cartographic tool and good database (Google Earth for instance) and to deduce floor space by identifying building typologies. This method is rather accurate but it is very time-consuming, and not always possible. In the case of Belo Horizonte's model, this method was employed to assess the amount of floor space per zone (see Figure 8), but in a very rough way due to the size of the metropolitan area and the time available for building the model.

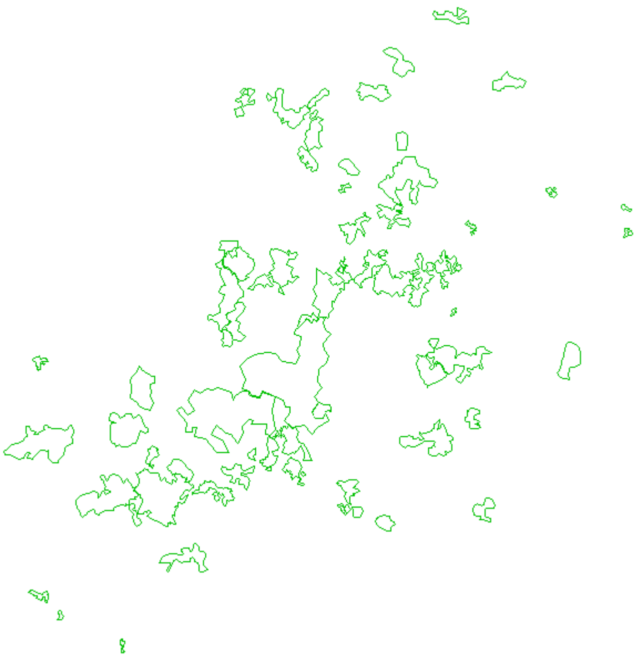

FIGURE 8: CONTOUR OF URBANISED AREAS IN RMBH (APART FROM BELO HORIZONTE)

Data collection requires access to good quality database and generally much time. It can take several weeks or even months to collect input data and to make it compatible with the model's sectors and zoning. In this research, we had not very good data, particularly concerning economic activities and floor space, nor we had time to refine the data. This created great limitations for the model and is to be improved in further works.

PRICES

Base prices should be fed into the model for land and floor space sectors, the most important being land prices, because land is a basic good (indirectly consumed by all other sectors, and does not consume any).

Floor space prices were obtained for all zones inside Belo Horizonte from the FIPE-ZAP index (2012). The index follows sale prices in every district of the city. There are around 3 times more districts than the number of zones considered in the model (72 in Belo Horizonte + 12 in other municipalities of the metropolitan area), so average prices on reasonable samples (5 to 10 sales) could almost always be calculated.

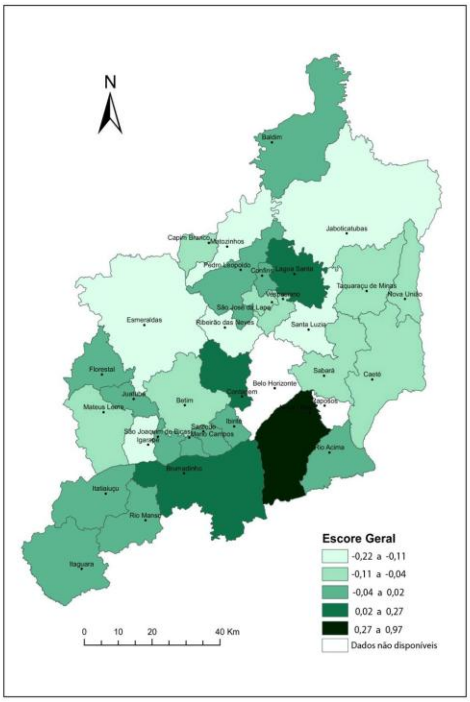

FIGURE 9: GENERAL SCORE OF REAL-ESTATE PRICES IN THE RMBH
SOURCE: PDDI-RMBH, 2010

Concerning municipalities outside Belo Horizonte, the average price was 30% lower than Belo Horizonte. The prices were obtained by adding to this average a deviation proportional to the general score calculated for the Metropolitan Area's Master Plan, based on the standard deviation of real-estate prices (see Figure 9 and Table 4). The adjustment coefficient was arbitrarily chosen (standard deviation = 3.6) so that the highest prices in municipalities out of BH correspond to the highest prices in BH. Indeed, cities such as Nova Lima located close to the richest districts of BH experiment very important residential development able to attract high income households commuting daily to Belo Horizonte to work.

	Belo Horizonte	Other municipalities
Minimum	10	3.7
Maximum	34	25.5
Average price	15.1	11.5 (BH -30%)
Standard deviation	3.6	-51% to +186%

TABLE 4: DETERMINATION OF FLOOR SPACE PRICES

INTER-SECTOR COEFFICIENTS

TRANUS activity model is based on input/output relationships between the different sectors. For example, producing an educational service will require a certain amount of floor space (square metres) and employees corresponding to households from every income class.

Some production is exogenous (P^{exo}), in sectors such as industry, meaning that this production does not respond to a demand directly coming from the simulation area but is "exported". As a consequence this production is not consumed by any other sector. In Belo Horizonte's model, industry and government (public administration) sectors were considered exogenous: industry supplies the whole country and public administration works for the whole state of Minas Gerais.

Other production (P^{ind}) is induced by the other sectors such as economic activities that require workforce and floor space. All production in education and household sectors is induced for instance (intermediary goods). Land, and in some cases floor space (when there is no land sector), are basic goods, meaning that they do not consume anything. Their production is also induced by other sectors.

These input/output relationships are quantified by the inter-sector coefficients (c_{ij}):

c_{ij} corresponds to the amount of sector j consumed by one unit of sector i. Red arrow = "consumes"

Sector	Educ.	Gov.	Indus.	Health	Serv.	Higher inc. HH	Med. Inc. HH	Lower inc. HH	Floor space
Education						0.25	0.45	0.19	27.4
Government						0.23	0.60	0.10	3.4
Industry						0.12	0.52	0.21	7.1
Health						0.09	0.54	0.21	13.4
Services						0.06	0.39	0.33	17.6
High inc. HH	0.05			0.06	1.87				150.8
Medium inc. HH	0.04			0.05	0.48				90.5
Lower inc. HH	0.02			0.05	0.11				55.3

TABLE 5: INTER-SECTOR I/O MATRIX

The inter-sector coefficients (see Table 5) were not determined specifically for this research, but were taken from the model built for another project in the same area and with similar sectors. In this former project, statistics from the Brazilian Institute of Geography and Economy (IBGE) and from the Ministry of Work (MTE, 2010a) were used to determine, among others, the number of hospital beds per inhabitant, and the education consumption, judging by the level of education of the different classes of revenue.

Floor space consumption coefficients were determined with the help of the municipal register of tax-paying companies. These activities are classified following the National classification of economic activities (MTE, 2010b), so it was easy to identify which sector in TRANUS the activities corresponded to. The surface occupied by each activity was informed, so we could calculate average surface ratios per activity sectors.

However, some adjustment had to be made to these coefficients so that the offer-demand equality was respected in every sector (see Equation 1). This can already be considered as model calibration, as parameters that are supposed to reproduce a real dynamic (e.g. average floor space consumption by the education sector) have to be modified so the model can converge to an equilibrium that hopefully corresponds to the reality.

$$\forall j \in \{1..n\}, \sum_{i=1}^{n} c_{ij}\left(P_i^{exo} + P_i^{ind}\right) = P_j^{ind}$$

EQUATION 1: OFFER-DEMAND EQUALITY IN TRANSUS ACTIVITY MODEL
SOURCE: MODELÍSTICA, 2012

Concerning floor space, which is not transportable (so it should be consumed in the zone where it is produced), the equality should be respected not only at the city level but in every zone. Instead of a fixed demand c_{ij}, an interval of demand should be defined. If the demand for floor space is lower in a zone, what's left cannot be "exported" so the price will decrease which will result in a higher consumption of floor space per unit of activities and households. In other zones where there is a shortage of floor space, the price will increase which will result in a lower consumption per unit of activities and households.

Demand is an exponential function of price in TRANUS (see Equation 2). It cannot be lower than Min Demand nor higher than Max Demand, and its slope is controlled by the demand elasticity δ:

$$c_{ij} = min_{ij} + \left(max_{ij} - min_{ij}\right) \times \exp\left(-\delta_{ij} U_i^n\right) \text{ where j = floor space}$$

EQUATION 2: DEMAND FUNCTION IN TRANUS
SOURCE: MODELÍSTICA, 2012

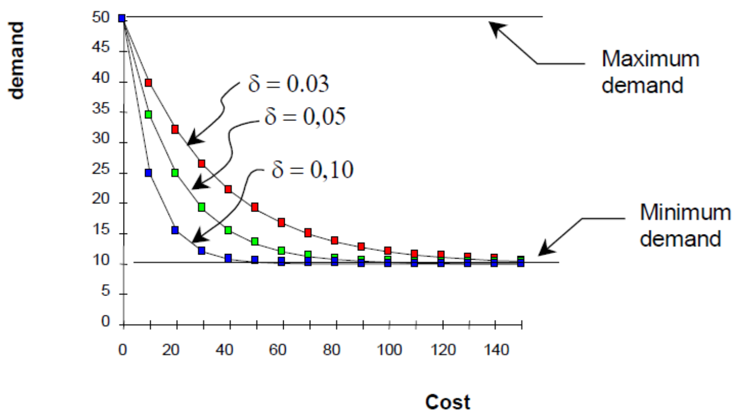

FIGURE 10: EXAMPLES OF DEMAND FUNCTIONS
SOURCE: MODELÍSTICA, 2012

The parameters of floor space demand function were determined on the base of the actual consumption in the different zones: for each zone, the amount of floor space that was desired by all other sectors present in the zone ($\sum_i c_{ij} P_i$ where j = floor space) was compared to the actual amount of available floor space. The consumption varied between 38% and 648% of the available floor space, which led to choose:

$$min_{ij} = 0.38 \times c_{ij}$$

$$max_{ij} = 6.48 \times c_{ij}$$

EQUATION 3: MINIMUM AND MAXIMUM DEMAND FOR FLOOR SPACE SECTOR

Sectors	Educ.	Gov.	Indus.	Health	Serv.	High income HH	Medium income HH	Lower income HH
Average consumption	27.39	3.35	7.08	13.37	17.58	150.80	90.50	55.30
Minimum	10.48	1.28	2.71	5.12	6.73	57.71	34.63	21.16
Maximum	67.95	8.31	17.56	33.17	43.61	374.11	224.52	137.19
Elasticity	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

TABLE 6: CALIBRATION OF FLOOR SPACE DEMAND FUNCTIONS

In order to adjust the elasticity parameter, the demand of floor space by every sector was calculated for an expected range of prices (from 5 to 30 R$/sqm/month), corresponding to the observed floor space prices (see on page 26) with a "safety" margin when the prices would evolve.

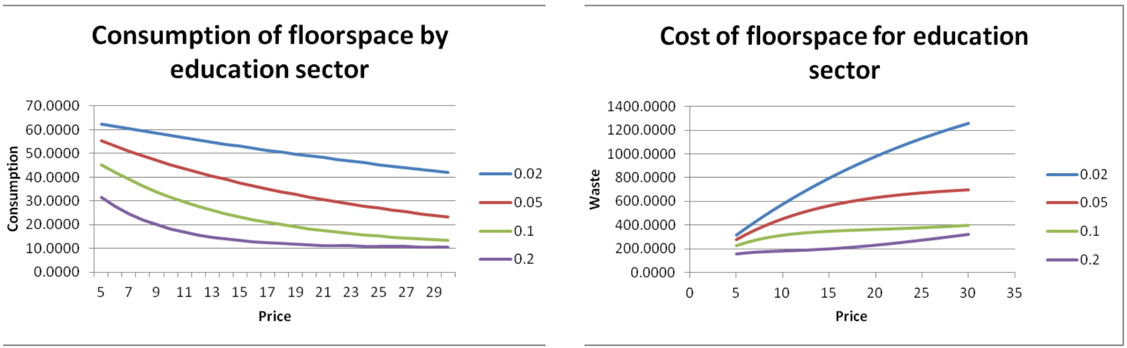

FIGURE 11: ELASTICITY CALIBRATION FOR FLOOR SPACE CONSUMPTION BY LAND

In Figure 11, each curve corresponds to a different value of demand elasticity. The value 0.04 was chosen, as it enabled to reach consumption values both near the Max Demand and near the Min Demand, and it made the activity model converge.

I still consider elasticity choice as one of the most unclear and arbitrary steps of the model calibration, although such curves make it a bit more rational. I was given this advice by Fausto Lo Feudo, a PhD student who is building and calibrating a regional model with TRANUS for Nord-Pas-de-Calais region (Northern France). We got contact through TRANUS forum, and sent our respective models to each other in order to find potential improvements.

Elasticity choice may be improved in further works, and good ideas can be taken from the works realised on that topic by a research team in Grenoble (Iarussi, 2010), whom I met in the latest stages of my master thesis.

TRIP GENERATION AND DISTRIBUTION

TRANUS activity model is based on input-output relationships that correspond to economic flows (e.g. government consumes household). Most economic flows will generate trips, which constitutes the interface between the activity and transport models in TRANUS. Only the consumption of non-transportable goods (basically floor space in our model) does not generate trips.

MODELLING PERIOD

In TRANUS, many parameters depend on the time period that is considered (such as average frequency of the routes for transit operators, total capacity of the transit routes and ways, cost of sectors). The model cannot simulate variations over time, so it is important to choose a time period short enough to present rather homogeneous transport demand and supply, but long enough to limit uncertainty due to the input data. The modelling period should also be coherent with the modelling area (see the concept of space-time prisms by Hägerstrand, 1970).

The morning or afternoon peak is a good choice from this perspective. It corresponds to the time of the day (one speaks of peak hour when it lasts one hour) when most people are travelling, often from home to their daily activity, job or studies (in the morning), or back home from this activity (in the afternoon). These are critical situations that determine people's location and activity choices and when one can analyse the capacity of the system to respond the demand for transport.

It is also observed that when transit routes and infrastructure reach their maximum capacity, the volume of transit at peak hour doesn't increase, but the society adapts, which results in an increase of the time period of peak transport demand. This makes it interesting to choose a little longer modelling period to be able to observe better the evolution of the peak in future scenarios.

Concerning Belo Horizonte's model, there where various possibilities for the choice of modelling period, all of them presenting advantages and disadvantages (see Table 7). Our choice stems from an analysis of the daily traffic demand, based on measures realised at 21 cross-points in the city of Belo Horizonte in 2006 (screen line method; TECTRAN, 2008). We considered that these measurements were more reliable concerning the repartition in the day of the total volume of passengers (and it is also more recent) than the OD matrix that resulted from the 2001-2002 origin-destination survey (FJP, 2003), which we could also have taken as a reference for the choice of the modelling period. Nevertheless, this 2002 OD matrix has been taken as a reference for the calibration of trip generation and distribution, as explained further.

According to the shape of the daily traffic demand (see Figure 12), we defined the morning peak as the period of time when transit was above 85% of the maximum number of people travelling simultaneously (volume of the morning peak). The afternoon peak was defined the same way. Both of them presented duration of two hours and around 14% of the total daily trips.

Time period		Volume of passengers	% of the day	Advantages	Disadvantages
Whole day	00:00-24:00	2,491,264	100.0%	Better statistics and projections	Not homogeneous
Working day	05:00-23:00	2,382,291	95.6%	Better statistics and projections	Not completely homogeneous
Morning peak hour	07:15-08:15	184,844	7.4%	Very homogeneous	Hard to make projections
Afternoon peak hour	17:30-18:30	182,347	7.3%	Very homogeneous	Hard to make projections
Morning peak	07:00-09:00	355,865	14.3%	Homogeneous	Projections are easier
Afternoon peak	17:00-19:00	360,873	14.5%	Homogeneous	Projections are easier

TABLE 7: TRAFFIC DAILY DISTRIBUTION IN BH
ADAPTED FROM TECTRAN, 2008

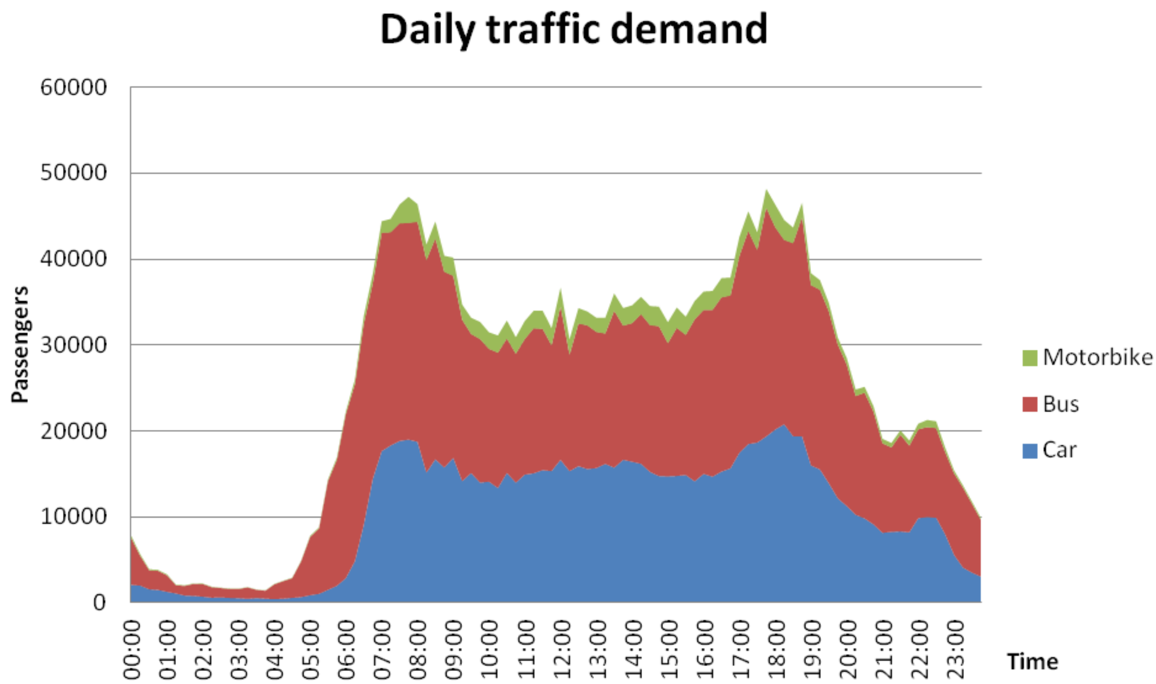

FIGURE 12: DAILY TRAFFIC DEMAND (PASSENGERS) IN BH
ADAPTED FROM TECTRAN, 2008

An analysis of traffic demand in terms of vehicles has also been realised (see Figure 13), including freight trips (by truck). It leads to the same results for the definition of morning and afternoon peaks.

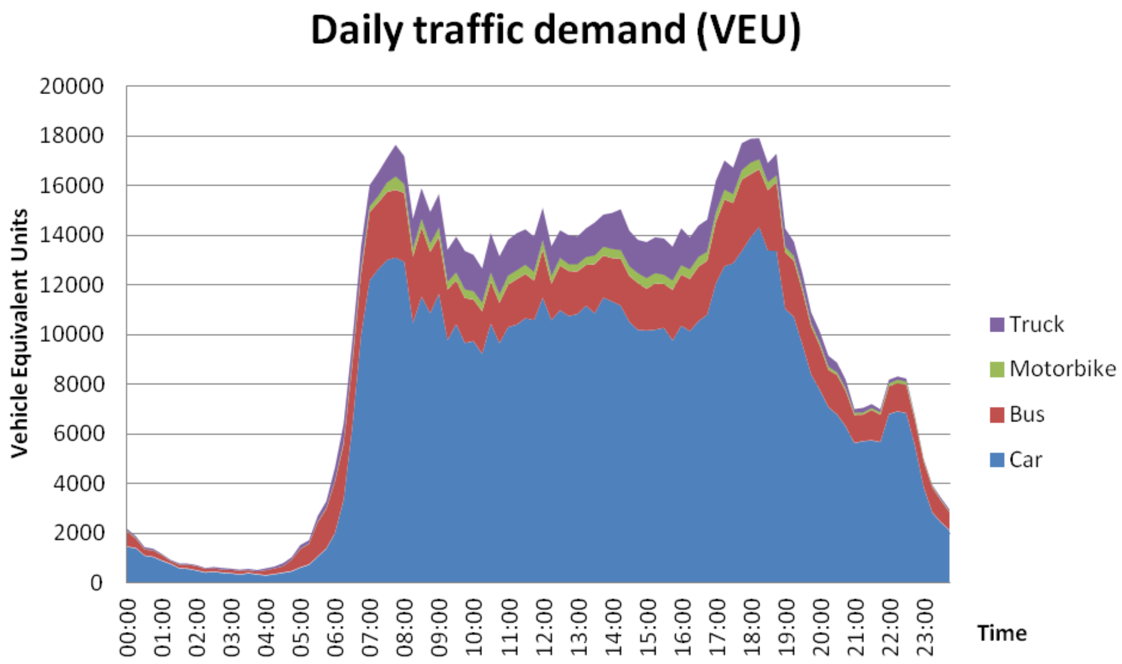

FIGURE 13: DAILY TRAFFIC DEMAND (VEHICLE EQUIVALENT UNITS) IN BH ADAPTED FROM TECTRAN, 2008

Our final choice was to model the morning peak, starting at 7:00 and ending at 9:00.

Travel categories

TRANUS generates trips according to travel categories, defined for input-output couples. These categories possess different characteristics in terms of value of time, vehicle availability (which will determine mode choice) and trip generation rate.

The most important coefficient is the Trip generation rate (Min and Max). For instance, the consumption of one household by industry sector will generate 1 trip at the morning peak hour (commuting trip), most often by car and with values of travel and waiting time corresponding to 1/3 and 2/3 of one hour salary, according to the recommendations for modelling with TRANUS (De la Barra, 1989).

The following travel categories were defined that are based on the income classes and trip purpose:

- *TrabalhoBaixa*: trips from higher income households to work
- *TrabalhoMedia*: trips from middle income households to work
- *TrabalhoAlta*: trips from lower income households to work
- *Estudos*: trips from all households to education
- *Saúde e serviços*: trips from all households to health and services

Their characteristics are presented in Table 8.

Name	Generated by consumption of (sector)	By (sector)	Value of Travel Time	Value of Waiting Time	Min Trip Generation Rate	Max Trip Generation Rate
TrabalhoBaixa	Lower income HH	All activity sectors	0.54	1.08	0.19	0.28
TrabalhoMedia	Medium income HH		2.70	5.40	0.39	0.49
TrabalhoAlta	Higher income HH		14.68	29.36	0.714	0.808
Estudos	Education	All households	1.98	3.96	3.11	3.36
Saúde e serviços	Health and Services	All households	11.96	23.92	0.037	0.049

Table 8: Characteristics of the Travel categories

In the case of education (and the same for health and services) the number of trips should correspond to the number of students, not to the number of education-related workplaces. According to the 2011 National Inquiry, there were 1,301,000 students in the Metropolitan Area of Belo Horizonte (IBGE, 2011), for 57,961 education-related jobs, which corresponds to 22.45 students for every employee (teacher, assistant, administrative and cleaning staff, etc.).

As a consequence, the consumption by one household of one unit of Education sector (one unit = one job) corresponds to 22.45 students going to school. Or, as students go to school in average 5 days a week, it generates 16.03 commuting trips (back-and-forth) per day, or up to 8 trips (one way) during the morning peak, as all the students do not actually go to the university during the morning peak. This first estimation of trip generation rates enabled us to run the model a first time and to compare the resulting number of trips per category with the actual number that we got from the 2001-2002 OD survey, as explained further. This explains why households would generate 3.11 to 3.36 trips to education at morning peak in our model, and not 8 as in the example.

Time value was determined for each travel category based on the average income of the category travellers. Concerning Determination of time value for each travel category (income and trip-purpose based). People/dwelling = 3.101364039. Minimum salary = 512 R$/month (2010) or 2.97 R$/hour (legal working time = 172 hours/month).

Trip generation rates are defined on the base of the number of trips actually realised in the metropolitan region of Belo Horizonte (RMBH), relatively to the inter-sector consumption volume as informed in TRANUS. The source of data is the 2002 origin-destination survey, actualised to 2010 on the base of a 2006 study (TECTRAN, 2008). In 2002, 1,435,614 trips were realised from and/or to the RMBH at morning peak (7:00am to 9:00am). Trips realised within unique TRANUS zones are not generated by TRANUS, so we could not consider them, which may have generated important uncertainty on trip generation results. Trips from out of the RMBH were not considered in this study either, although TRANUS enables it.

Trips by origin/destination	Number of trips	% total trips	Considered
Within unique TRANUS zones	632,473	44.1%	NO
Between different TRANUS zones	787,211	54.8%	YES
From or to out of the RMBH	15,930	1.1%	NO

TABLE 9: DAILY TRIPS REALISED BETWEEN 7AM AND 9AM IN THE RMBH IN 2002
ADAPTED FROM FJP, 2003

This volume of trips is actualised to 2010 by using an annual growth rate of 2.59% (see on page 43).

We deal with a total number of **965,898 trips** realised daily between 7am and 9am.

TRIP ASSIGNMENT

In TRANUS, activities generate trips that are assigned in the transport network, based on nodes and links and where a transport service is supplied by operators.

TRANSPORT OPERATORS

TRANUS works with transport operators, corresponding to what one classically calls transport modes, but the word "mode" corresponds to a different concept in TRANUS, which lost importance in the recent versions of the software. Various characteristics are specified for each operator, which are proper to this operator (see Table 10). Transfer costs between operators are also defined, as well as operators' speed on each link type.

Characteristics	Examples
Operator	Pedestrian, Bike, Car, Bus, Train, Taxi, Plane, etc.
Type	Non-motorised, Normal, Transit, Transit with routes
Occupancy	Pedestrian: 1 Car: generally slightly higher than 1 Train: up to thousands
Costs for the user	Car: energy cost (considers only costs of use) Bus, metro: boarding cost Taxi: Boarding, time and distance cost
Fixed waiting time	Pedestrian, bike, car: No Bus: Generally not (waiting time is function of frequency) Metro, plane: Yes (buying ticket, checking and boarding)
Modal Constant	Default: 1. Higher for less attractive operators.

TABLE 10: TRANSPORT OPERATORS' MAIN CHARACTERISTICS, OWN EDITION

Four operators were defined in Belo Horizonte's model (see Table 11, the mentioned costs are the ones directly paid by the passenger), corresponding to 95% of the passenger trips in RMBH (see Table 15, further detailed):

Operator	Type	Occupancy (at peak)	Modal constant	Boarding Tariff (R$)	Energy cost (R$/km)
Car	Normal	1.45	1	0	0.63 to 1.90
Bus	Transit with routes	80	1.2	2.65	0
Metro	Transit with routes	1000	1.2	1.8	0
Pedestrian	Non-motorised	1	2	0	0

TABLE 11: TRANSPORT OPERATORS' MAIN CHARACTERISTICS IN THE MODEL

TRANSPORT NETWORK

Our model is composed of 5,173 nodes and 13,932 links, imported from a GIS database provided by Belo Horizonte's transport authority (BHTrans). This network is a simplification of the real network. It also contained some errors, particularly concerning links' capacity. The full network was also available (with 89,839 nodes and 130,089 links), provided by the firm BH SETRA, but too heavy for running TRANUS in reasonable time (around 20 minutes per scenario on a personal computer). Having both made it possible to correct the mistakes in the first and to import routes in TRANUS, not without difficulties as explained further.

The transport network was exported to TRANUS from a GIS database edited on the software TransCAD, through 4 network files:

- **Nodes**: the file must specify zone centroids (where the trips generated by the zones enter the transport network);
- **Links**: physical ways (streets, train ways, highways, and if needed cycleways and pedestrian ways), shared by different operators or exclusive;
- **Opers**: list of transit routes and their characteristics (for e.g. buses, trains, planes);
- **Routes**: geographical description of the routes, specifying the links they pass by and whether they stop at a link (making transfers possible)

The network files were exported in the database format DBF (initially for the transport model EMME/2), then opened and edited with Excel, and saved in *comma-separated values* files (CSV). CSV extensions were changed into ".NODES", ".LINKS", ".OPERS" and ".ROUTES" so TRANUS could recognise it. A slightly different process was used for exporting routes files, as explained further.

This step requires good-quality databases, including network files that inform links direction and capacity, as well as transit route system files that inform capacity and frequency of the routes. It is also possible to import files informing turn restrictions, but this possibility was not explored in our model, for the sake of simplicity and time restrictions.

Link types

The links were classified in 11 types, as shown in Table 12.

Link type	Details	Capacity (BH Setra, 2012)	Capacity (TRANUS)	Speed	
				Cars	Buses
Access to centroids	doesn't correspond to a physical link	no capacity restriction	999999	30	15
Terminal	for pedestrians exclusively, corresponding to bus-to-metro transfer stations	no capacity restriction	999999	Ø	Ø
Access to metro	for pedestrians exclusively	no capacity restriction	999999	Ø	Ø
Local way	street	1000 (avg: 1000)	1000	30	15
Collector way	medium streets	1000 (avg: 1000)	1000	40	15
Central arterial way	city centre (planned in the end of the 19th century)	1000-7200 (avg: 3000)	no change in the original network	40	20
Secondary arterial way	municipal important axes	500-5400 (avg: 2000)	2000	50	30
Primary arterial way	municipal main axes	3000-7200 (avg: 5000)	5000	60	40
Urban highway	intra-municipal highways	3600-7200 (avg 5400)	5400	90	60
Highway	inter-municipal highways	1800-3600 (avg: 2700)	no change in the original network	90	60
Metro line	exclusively for metro operator	3 min between 2 trains	20	Ø	Ø

TABLE 12: DEFINITION OF LINK TYPES

We observed important mistakes on capacities of various links in the simplified network we got. In various cases, very important corridors had lower capacities than local streets. Another clue was that in a sequence of portions of the same corridor (without crossing any other way), the capacity could vary between 600 and 3,600 veh/hour from one link to the following. A quick review was realised on a dozen of links of each type randomly picked up in the full network to observe the range of capacities for each link type. We could observe little variation, so the average capacity was adopted for TRANUS model, with three exceptions:

- Access to centroids, Access to metro and Terminals should not suffer capacity restriction, so their capacity was fixed to 999,999 veh/hour. This has no impact as pedestrians never suffer capacity restrictions in TRANUS, and they are the only users of Access to metro and Terminals;
- Metro line capacity was defined according to standard safety rules (two trains should be distant of at least 3 min from each other). As the metro frequency is 8 trains/hour, this figure is not restrictive;
- The capacities of Central arterial ways (between 500 and 4,800 veh/hour) and inter-municipal Highways' (between 1,800 and 10,800 veh/hour) appeared to be rather right in the simplified network, so we chose not to change them in order to keep the variations.

THE PARTICULAR CASE OF TRANSIT ROUTES

In the former model, no operator had routes. After examining the choice of paths between zones the model made, it appeared to be almost indispensable to trace routes for the two transit operators: bus and metro. Indeed, bus worked almost as a very cheap taxi, as direct "routes" were created for each origin-destination pair.

Importing the route system caused many difficulties, due to incompatibility of the transport network with the route system: the network we used in our model was a simplification of the real network, which would have been too heavy (causing long running time) and harder to calibrate. But no correspondence could be established between this simplified network and the real one, so the routes could not be imported into the model. As there are 2,032 routes (one route in each direction for all 1,016 lines of the RMBH), it was not realistic to trace them directly on TRANUS. We found a solution, following advice by Juancarlo Añez, co-developer of TRANUS: "*when computing power is not up to a full transit route inventory, or when funding doesn't allow for it, the solution is to aggregate similar routes to have a simpler link-route network.*" (J. Añez, TRANUS forum, 25/1/2013). We created aggregated routes of three kinds:

- **11 municipal routes** that would follow the main transport corridors within the city of Belo Horizonte, from the periphery to the centre (trunk lines);
- **15 inter-municipal routes** linking the other municipalities to Belo Horizonte;
- **7 feeder lines** within different districts of Belo Horizonte (almost one for each "*regional*", name for the 8 macro-districts of Belo Horizonte)

Inter-municipal routes stopped at the limit of Belo Horizonte, with automatic connection to the municipal network (granted by the high frequency of the aggregated routes). By this way it was possible to express the difference in frequencies and prices between the municipal (R$ 1.85 to R$ 2.65 per boarding) and inter-municipal lines (around R$ 5 per boarding) without having to define a second bus operator *a posteriori*.

This solution is far from ideal: the aggregated routes do not cover the territory as well as the real network (problem of accessibility to the transport network that may cause different modal and path choices) and it is very hard to determine their frequency, which had to be calibrated. We first tried to count the number of buses passing by each corridor in the real Route System file (2,032 routes), but this was not without some problems:

- It is not possible to determine with certainty which routes are of the city of Belo Horizonte, of other municipalities (which should not be considered as TRANUS doesn't generate intra-zone trips) or inter-municipal (more expensive in average, around R$ 5 per boarding),
- The routes that are selected because they pass by a certain point of the corridor might not follow this corridor on a long distance and might continue on another corridor.

Due to these limitations, another method was adopted to determine frequencies, based on the total number of trips operated in the RMBH, which was known, per direction (see Table 13):

Period	Time	Number of bus trips	% of the whole day
Whole day	00:00 to 24:00	55267	100.0%
Working day	05:00 to 23:00	52547	95.1%
Morning peak	07:00 to 09:00	7116	12.9%

TABLE 13: BUS TRIPS IN RMBH
ADAPTED FROM BH SETRA, 2012

It is interesting to notice that the proportion of bus trips realised during the morning peak in the metropolitan region of Belo Horizonte (RMBH) corresponds to the proportion of passengers travelling during the morning peak (see on page 30). In other words, there is a good correspondence between the curves of bus frequencies (BH SETRA, 2012) and passengers transit (TECTRAN, 2008).

With the help of corridors' maps from Belo Horizonte's mobility plan (see Figure 14, Logit, 2008), a weight (w_i) was given to each route depending on its relative estimated importance in the route system. The total number of trips per hour that are realised during the morning peak in the RMBH (7116 trips, i.e. 3558 trips/hour) are then distributed according to this estimation (see Equation 4). This step is very arbitrary, but it presents the advantage to keep the right volume of trips, and no better method was found that could be realised in a reasonable time with the available data.

$$f = 3558 \times \frac{w_i}{\sum_i w_i}$$

EQUATION 4: BUS ROUTE FREQUENCY

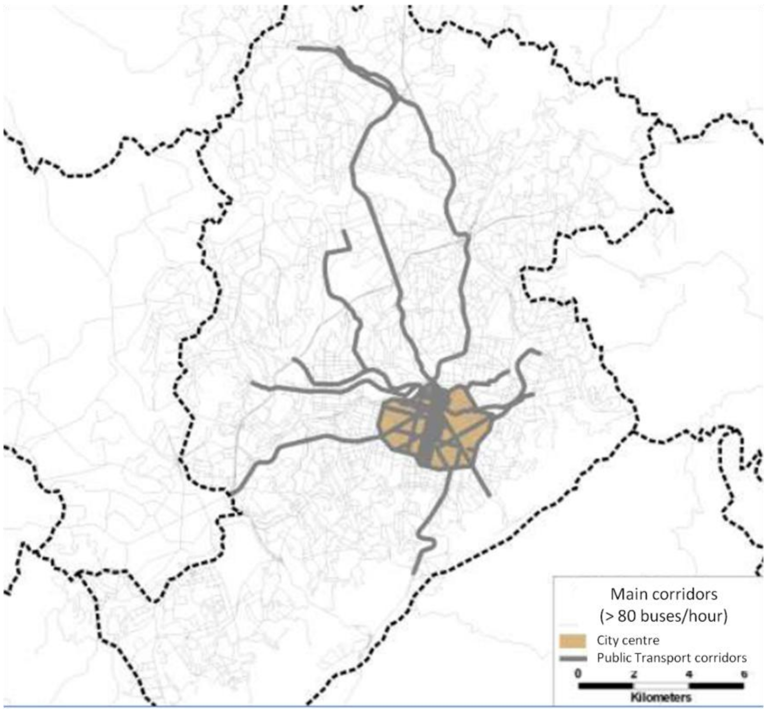

FIGURE 14: MAIN PUBLIC TRANSPORT CORRIDORS OF BH
SOURCE: MOBILITY PLAN, 2008

TRANUS generates trips according to the location of population and economic activities in the different zones of RMBH. In some cases, the number of trips generated and allocated to the different transport operators goes far beyond the capacity of these operators. This happens particularly in the case of bus routes, due to the way bus frequencies were determined. It is then necessary to adjust the bus frequency of these routes.

Route frequencies were increased when the average occupancy of the buses was higher than 80%, in order not to get overloaded lines. This is justified in the current scenario because these adjustments are made by the transport authorities (BHTrans and DER) and no bus can drive with occupancy going up to 800%. As our model is calibrated based on a real OD matrix, it is reasonable to think that the bus system is dimensioned so that there is no such overloading (but unfortunately the system is far from being perfectly dimensioned).

As a consequence, for overloaded routes, the weights used to distribute the total number of trips are multiplied by the factor average occupancy / 80% (see Equation 5). The weight of these routes in the distribution of trips will then increase, so their frequency increases as well, which will reduce the average occupancy of the route.

$$f' = 52457 \times \frac{w_i'}{\sum_i w_i'} \; and \; w_i' = w_i \times \frac{AvgOcc}{80\%}, when \; AvgOcc > 80\%$$

Equation 5: Correction of Bus route frequency

To import routes files into TRANUS, we used a slightly different process than for nodes and links:

- A short programming code was written for the first step: exportation from TransCAD of a DBF file with the sequence of links of each route (see Appendix A);
- The second step is realised on Microsoft Excel and consists in associating each link with two nodes, origin and destination in the right order (origin of link n+1 = destination of link n), checking that there is no back-and-forth section (produces error in TRANUS) and checking route stops;
- The links sequences of all routes are saved in a CSV file, which extension should be changed to “.ROUTES” before being imported into TRANUS.

MODEL CALIBRATION

Models generally pretend to be an "as perfect as possible" representation of a reality. They can be compared to small worlds where functions describe the dynamics of the model, i.e. the way the different elements interact one with each other and evolve in time:

> "*Instead of making experiments in real environments, the analyst recreates a simplified version of reality in a computer model. Once satisfied that the model reproduces reality to an accepted degree of accuracy, the analyst can perform experiments on the artificial environment.*" (De la Barra, 1989)

The base scenario in TRANUS is used to calibrate the model by adjusting parameters and correcting input data if necessary, after comparing the outputs to the observed reality.

REFERENCE OD MATRIX

The main set of data that we used for comparison was 2002 metropolitan origin-destination survey, actualised to 2010. The data from this survey was stored as a list (array) of all possible trips observed in a day, with the following important variables:

- **Origin and destination of the trip**, in two different columns. This survey was based on a more detailed zoning (AH 2001: "áreas homogêneas", which is a division of the RMBH into 1049 zones of equivalent population) than in our model, but our zones are an aggregation of these "áreas homogêneas", which made it possible to attribute a TRANUS zone from our model to each origin and destination after crossing data;
- **Time of the day** (from 1 to 48, half an hour per half an hour): only trips from 14 (7:00-7:30) to 17 (8:30-9:00) were considered;
- **Nature of the origin and of the destination**, in two different columns, among: Residence, Work, Studies, Service, Transfer, Other; this information was made compatible with our TRANUS model's travel categories with the following table:

To \ From	Residence	Work	Studies	Service	Transfer	Other
Residence	Other	Work	Studies	Service	Other	Other
Work	Work	Work	Work	Work	Work	Work
Studies	Studies	Studies	Studies	Studies	Studies	Studies
Service	Service	Service	Service	Service	Service	Service
Transfer	Other	Work	Studies	Service	Other	Other
Other	Other	Work	Studies	Service	Other	Other

TABLE 14: CORRESPONDENCE BETWEEN THE OD MATRIX ORIGIN/DESTINATION NATURES AND OUR MODEL'S TRAVEL CATEGORIES

- Transport mode: up to 5 different modes used for each trip (in practice up to 3) among:

OD matrix mode	TRANUS operator	Percentage of trips
Walking	Walking	11%
Car Car passenger	Car	29%
Train or metro	Metro	1%
Bus Combi	Bus	55%
Other Truck Moto Taxi School bus Special transport Bike	Other (not considered in TRANUS)	5%

TABLE 15: TRANSPORT MODES IN THE REFERENCE OD MATRIX / IN TRANUS

- **Number of occurrences** of trips with the exact same former characteristics.

All internal trips (realised within the same zone of our model) were removed from the reference OD survey, as these trips are not modelled by TRANUS. Finally, the survey data (different lines for each origin-destination couple) was turned into a bi-dimensional origin-destination matrix, with the help of INDEX Excel function.

ACTUALISATION OF REFERENCE DATA

The 2002 OD matrix was actualised to 2010 with the use of an annual growth rate of 2.59%. This rate has been calculated for 2002-2006 variation, based on a work by Tectran (TECTRAN, 2008) for an OD matrix of daily car trips within Belo Horizonte and Contagem. The engineers used a screen line method.

The city zones are divided into two groups (or macro-zones) separated by an important infrastructure (train line, highway) or geographic element (river). The number of cars / passengers crossing this line in both directions is counted during a period of time (in this case, 21 crossing points were observed during 15 to 24 hours, from 5/31/2006 to 6/21/2006). As the screen line is an important barrier, only a few checkpoints are needed to observe all traffic between A and B. The zones of the OD matrix are grouped depending on their location relatively to the screen line (macro-zones A and B), and coefficients are applied to "A to B" and "B to A" trips corresponding to the number of trips observed across the screen line. Internal trips ("A to A", "B to B") are multiplied by the average of "A to B" and "B to A" coefficients.

Transport mode	Vehicles per day (across the screen line)	Modal split (vehicles)	Equivalent Vehicle Units	Equivalent Vehicle Units per day	Average occupancy	Modal split (passengers)
Cars	350,888	78%	1.0	350,888	1.455	39%
Buses	30,036	6%	2.5	75,090	23.14	54%
Motorbikes	54,517	12%	0.2	10,903	1.1	5%
Trucks	18,144	4%	2.0	36,288	1.65	2%

TABLE 16: RESULTS OF THE 2006 TRAFFIC SURVEY IN BH
SOURCE: ADAPTED FROM TECTRAN, 2008

The average variation observed in the daily traffic volume across the 21 points between 2002 and 2006 was 10.71% in the direction North-South and 10.78% in the direction South-North, which represents an annual variation of 2.59%. In the absence of other more recent data, we extrapolate the volume of traffic from 2001 to 2010 with the same growth rate, without considering local variations, and we apply the same growth rate for the whole RMBH (although the study only considers BH internal trips). We do not consider either variations in modal split, although Belo Horizonte's car fleet has increased very much in the last decade (5,92% average per year between 2001 and 2007), while bus fleet did not increase significantly (Logit, 2008).

Vehicle	Occupancy
Car	1.45
Taxi	1.62
Van (informal transit)	4.2
Bus	23.14 (40 at peak hour)
Truck	1.65

TABLE 17: AVERAGE NUMBER OF PASSENGERS PER TRANSPORT MODE IN BH IN 2002
SOURCE: FUNDAÇÃO JOÃO PINHEIRO, 2003

Modal split

TRANUS produces OD matrices of trips per operator, considering a new trip at each transfer, even for a single purpose. For example, if one goes working by metro, but has to walk to the metro station A and to walk from the metro station B to the work, TRANUS counts 2 walking trips and 1 trip by metro (see Table 18). The total number of trips is thus higher when counted per operator than per purpose.

Operator	Number of trips/day	% trips
Car	2,357,325	24.9%
Bus	3,586,635	37.9%
Metro	326,727	3.5%
Walking	3,183,166	33.7%
TOTAL	9,453,853	100.0%

TABLE 18: TRIPS PER OPERATOR, EXAMPLE OF RESULTS FROM TRANUS

In order to calibrate the modal split, the results should be made compatible with the available surveys, for instance considering one main operator for each trip. It is possible to get rather good comparisons from the matrix of transfers between operators, with hypotheses on the number of trips beginning by walking (depending on the expected modal split: for instance car users never walk): most of walking trips will not be counted as walking trips as they are only realised to transfer from and/or to another operator (e.g. bus, walking, bus). On the other hand, car and metro can always be considered as the main operator for the whole trip (see Table 19).

Car	Car	Bus	Metro	Walking	TOTAL
Boarding	320,771	177,661	-	419,376	917,807
Car	-	-	-	-	-
Bus	-	327,822	-	558,588	886,409
Metro	-	-	-	52,083	52,083
Walking	-	450,659	52,083	-	502,741
TOTAL	320,771	956,141	52,083	1,030,046	2,359,041
Trips considered	320,771	453,130.55	52,083	91,823	917,807

TABLE 19: TRANSFERS BETWEEN OPERATORS AND MODAL SPLIT THAT IS CONSIDERED (75% OF TRIPS BEGINNING BY A WALK)

OBJECTIVE ANALYSIS FOR CALIBRATION

The last step after collecting data, calibration is the hardest part of TRANUS model building and it can last several months. Indeed, there generally exists one (possibly various) equilibrium that the model can reach if the parameters are well calibrated. In this case, the model converges after some iteration. But due to the high number of parameters and the errors caused by the quality of the data, it proves to be hard to find equilibrium, and if equilibrium is reached, one should take care that it corresponds to the reality.

Before running TRANUS, it is worth checking for basic errors with the “Project / Validate” function in TRANUS User Interface. This function helps getting rid of errors in the input data such as:

- Lack of information (e.g. links with no type or no capacity);
- Connection errors (e.g. dead ends, cuts in routes, inaccessible links);
- Incoherent economic data (e.g. Max production < Min production)

Running TRANUS model produces various outputs concerning activity location, trip generation, trip distribution and costs models that can be compared to available “real” data. A good way to calibrate the model is to define an objective function that measures the distance between these outputs and the observed reality. This function is generally a distance function of n variables (such as: loading at different important points of the network, modal share of the different operators, number of trips per motive, etc.):

$$f(\tilde{X}_n) = \sum_{i=1}^{n} a_i \frac{\left(X_i - X_i^0\right)^2}{\left(X_i^0\right)^2}$$

The work of the modeller is first to identify the relevant variables and, for each scenario, their value X_i^0 in the reality and the a_i coefficient. Then, the model should be run repetitively with slight modifications of one parameter at each time (most parameters have some influence on each other, as the program works as a loop that is iterated), in order to minimize the objective function.

Path choice is independent from the activity model and runs before all other sub-programs, although it is not independent from trip distribution parameters (such as operators’ costs), so it should be the first step of calibration. A good knowledge of the modelled area and its transport system is required to check path choice, but tools such as TransCAD or even classical route finders (e.g. Google Maps, Bing Maps) can be used to check if TRANUS calculates optimal paths.

The following items are elements of comparison:

- **Activity location**;
- **Path choice** (including **operator choice**, **transfers**, **travel time** and **cost**);
- **Total volume of trips**;
- **Modal split**;
- **Trips per category**: volume of trips per purpose and income classes;
- **OD matrices**: number of trips for each origin-destination peer (can measure the correlation between matrices);
- **Link loading**.

However, in this study, we lacked the computational skill to be able to implement automatic calibration and we did not engage into defining and calibrating an objective function, although that would have been ideal. As an alternative, we set up a routine composed of a series of controls in order to get a qualitative but reasonable measure of the distance between the outputs and the reality. These controls were made easier by some Excel spreadsheets developed for this study:

1. *Location indicators*: a compilation of the outputs that appeared after the last iteration of activity location sub-model (LCAL/LOC);
2. *Transport indicators*: a compilation of the outputs that appeared after the last iteration of trip distribution sub-model (TRANS);
3. *Comparison of OD matrices* (output and 2002 actualised), through global correlation and local variations;
4. *Routes frequency*;
5. *Trips per category* (trip generation)
6. *Modal split* (trip distribution)

The initial set of indicators was based on observations from the reality. For instance, transport operators' penalties (not monetary) were given to favour cars for the most wealthy, as this income class of people uses public transport very few. Beginning from this first set, path choice was first calibrated, independently from the other sub-programs of TRANUS. In the next phase of calibration, we would check that the modification of the parameters did not have significant impact on path choice, which was rather stable.

The routine that we used after modifying a parameter and running the model was:

1. Copy the results of location_indicators_00A.csv into the compilation spreadsheet and check for the distance towards the expected location. In the base scenario, location choice was rather stable.
2. Copy the results of transport_indicators_00A.csv into the compilation spreadsheet and:
   - Check for the travel and waiting times, and the number of suppressed trips. Infinite waiting times and a high number of suppressed trips (that were generated but could not be distributed) appeared in situations of high congestion (either on roads or in public transport), which should then be corrected in priority. This generally blocked transport distribution after the first iteration.
   - Check for the average cost, time and distance of trips, depending on the operator.
3. From this last sheet:
   - Copy the number of trips per category to *Trips per category*, to be compared with the real values taken from the 2002 OD survey;
   - Copy the number of trips per operator to *Modal split*;
4. Generate the report of transfers between operators, and compare the modal split after taking the transfers into account. Operators' share were compared with the real values taken from the 2002 OD survey (FJP, 2003) and corrected with the VIURBS research (TECTRAN, 2008).
5. Copy the results of route_profile_00A.csv to the Routes frequency compilation spreadsheet, and check:
   - the average speed of the bus lines, which should be between 10 and 50 km/h (very low speeds are signals of congestion);

- the maximum occupancy of the buses, that should not exceed 100%, given that the nominal bus capacity in the model (80 passengers) corresponds to the maximum occupancy, only observed during the morning peak in the direction of the city centre;
- the average occupancy of the buses, that should generally not exceed 50%, even during the morning peak (the passenger flow is mainly in one direction).

6. Generate the link loading report and check that no link had a congestion level higher than 150% (which would tend to block the model), and in last steps of calibration compare the flows in some crucial points (main corridors and city centre).
7. Generate the OD matrix, aggregate trips into the same 21 macro-zones as the 2002 OD matrix, and check:
    - The correlation between the two whole matrices (trip generation),
    - The correlation between the total trips per origin (trip production),
    - The correlation between the total trips per destination (trip attraction).

FINAL CALIBRATION

Activity location

After the model ran, we could observe in a few zones that production was more than 4 times higher or lower than the actual offer. In those cases, the corresponding zones were examined one by one, which sometimes enabled to detect and correct errors in the input data. For example, the education offer in UFMG (the Federal University) campus area was widely underestimated, probably for fiscal reasons: this university is federal so it may be fiscally registered in Brasília, the federal capital of Brazil.

Trips by category

Calibrating the travel generation by category (total number of trips and trips by category) was rather easy as all variables were independent of each other and controlled by the trip generation coefficients. As a consequence, we managed to get good values of trips by motive (see Table 20).

Trip purpose	Work	Studies	Services & Health	Other	TOTAL
2002 OD survey (actualised)	706,314	187,763	42,750	29,071	**965,898**
	73%	19%	4%	3%	**100%**
Results TRANUS	688,406	188,215	41,185	0	**917,806**
	75%	21%	4%	0%	**100%**

TABLE 20: TRIP GENERATION BY PURPOSE - BASE SCENARIO VS. REALITY

Trips by operator (modal split)

Calibrating the modal split proved to be harder than expected, mainly due to the high number of dependent variables and parameters impacting the modal choice, either related to cost, time penalties, comfort penalties, car ownership, etc.

As a consequence, we did not manage to reach perfect correlation between the model's modal share and the real modal share (see Table 21).

	Cars	Bus	Metro	Walking	TOTAL
2002 OD survey (actualised)	237,533	553,013	15,786	104,244	**910,576**
	24.9%	58.0%	1.7%	10.9%	**100.0%**
Results TRANUS	320,771	453,130.55	52,083	91,823	**917,807**
	34.9%	49.4%	5.7%	10.0%	**100.0%**

TABLE 21: MODAL SPLIT - BASE SCENARIO VS. REALITY

Trip generation and trip distribution

74% correlation was observed in the trip generation pattern between the real OD matrix and the one produced by the model, the measured variable being the total number of trips generated by each zone (total column of an OD matrix).

36% correlation was observed in the trip distribution pattern between the real OD matrix and the one produced by the model, the measured variable being the whole OD matrix.

Conclusion

This master thesis research aimed at building and calibrating a land-use and transport model for the metropolitan area of Belo Horizonte, Brazil, and to use it in an application to the case of *Operação Urbana Consorciada*. A central issue was whether a LUTI model is a good and operational tool to assess the impacts on transport demand of extensive changes in land use.

With the suggested methodology, we were able to build and calibrate Belo Horizonte's land use and transport model. OD matrices could be produced for different development alternatives. However, many simplifications of the input data and strong hypotheses for the calibration phase were made, which brings serious doubt on the validity of the results.

The main limitations of this research were not as much time restrictions (6 months for the whole research) as the low quality of input data (particularly concerning land and floor space) and of the transport network, which was a simplification of the real network, which induced other simplifications. Moreover, calibration was made with an old actualised origin-destination survey, which brought much uncertainty.

As a consequence, some effort should be made on gathering better data if this model is to be used further. Moreover, the results of the 2010 OD survey will be available by the spring, 2013, and data from 2012 OD survey are already being processed, which will make possible to calibrate the model with base scenarios at two different stages, thus testing the dynamics of the model over time.

Concerning the methodology, further improvements could be to create an objective function in order to calibrate the model with much more accuracy. This will probably be a very long work. In order to accelerate the calibration process, a short script able to run the model various times with slightly different values of a parameter would be very helpful. The program could also extract the results from the files generated by TRANUS and to compile them in order to make their analysis easier. Such a program seems to be under development a French team at IDDRI.

I am currently planning to go back to Belo Horizonte and continue working with Tectran, so I might have the opportunity to realise some of these improvements.

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APPENDICES

Appendix A. CODE FOR TRANSPORT NETWORK EXPORTATION FROM TRANSCAD

This code was used t the routes file from TransCAD, using the GIS Developer's Kit. It's been originally developed by engineers from Grupo Tectran (Traffic and Transit Engineering Consulting). We adapted it for the use of this project.

It takes as inputs the highway network (Network) and route system (Route System) of the modelled area, and produces a database file (DBF) containing the sequence of links of each route.

The colours stand for input files and variables, internal variables, output files and variables.

```
SetLayer("Route System")

qry1 = "Select * where Route_name <>null"
AllRoutes=SelectByQuery("Routes", "Several", qry1)
viewR=GetView()
CountRoutes = GetFirstRecord(viewR+"|Routes", {{"Route_ID", "Ascending"}})

Create_Route_File = CreateTable("Route_File","c:\\...\\Routes.dbf","DBASE", {
        {"Route_ID", "Integer", 9, null, "Yes"},
        {"Sequence", "Integer", 5, null, "No"},
        {"Link_ID", "Integer", 10, null, "Yes"},
})

for y=1 to AllRoutes do
        RouteY=viewR.Route_Name
        RouteLinks = GetRouteLinks("Route System", RouteY)
        NLinks=ArrayLength(RouteLinks)
        SetLayer("Network")
        viewL=GetView()
        For i = 1 to NLinks do
                LocateLink = LocateRecord("Network|", "ID", {RouteLinks[i][1]}, {{"Exact",
                "True"}})
                WriteLink = AddRecord("Route_File",{
                        {"Route_ID", viewR.Route_ID},
                        {"Sequence", i},
                        {"Link_ID", viewL.ID},
                })
        end
CountRoutes = GetNextRecord(viewR+"|Routes",null, {{"Route_ID", "Ascending"}})
End
```