# The use of qualitative modeling to derive qualitative policy implications from structural aspects of a model – a practical case

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**Abstract.**

This paper reports about and interprets a qualitative system dynamics effort undertaken in the context of urban transportation systems in Latin America. In this case, the available time was too short to attempt model quantification and simulation. A stock-and-flow diagram with units of measure and tentative equations was developed and its structure analyzed. The analysis of the reachability between variables and of the shortest independent loopset around one centrally important variable have allowed to elaborate a series of qualitative indications and recommendations. The case is used to argue that, if cautiously interpreted, a qualitative model can yield helpful insights.

**Keywords**: qualitative system dynamics, stock-and-flow diagrams, structural validity, structural analysis, urban transportation system

## Introduction

This paper reports from a qualitative modeling effort conducted in a very short time frame, which has been undertaken to capture the understanding that a group of experts have of the problematic interaction of land use and transportation system in cities in Latin America. The main cities of Latin-America – Mexico City, Sao Paulo, Lima, Bogotá and Santiago de Chile – have been receiving ongoing population inflows; a recent survey has found sustained growth rates (Jordán et al., 2010). In this context, the transportation system is one of the key infrastructures, together with others like energy, water, health, education and waste collection.

As in any large city, transportation is a source of long-lasting problems of congestion and air pollution – therefore as soon as the quality of life and the sustainability of human activity come into consideration, the transportation system becomes a relevant subject. Therefore several cities have undertaken substantial efforts to improve their transportation systems; however the lack of decision-taking structures and processes that would span the entire functional city area as one whole unit, has lead to fragmentary approaches that have usually focused on the short-term adjustment of the transportation infrastructure to the changing demand (usually in a 10-years time horizon).

This leaves the links between the transportation system and especially the land use out of consideration. By consequence, many feedback loops that have long been pointed out (Sterman, 2000; Pfaffenbichler et al, 2010) are not taken into account and an important policy lever is not used.

The "Sustainable Development and Human Settlement Division" of the ECLAC (Economic Commission of the United Nations for Latin Amreica and the Caribbean, located in Santiago de Chile) has been developing efforts in pro of greener transportation systems, in the framework of the project " Proyecto Innovación ambiental de servicios urbanos y de infraestructura: Hacia una economía baja en carbono" (environmental innovation in urban services and urban infrastructure: towards low carbon economy). Their driving question was "how to influence the transformation of the urban transportation system towards lower emissions, without negative side lateral effects in other urban systems?" Inspired by system dynamics model dealing with national development (the Threshold 21 or T21 model developed by the Millenium Institute),

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the question arose if system dynamics modeling could help to bring forward a more systemic approach to transportation system development. The time and resources available for an initial step were limited to 5 weeks. Therefore, it was out of question to develop a full application of the existing system dynamics model (MARS; see Pfaffenbichler et al., 2010; Pfaffenbichler, 2003) or even develop a completely new model.

It was decided to attempt the development of a qualitative model dealing with the interdependencies between the transportation system and land use over a time horizon of 25 years. Since stock-and-flow diagrams are able to represent more important information than causal loop diagrams, we opted for the former alternative. The team, consisting of a group of ECLAC officers and one system dynamicist, would proceed from what earlier publications have made public (Forrester, 1969; Sterman, 2000; Pfaffenbicler et al., 2010; Alfred, 1995; Duran-Encalada and Paucar-Caceres, 2007, 2009; Levine et al., 2006; Peña and Fuentes, 2007; Sonar, 2008; Stave, 2002; Winz, 2005; Yevdokimov, 2002) and open in-depth interviews with the members of the ECLAC team. These had participated in 7 three-hour training sessions dealing with a simplified version of the T21 model, which gave them a possibility to read and discuss stock-and-flow diagrams. So a first stock-and-flow diagram was developed. Then four rounds of revision – open discussion of each of the aspects of the sock-and-flow diagram – allowed to enrich the diagram and come to a version in which each variable and each link is believed to be conceptually valid and dimensionally consistent.

This version was then analyzed in order to detect important relationships and come to a conceptual and systemic understanding of the situation. It must be noted that a model of the size developed, which has not been put through the behavior tests as part of the validation effort, has to be used cautiously; not only should one refrain from interpretations in terms of behavior (Lane, 2008; Schaffernicht, 2010), but also some of the variables and links which are sincerely believed to be relevant for the problem, might not be there (in the same form) after validation, because an important part of the learning process (Mass, 1991) has not occurred yet.

Still, the model is believed to be trustworthy, at least for analyzing their structure: many pieces have been formulated along previously published material (Forrester, 1969; Sterman, 2000; Pfaffenbichler et al., 2010), and the remaining variables have been scrutinized repeatedly by the CEPAL experts.

The remainder of this paper is organized as follows. The next section presents the main aspects of the stock-and-flow diagram. It is followed by a section that analyzes the structural relationships and identifies some relevant parts of the model which deal with relative attractiveness of transportation modes. According to the structural analysis, a series of qualitative guidelines for strategic planning of urban transportation systems are derived. Some reflection about the experience is offered in the discussion session, and the conclusions underline important results and suggest that qualitative modeling may be a viable option as long as its limitations are taken into account.

## The qualitative model

The model was developed using the VenSim software. It represents a series of conceptual entities and the relationships between them. These entities belong to the thematic realm of transportation; the most relevant ones will be briefly introduced here. A city has an *area* which is occupied by

- *streets* and pathways: simple *streets* (S), *segregated tracks* for buses only (ST), *urban highways* (UH), *bicycle paths*(B) and *pedestrian areas* (PA*)*;
- *buildings* for different purposes (Bld);
- *parking spaces* (P);
- *green areas* (GA);
- abandoned areas (excluded here).

Different types of *vehicles* (*cars*, *buses*) are used mainly by different "*modes*" of transportation: *public* or *private motorized transportation* and *pedestrian transportation* [2]. The whole infrastructure is used to make "*trips*", mainly due to the needs of education or work. The two motorized modes compete for the use of the street infrastructure; the different forms of land use also compete amongst each other. Infrastructure is not only used, but must be constructed, maintained and sometimes demolished; each of these phases of the lifecycle generate jobs (and costs) and emissions.

The model is organized in 13 "views" (or "sectors") listed in the following table:

| **Sector** | **Role in the model** |
|---|---|
| Street decisions | For each of the forms of land use contained in the model, there is a desired quantity which is compared to the actual quantity; differences lead to adjustment decisions, which in turn affect at least two forms of land use. For instance, if more parking space is needed, the necessary area will be taken from streets and buildings, so the desired quantity of streets and of buildings diminishes and then demolition/construction work is initiated. |
| Jobs | There are several kinds of jobs: construction jobs (for building and demolishing diverse types of roads and pathways), driver jobs (for buses and taxis) and other vehicle-related jobs (maintenance). All are affected by decisions to change land use and to buy or sell vehicles. |
| Population | There are three status of population: stratus 1 inhabitants have low income and mainly use non-motorize transportation (bicycle or walking); stratus 2 has more income, but a low rate of motorization, and mainly uses public transportation; stratus 3 has sufficient income to own a car (and use it). |
| Transportation costs | Transportation costs stem from buying vehicles and from using them. |
| Money | Money is transferred between several types of agents: households, transportation firms, employers, developers and the (city) government. The payments are triggered by the modes of transportation and transport system modifications. |
| Subway | The development of subways. |
| Emissions | Emissions are caused by the construction, maintenance and demolition of infrastructure and by its use in the forms of public and private transportation. |
| Construction costs | Construction costs result from the construction and use of the diverse types of roads and pathways and the metro system. |
| Vehicles | There are small vehicles (with subscripts for private cars and taxis) and big vehicles (thee sizes of buses). Their purchase causes expenses and their existence is connected with jobs (drivers, maintenance). |
| Area expansion | As population density increases, so do land prices and construction costs; this is an incentive for developers to move outwards, and the city area augments. This is important, since it impacts public transportation's attractivity. |
| Trips | According to the different mode choices, the city's inhabitants make daily trips (mainly for work and education) of a certain distance. The total occupation of the transportation infrastructure and the accidents depend on how trips are distributed over the modes. |
| Modes | The model distinguishes between a non-motorized and two motorized modes – public and private. The modal choice depends on the relative attractivity of public transportation (PT). Each mode's attractivity depends on the monetary cost and the time required for trips, which depends on the infrastructure, the population (stratus) and trips. |
| Land use | The city's area is used for green areas, buildings or diverse forms of streets and pathways. This sector describes how they can be converted from one form into another; it is very interrelated with the street decisions sector. |

*Table 1: the sector's roles*

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[2] This is a deliberate simplification, as usually a difference is made between cars and motorbikes.

Of course, by cutting the whole model into sectors, some redundancy is generated by the causal links joining variables from different sectors. The following figure displays these relationships:

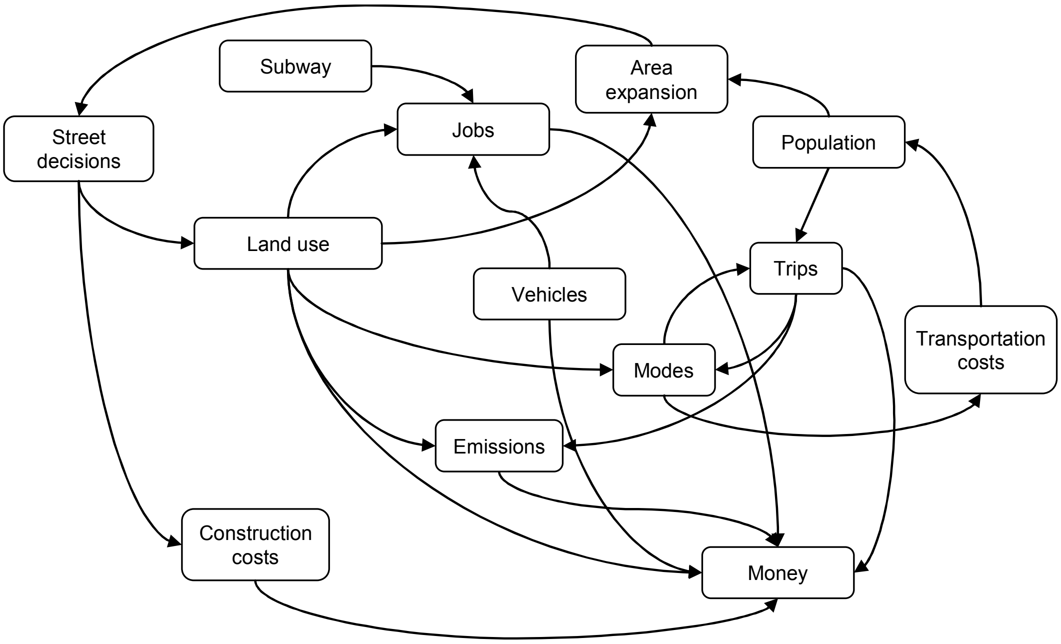

*Figure 1: the model's organization*

The road decisions influence land use, but also construction costs; these decisions are influenced by the expansion of the urban area. Land use and population changes can lead to the expansion of the urban area. Land use, vehicles and subway have an impact on jobs. Emissions are influenced by trips and land use. Trips and modes are interdependent; modes react to changes in land use and influence transportation costs, which have an impact in the population sector. Changes in trips, jobs, land use, vehicles, emissions and construction costs trigger changes in the money sector.

Overall, the model consists of 70 stocks, 67 flows, 359 auxiliary variables, 20 table functions and 135 parameters. Each variable has been described by its unit of measure, a comment and a tentative equation expressing the nature of the relationship with the linked variables. Parameters have not been measured or estimated, so these equations are not meant to support simulations; rather, their formulation was part of a deliberate effort to be as accurate as possible while remaining in a purely qualitative modeling process. Each of the variables has been discussed and found relevant and well-defined by the entire team; the equations are dimensionally consistent.

A complete description of the model, including equations and comments, is not in the scope of this paper; the interested reader is referred to the supplementary material [3]. Here we will concentrate on the parts of the model dealing with the relative attractiveness of transportation modes and with some interdependencies, which allow to formulate qualitative policy implications for the strategic management of an urban transportation system.

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[3] As for this date (3/17/2011), this document is still in Spanish language. It will be translated soon.

## Exploiting the qualitative structure to derive policy implications

### *Migrations*

Forrester has shown (1969) that people move into and out of cities according to the perceived relative attractiveness: if a city promises better perspectives, people move in. This is what happens in Latin America's countries. Also in line with Forrester's arguments, people have different stocks of human capital, mostly related to their education. Since in Latin America, educational opportunities are not equally distributed, most individuals have low employment opportunities; still, the metropolis offers a promising perspective to many individuals. Accordingly, of the many individuals leaving the countryside or smaller towns, the majority have little education, thus reducing the mean productivity of the city's population.

This leads to a rising need for infrastructure (of all kinds) and a sinking availability of money for construction and maintenance. As transportation problems rise, the city's relative attractiveness diminishes, which should be a stabilizer for the migratory stream. However, conditions in the city continue to be less bad than on the countryside and people continue to flow in; as far as their economic situation improves, those who did not have the means to have their own car buy vehicles, thus accentuating the transportation problems.

Infrastructure life cycles are slow – they take decades or centuries (as exemplified by the "urban dynamics" model). So it is clear that rapid changes in the (transportation) infrastructure are improbable. Also, not only would such investments make the city even more attractive, they would also have rather limited effects due to multiple negative feedback loops (many of which have been explained in Sterman, 2000 and MARS, 2010).

From these considerations, we derive two initial indications for decision makers:

1. The slowness of the processes of changing transportation infrastructure has it that progress in the transportation performance will be hardly perceptible during the first years; this poses a communication challenge to maintain the efforts over time.
2. Advancements achieved in transportation performance will in turn lead to increased (population) pressure on the city, thus limiting further advancements.

### *Competing time scales*

When transportation problems make it into the city population's (and voters') awareness, pressure on decision makes will rise. The very awareness augments people's sensitiveness, and therefore "solutions" will be expected in a short time frame (one or two years). This leads to a conflict between short term and long term needs, well described by Senge (1990) as "rapid fixes that backfire": traffic congestion appears as a problem, but it is only a symptom. Expanding the transportation system appears to be a means to control congestion, which appears as a first balancing loop:

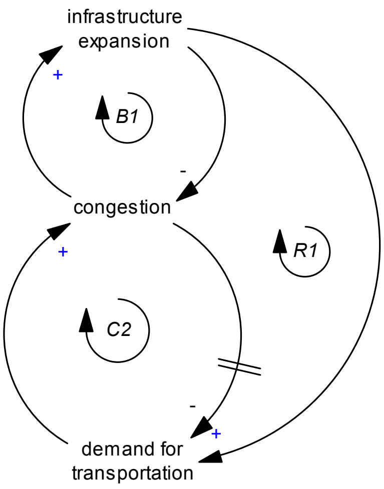

*Figure 2*

However, expanding the infrastructure also leads to an increased demand for transportation, which in turn will leave us with rising congestion. The fundamental solution would be detaining the rising demand; congestion can do that, but it is certainly not a popular political measure. Other measures – like improving the land use such as to reduce the number and length of trips – would only play out on a large time scale, to be measured in decades.

Since decision makers will be under a political pressure measured in years, we formulate two additional indications meant to alleviate the conflict between the long tome scale of fundamental solutions and the short time scale of voting:

3. The public's attention must be actively directed towards those aspects that allow to correctly see if transportation conditions are developing in a positive way;
4. The previous point implies the identification of these key aspects and the availability of easily accessible public information, which requires appropriate procedures and tools.

### *Interdependency*

The above indications can be considered valid for almost any urban infrastructure. We now turn to some aspects which are specifically important for the strategic management of the transportation infrastructure, where "strategic management" shall mean that the transport infrastructure is managed in a proactive way such as to achieve overarching goals for the quality of life in the city.

As stated above, the transportation system is a complex of many components – streets of different types, parking space, bus-stop network, buses, fees – that interact amongst each other and with other components over the use of the land area, like the population (with its levels of education and of income) and economic activity (and its impact on income). Based upon the stock-and-flow structure, this section elaborates on these interdependencies. As will be shown, none of the decision variables has one single effect – rather, there is a multiplicity of effects (not all desirable) and diverse feedback loops are affected by these variables and then develop their own activity. We will thus show that a big city requires an integrated management of its transportation system with all these interdependencies, and accordingly an institutional organization and procedures capable of generating such a management.

As far as the goal of this urban transportation management is to support a favorable economic development with a low carbon footprint, it seems advisable to try to increase the relative attractiveness of public transportation (PT), since PT has a smaller carbon footprint per km travelled. The other possibility is to reduce the mean distance per trip, which requires smaller distances between home and work or school – this would be a land use measure. The modal choice between public and private motorized transportation depends on how the attractivity of PT compares to the one of private transportation; this is a relative attractivity.

Those in charge of managing the transportation infrastructure can chose amongst many options:

- change the stock of urban highways;
- change the stock of segregated tracks (to be used by buses only);
- change the stock of parking spaces;
- change the cost of using streets (tolls);
- change the density of bus stops;
- change the bus frequencies;
- change the mean distance between bus stops;
- change the stock of buses or subway trains.

Once the urban transport management attempts to influence the trip and modal decisions of a city's inhabitants, it also affects other agents (transport firms, construction firms and developers) who take other decisions in pursuit of their interests, but which also have an influence on modal choices. Many such feedback loops have been discussed by Sterman (2000), others have been described by Pfaffenbichler et al. (2010). Our model has the same loops and others, but their discussion is beyond this paper's scope.

Rather, we will focus on how decision variables have diverse impacts across the model. The following table presents the model's decision variables (in columns) and important model variables that are touched when a decision maker uses one of the decision variables. The table has been constructed by constructing the "reachability" matrix (Oliva, 2004). This matrix is based upon the adjacency matrix, where causal links between pairs of variables are indicated; a reachability matrix also contains indirect links.

| Infuences | | UH desired | B desired | GA desired | Bld desired | buses desired | S desired | PA desired | subway desired | ST desired | P desired | street toll per km | PT fare | distance between bus stops | distance per trio per stratus | bus frequency | Stratus 2 | Stratus 3 | Population | sensitivity for motorless modes per stratus | population density | trios per inhabitant per stratus | **Sensitive to** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conditions | PT net in km | 1 | 1 | | | | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | **7** |
| | distance between bus stops | 1 | 1 | | | | 1 | 1 | 1 | 1 | 1 | | | 1 | | | | | | | | | **8** |
| | PT coverage | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **13** |
| | bus frequency | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 | | | | | 1 | | | | | | | **9** |
| | percieved transportation costs | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| Attractivity | relative attractivity PT | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | attractivity private transport | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | attractivity PT | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | | 1 | | **17** |
| Modes | unmotorized mode per stratus | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | 1 | | | **7** |
| | TP mode per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | private mode per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| Trips | annual km PT per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | annual km private transport per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| Emissions | emisiones anuales por infraestructura | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | emissinos PT | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | emissions private transport | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | emissions | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| Costs | emission costs | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | value of accidents | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | private transport expenses | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| | infrastructure expenses | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | construction costs | 1 | 1 | | 1 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **7** |
| | land costs | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| Jobs | car driver jobs | | | | | | | | | | | | | | | | 1 | 1 | | | | | **2** |
| | other car jobs | | | | | | | | | | | | | | | | 1 | 1 | | | | | **2** |
| | bus driver jobs | | | | | 1 | | | | | | | | | | | | | | | | | **1** |
| | other bus jobs | | | | | 1 | | | | | | | | | | | | | | | | | **1** |
| | construction jobs | 1 | 1 | | 1 | | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | **8** |
| Money | M employers | 1 | 1 | | 1 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **7** |
| | M households | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | | | | 1 | 1 | 1 | | 1 | | **15** |
| | M government | 1 | 1 | | 1 | | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | **8** |
| | M developers | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| Density | population density | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| Area | greenfield areas | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| | total area | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| Land use | GA | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 | | **12** |
| | S to construct | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | S U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | P C | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | P U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | UH C | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | UH U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | ST U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | ST C | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | B C | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | B U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | PA C | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | PA U | 1 | 1 | | | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **6** |
| | Metro U | | | | | | | | 1 | | | | | | | | | | | | | | **1** |
| | Bld C | 1 | 1 | | 1 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **7** |
| | Bld U | 1 | 1 | | 1 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | **7** |
| Population | Stratus 2 | | | | | | | | | | | | | | | | 1 | | | | | | **1** |
| | Stratus 3 | | | | | | | | | | | | | | | | | 1 | | | | | **1** |
| | population | | | | | | | | | | | | | | | | 1 | 1 | 1 | | | | **3** |
| **Number of reached variables** | | **46** | **46** | **22** | **28** | **18** | **46** | **46** | **22** | **46** | **46** | **13** | **15** | **15** | **13** | **15** | **26** | **26** | **23** | **14** | **22** | **13** | |

*Table 2: variables reached by changing decision variables*

A first set of decision variables refers to land use, specifically how land is occupied by the diverse types of street:

| Variable | Meaning |
|---|---|
| UH desired | Urban highways desired (km) |
| B desired | Bicycle ways desired (km) |
| GA desired | Green areas desired (ha) |
| Bld desired | Buildings desired (ha) |
| S desired | Streets desired (km) |
| PA desired | Pedestrian areas desired (km) |
| subway desired | subway desired (km) |
| ST desired | Segregate tracks (for buses) desired (km) |
| P desired | Parking space desired (ha) |

*Table 3: land-use decision variables*

It is fundamental to acknowledge that, whilst the urban area is held constant, one cannot change the area occupied by one type of land use without changing at least one other type of land use. For instance, an additional urban highway reduces streets and buildings to some extent; increasing segregated bus tracks reduces normal streets.

Any change in the desired quantity of some transportation infrastructure reduces some other item:

| | Urban highway | Segregate track | Street | Parking space | Bicycle ways | Pedestrian paths | Buildings | Green areas |
|---|---|---|---|---|---|---|---|---|
| Urban highway | | | 1 | | | | 1 | |
| Segregate track | | | 1 | | | | | |
| Street | 1 | 1 | | 1 | | 1 | 1 | 1 |
| Parking space | | | 1 | | | | 1 | |
| Bicycle ways | | | 1 | | | | | |
| Pedestrian paths | | | 1 | | | | | |

*Table 4: interdependencies*

The model assumes the interdependencies that can be seen in the above table. If, for instance, the desired stock of parking rises, some of the required additional area will be taken from streets, and some from buildings. However, reducing streets will have an impact on the transport situation (lower mean speed, more congestion, more emissions, less attractivity of private motorized mode, modal choice, which then again increases the stress on PT with the subsequent change in relative attractivity and the resulting modal choices…)

According to table 2, some other decision variables do not affect jobs, but do have effect on PT relative attractivity:

- tolls for street use
- PT fee
- distance between bus stops
- bus frequency

The mean trip distance is a consequence of the urban area and the way how home, work and school (the main trip motives) are located (closer or further apart). It is a powerful influence; however, it cannot change but in the long range, as buildings and city districts age through their life cycle and progressively get replaced. As indicated above, this time scale exceeds by large the one of elections and the inhabitants' perceptions.

Additionally, some influential factors do not directly react to transport system decisions:

- The progression of inhabitants from stratus 1 to 2 and 2 to 3 increases the choice of the private motorized mode, in turn increasing emissions, accidents and traffic congestion. However, this progression is part of economic growth and should not be slowed down.
- The population of Latin America's metropolis will continue to grow. This will first increase population density and then lead to expanding the urban area, because developers will move outwards to accommodate their construction costs to the low purchasing power of the arriving populations. This in turn poses stress on the PT system, as buses have to drive further - and either the waiting timers of passengers or the fees (needed to pay additional buses and bus stops) will rise, both of which reduces PT's relative attractiveness.
- Sensitivity towards non motorized modes of transportation: currently, the automobile is a status symbol and non motorized transportation modes are viewed as sign of poverty. The values underlying these preferences may evolve over time, reducing the stress on the infrastructure needed for motorized transportation and also the carbon footprint. However, such changes are slow. Even though it seems advisable to educate inhabitants toward such an evolution, no perceptible effects should be expected in the short run.
- The number of trips per person per day in the three different strata: being part of the inhabitants' habits, the number of trips per day influences the total distance travelled daily. Just like in the previous point, habits can change, but the do so slowly

Last not least, the following table resumes the different sources of influence, together with the number of reached variables, the grade of control over the variable (can decisions be taken and direct influence be exerted?) and the time horizon of its changes:

| Variable | Influences | Control | Speed |
|---|---|---|---|
| UH desired | 46 | Yes | intermediate |
| B desired | 46 | Yes | intermediate |
| S desired | 46 | Yes | slow |
| P desired | 46 | Yes | intermediate |
| PA desired | 46 | Yes | fast |
| ST desired | 46 | Yes | fast |
| Bld desired | 28 | No | intermediate |
| Stratus 2 | 26 | No | slow |
| Stratus 3 | 26 | No | slow |
| population | 23 | No | slow |
| population density | 22 | No | slow |
| subway desired | 22 | Yes | intermediate |
| GA desired | 22 | Yes | intermediate |
| buses desired | 18 | No | fast |
| distance between bus stops | 15 | No | fast |
| bus frequency | 15 | No | fast |
| PT fare | 15 | Yes | fast |
| sensitivity for motorless modes per stratum | 14 | No | slow |
| street toll per km | 13 | Yes | intermediate |
| distance per trip per stratus | 13 | Yes | slow |
| daily trips per inhabitant per stratum | 13 | No | slow |

*Table 5*

It becomes clear that not only most decision variables are very interdependent, but also most of the other variables (which can only be reached indirectly, but also can change due to lateral effects) are very much interconnected. One can limit analysis to the decision variables and classify them according to the number of reached other variables (where the most connected variable serves as base and connectedness is expressed as percentage) and the speed of change (100%= fast, 67%= intermediate and 33% = slow) and rank the variables, as shown in the following table:

| Variable | Influences | Speed | Score |
|---|---|---|---|
| B desired | 100 | 100 | 200 |
| S desired | 100 | 100 | 200 |
| PA desired | 100 | 100 | 200 |
| ST desired | 100 | 100 | 200 |
| UH desired | 100 | 67 | 167 |
| P desired | 100 | 67 | 167 |
| PT fare | 33 | 100 | 133 |
| subway desired | 48 | 67 | 114 |
| GA desired | 48 | 67 | 114 |
| street toll per km | 28 | 67 | 95 |
| distance per trip per stratus | 28 | 33 | 62 |

*Table 6*

As we see, decisions concerning land use change in favor of one or another type of transportation infrastructure are very connected and will tend to lead to effects on a short time scale. The distance per trip per stratus is ranked in the last position; changes in this aspect are slow to achieve and slow to influence other variables; also, fewer variables are reached.

Up to this point, information generated by analyzing the stock-and-flow diagram's structure has been presented as tables, avoiding any kind of diagrams. As stated above, the entire diagram is far too large and complex for individuals outside the project team. Since this is not an executable model, there is no way to access behaviors, and therefore no BOT appear and no attempt is made to talk about the polarity and relative strength of causal links. However, the strong interdependence and the points resulting from it can be safely stated and interpreted.

Nevertheless, it was chosen to extract one part of the causal structure for representation as causal loop diagrams, because it is very relevant and not very complex: the relative attractiveness of public transport and its probable behavior. Making public transportation more attractive appears to be a very intuitive strategy for reducing emissions and other transport-related costs (like traffic accidents). However, relative attractiveness of PT is part of 28 feedback loops in the stock-and-flow model, involving 37 different variables and with loop lengths from 10 to 21. The following table illustrates how these variables participate in the respective loops:

| Variable | Loop | | | | | | | | | | | | | | | | | | | | | | | | | | | | Count |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | |
| relative attractivity PT | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **28** |
| PT mode per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **28** |
| total time private | | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **25** |
| total time in PT | 1 | 1 | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **24** |
| trip time PT | 1 | 1 | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **24** |
| daily trips per ihnabitant per stratum | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| possible trips | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| shortest time per trip | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| trip time private | | | | | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | **21** |
| average PT trip distance | 1 | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | | | | **16** |
| daily trips PT per stratus | 1 | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | | | | **16** |
| private mode per stratus | | | 1 | | 1 | 1 | 1 | | 1 | | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | 1 | 1 | 1 | **16** |
| attractivity PT | 1 | 1 | | 1 | | | | | 1 | | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | 1 | 1 | 1 | **15** |
| daily private transport trips per stratus | | | | | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | | | | | 1 | | 1 | **15** |
| time attractivity PT | 1 | 1 | | 1 | | | | | 1 | | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | 1 | 1 | 1 | **15** |
| attractivity private | | | 1 | | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | | | | | | | | 1 | 1 | 1 | | | | **13** |
| time attractivity private | | | 1 | | 1 | 1 | 1 | 1 | | 1 | 1 | | 1 | 1 | 1 | | | | | | | | 1 | 1 | 1 | | | | **13** |
| average trip distance private transport | | | | | | | | 1 | | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | | | | | | 1 | | 1 | **12** |
| private transport users per stratus | | | 1 | | | 1 | 1 | | 1 | | | 1 | | | | 1 | 1 | | 1 | 1 | | 1 | | | | 1 | | 1 | **12** |
| daily private transport distance | | | | | 1 | 1 | 1 | | | | | | | | | | | 1 | | | 1 | | 1 | 1 | 1 | | 1 | | **9** |
| average speed PT | | | | 1 | | | | | | | | | 1 | 1 | | | | | | | | 1 | | | 1 | 1 | 1 | 1 | **8** |
| daily PT distance | | | | 1 | | | | | | | | | 1 | 1 | | | | | | | | 1 | | | 1 | 1 | 1 | 1 | **8** |
| daily PT distance per stratus | | | | 1 | | | | | | | | | 1 | 1 | | | | | | | | 1 | | | 1 | 1 | 1 | 1 | **8** |
| PT demand supply ratio | | | | 1 | | | | | | | | | 1 | 1 | | | | | | | | 1 | | | 1 | 1 | 1 | 1 | **8** |
| PT users per stratus | 1 | 1 | | | | | | 1 | | 1 | 1 | | | | 1 | | | | | | | | 1 | 1 | | | | | **8** |
| total daily PT distance per stratus | | 1 | | | | | | 1 | 1 | | | | | | 1 | | 1 | 1 | | 1 | | | | 1 | | | | | **8** |
| total daily PT trips | 1 | | | | | | | | | 1 | 1 | 1 | | | | 1 | | | 1 | | 1 | | 1 | | | | | | **8** |
| average speed private transport | | | | | 1 | | | | | | | | | | | | | 1 | | | 1 | | 1 | 1 | 1 | | 1 | | **7** |
| daily private transport distance per stratus | | | | | | 1 | | | | | | | | | | | | | 1 | 1 | | | 1 | 1 | 1 | | | 1 | **7** |
| daily private transport trips | | | | | | | 1 | 1 | | | 1 | | | 1 | | 1 | 1 | | | | | | | | | 1 | | | **7** |
| private demand supply ratio | | | | | 1 | | | | | | | | | | | | | 1 | | | 1 | | 1 | 1 | 1 | | 1 | | **7** |
| total distance per stratus | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **7** |
| P saturation | | | 1 | | | | | | 1 | | | 1 | | | | | | | | | | 1 | | | | | | | **4** |
| private transport users total | | | 1 | | | | | | 1 | | | 1 | | | | | | | | | | 1 | | | | | | | **4** |
| time to park | | | 1 | | | | | | 1 | | | 1 | | | | | | | | | | 1 | | | | | | | **4** |
| distancia diaria priv por estrato | | | | | | | | | | 1 | | | 1 | | 1 | | | | | | | | | | | | | | **3** |
| transporte diario privado por estrato | | | | | | | | | | | | | | | | | | 1 | | | 1 | | | | | | 1 | | **3** |
| **Loop length** | **10** | **10** | **10** | **10** | **11** | **11** | **11** | **18** | **18** | **18** | **18** | **18** | **18** | **18** | **18** | **19** | **19** | **19** | **19** | **19** | **19** | **20** | **20** | **20** | **20** | **21** | **21** | **21** | **474** |

*Table 7*

There are over 400 links, if one counts each link for each loop separately. This indicates how densely the variables are woven together, reminding us that the relative attractivity of public transport is not to be managed by intuition. The qualitative nature of our work does not allow statements about which of these loops are the most relevant ones in behavioral terms. However, on can analyze the set of loops and develop one Shortest Independent Loopset (Kampmann, 1996; Oliva, 2004). Explained in few words, such a loopset is constructed in search of including each link which is in at least one loop into the loopset; therefore, one tries to avoid having a loop that does not add at least one causal link which was not already in the current loopset. Therefore, one starts with a (preferably) short loop, marks the links, and then looks for a connected loop which contains at least one additional link. This analysis allowed to detect one such SILS consisting of loops 1, 2, 3 4, 5, 6, 7, 8, 9, 10, 18, 19, 22, 23, all other loops being unions of previously included loops. This lead to a more compact table:

| **Variable** | **SILS loops** | | | | | | | | | | | | | | **Count** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **18** | **19** | **22** | **23** | |
| relative attractivity PT | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **14** |
| PT mode per stratus | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **14** |
| total time private | | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **11** |
| total time in PT | 1 | 1 | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **10** |
| trip time PT | 1 | 1 | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **10** |
| daily trips per ihnabitant per stratum | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **7** |
| possible trips | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **7** |
| shortest time per trip | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **7** |
| trip time private | | | | | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | | 1 | **8** |
| average PT trip distance | 1 | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | | 1 | **8** |
| daily trips PT per stratus | 1 | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | | 1 | **8** |
| private mode per stratus | | | 1 | | 1 | 1 | 1 | | 1 | | 1 | 1 | 1 | | **8** |
| attractivity PT | 1 | 1 | | 1 | | | | | 1 | | 1 | 1 | 1 | | **7** |
| daily private transport trips per stratus | | | | | 1 | 1 | 1 | 1 | | 1 | | 1 | | | **6** |
| time attractivity PT | 1 | 1 | | 1 | | | | | 1 | | 1 | 1 | 1 | | **7** |
| attractivity private | | | 1 | | 1 | 1 | 1 | 1 | | 1 | | | | 1 | **7** |
| time attractivity private | | | 1 | | 1 | 1 | 1 | 1 | | 1 | | | | 1 | **7** |
| average trip distance private transport | | | | | | | | 1 | | 1 | | 1 | | | **3** |
| private transport users per stratus | | | 1 | | | 1 | 1 | | 1 | | | 1 | 1 | | **6** |
| daily private transport distance | | | | | 1 | 1 | 1 | | | | 1 | | | 1 | **5** |
| average speed PT | | | | 1 | | | | | | | | | 1 | | **2** |
| daily PT distance | | | | 1 | | | | | | | | | 1 | | **2** |
| daily PT distance per stratus | | | | 1 | | | | | | | | | 1 | | **2** |
| PT demand supply ratio | | | | 1 | | | | | | | | | 1 | | **2** |
| PT users per stratus | 1 | 1 | | | | | | 1 | | 1 | | | | 1 | **5** |
| total daily PT distance per stratus | | 1 | | | | | | 1 | 1 | | 1 | | | | **4** |
| total daily PT trips | 1 | | | | | | | | | 1 | | 1 | | 1 | **4** |
| average speed private transport | | | | | 1 | | | | | | 1 | | | 1 | **3** |
| daily private transport distance per stratus | | | | | | 1 | | | | | | 1 | | 1 | **3** |
| daily private transport trips | | | | | | | 1 | 1 | | | | | | | **2** |
| private demand supply ratio | | | | | 1 | | | | | | 1 | | | 1 | **3** |
| total distance per stratus | | | | | | | | | | | | | 1 | 1 | **2** |
| P saturation | | | 1 | | | | | | 1 | | | | 1 | | **3** |
| private transport users total | | | 1 | | | | | | 1 | | | | 1 | | **3** |
| time to park | | | 1 | | | | | | 1 | | | | 1 | | **3** |
| distancia diaria priv por estrato | | | | | | | | | | 1 | | | | | **1** |
| transporte diario privado por estrato | | | | | | | | | | | 1 | | | | **1** |
| **Loop length** | **10** | **10** | **10** | **10** | **11** | **11** | **11** | **18** | **18** | **18** | **19** | **19** | **20** | **20** | **205** |

*Table 8: a SILS*

In order to allow the reader to reflect upon of such a tabular representation is easier to interpret than a diagrammatic one, the following figure displays a modified causal diagram of the variables and causal links in the SILS. The loops and their respective polarity are not shown (since they are not relevant at this stage of analysis), but the font size of the variables corresponds to the number of loops each variable is part of. Since the diagram's size cannot be reduced beneath the SILS' size, the diagram has been rotated 90°:

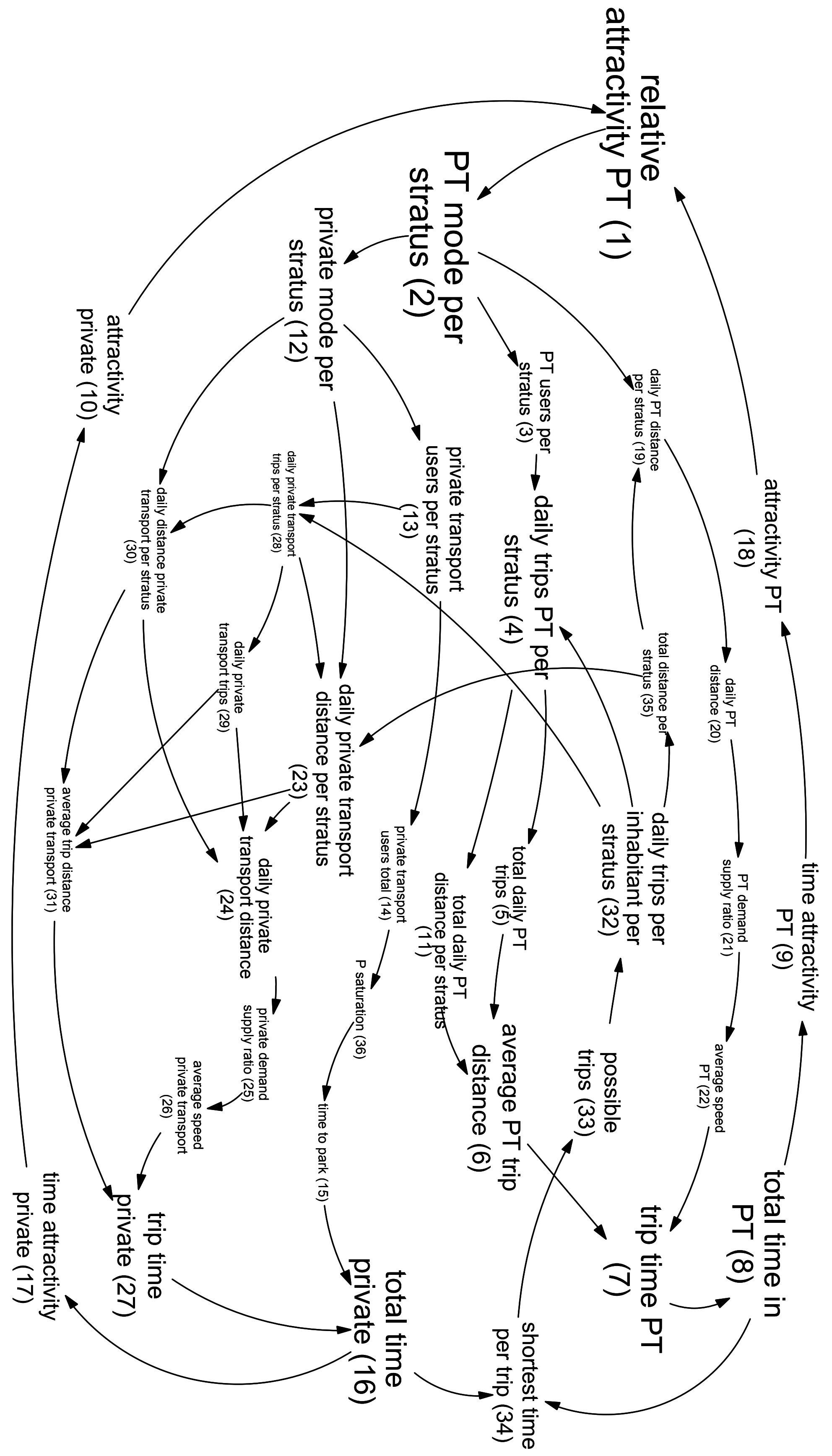

*Figure 3: SILS*

As the illustration makes apparent, some variables belong to many of the loops; therefore, they may be considered of special importance, since they will transmit impulses between feedback loops. Even if the SILS is a conceptually interesting construct which allows to simplify the extension of the loopset under study, this is clearly not a diagram that non-specialists can interpret. Therefore, we have selected four of them because they show the dilemma of relative attractiveness management in a pregnant way:

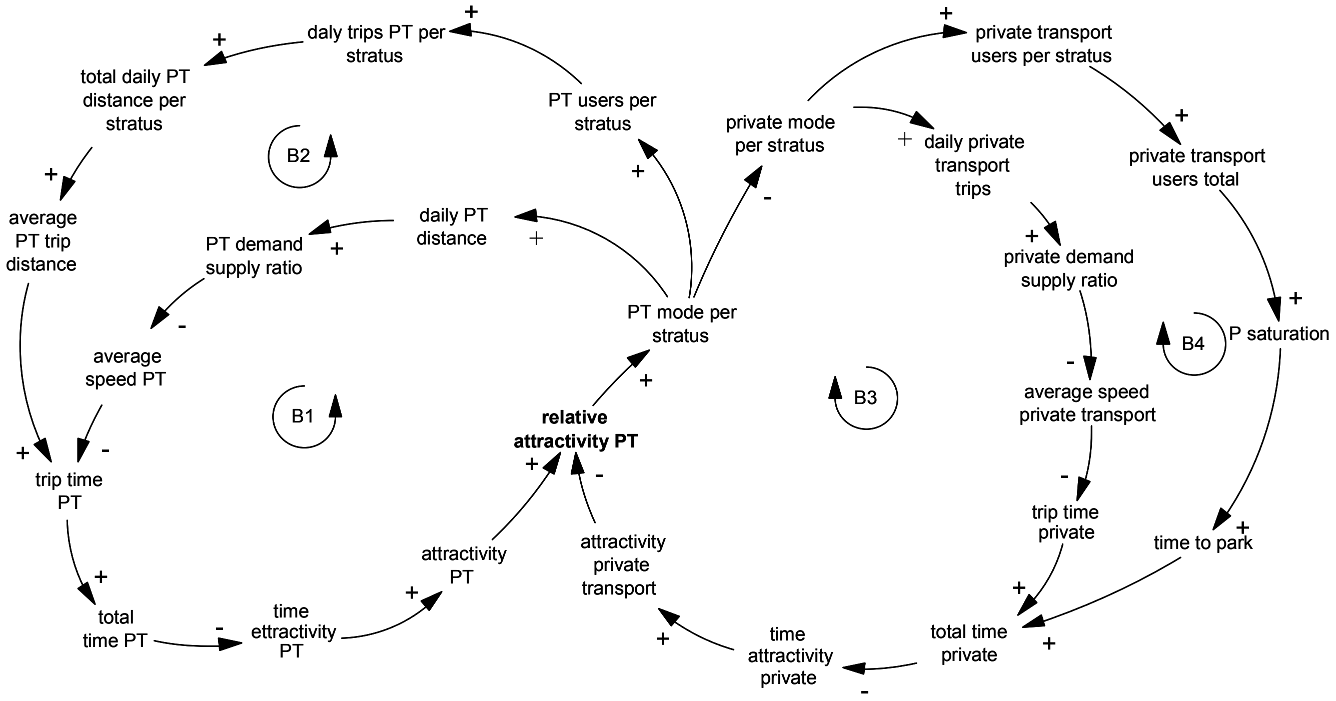

*Figure 4*

Any change in relative attractiveness of PT would instantly influence the operations of four balancing loops, starting with a change in the modal choices. Let us suppose relative attractiveness of PT has risen; so modal choices of all three population groups will change in favor of public transportation. According to loop B1 the daily distance travelled in PT will rise, pushing the demand/supply ratio to a higher value. By consequence, average speed of PT will sink and the trip time becomes longer, as does the total time in TP (which also includes the time to walk to the bus stop and waiting for the next bus). Time attractivity of PT diminishes, leading to a lower attractivity of PT and also a lower relative attractivity. At the same time, loop B2 presses in the same direction: more people use PT, augmenting the number of trips and the total distance travelled; the average trip distance rises, and therefore the trip time rises, too, leading to a lower relative attractivity. On the side of private transportation, two similar loops also move in the same direction. Since the modal choice of private transportation diminishes, loop B3 is pushed by a sinking number of trips, lastly leading to rising private transportation's attractiveness (thus lowering the relative attractiveness of PT). Also, loop B4 has less people opting for private transportation, which also presses relative attractiveness of PT back towards its previous level.

This reminds of the "the more you put pressure on the system, the more the system pushes back" (Senge, 1990). In these conditions, any effort made to make public transportation more attractive awakens processes inherent to the urban transportation system which diminish or even annihilate the intended effect. As remarked by Sterman (2000), this cannot achieve more than buy some time before the same problems rise up again.

Even though system dynamics strives to come to grips with dynamic complexity, the qualitative analysis stresses the structural complexity of the transportation system. As far as a strategic management and development of this system is pursued, some additional recommendations can be derived from the above:

5. a control panel or dynamic scorecard sowing the relevant factors and the links between them is needed;
6. such a scorecard will contain the information needed to inform the city's inhabitants about the system's behavior over time;
7. one needs an institutional organization which ensures that the interdependencies are taken into account in planning and decision-making. This is a huge challenge, since the Latin American metropolis are usually subdivided in many different districts and may not have a unified city government. In some cases, important decisions are spread over several national ministries and a local "transport bureau" which may be part of the municipality (recall that the city may consist of dozens of municipalities).
8. it also takes well-designed procedures and decision policies that assure efficient and transparent decision making.

### ***Specific recommendations***

Referring to the initial question – "how to influence the transformation of the urban transportation system towards lower emissions, without negative side lateral effects in other urban systems?" - some elements of an answer can be given.

First of all, the structure of this model suggests that modifying the transportation infrastructure to improve the relative attractivity of public transportation with respect to the attractivity of private (motorized) transportation, is counteracted by many negative feedback loops which will diminish the intended effect. This is due to the fact that the city area is limited (extending one type of infrastructure reduces another one) and the adjustment of the inhabitants' modal choices.

Second, the ongoing immigration of low income population and their economic (income) progress will lead to a rapid growth of the motorization rate which in turn favors the private transportation mode(s).

While such measures can indeed lead to temporary improvements ("buy time"), only two lines of intervention seem to be promising:

1. reducing the distances between homes, workplaces and education sites leads to shorter trips, which has a potential to reduce total stress on the installed infrastructure and to favor nonmotorized transportation modes;
2. increasing bicycle ways and pedestrian areas (walkways, vehicle-free zones) helps to facilitate the choice of nonmotorized modes of transportation, thus reducing the stress on motorized transportation infrastructure.

Both lines can only lead to substantial effects on a large tine scale. While this clearly exceeds the cycle time of political elections, there is at least one example of a major LA city where a visionary mayor has not only brought forward a strong pedestrian-friendly vision, but also prevailed in office for a longer period of time (Bogota, Colombia; Jordán et al., 2010). In other geographical regions, other cities have already made impressive progress in direction of accessibility with less motorized transportation (CEPAL, 2010). However, if LA cities are to take this path, the following recommendations should be taken into account.

A big city is one whole system in which countless agents take decision and cause complex effects, with many adjustment processes much to slow to be taken into account in the short political cycles of elections. A long-run oriented entity, able to manage these processes and to coordinate between the groups of agents, would have to be of technical nature and stay out of the election cycle. This poses a challenge on transparency and accountability towards the city's inhabitants. A council with technical experts and politically legitimized decision makers may be an option.

Such a council will need the scorecard mentioned above. The relevant variables (at least those displayed in Table 2, p.8) should be monitored on a regular basis. For instance, in Chile this is usually done by specific investigations on as 10 years bases with one update each 5 years; since some adjustment processes are "surprising", some decisions are later recognized as mistakes. Only a permanent monitoring of key variables will allow to perceive "surprising" tendencies on time.

The alluded scorecard should be designed above a validated mode. The developed model is very aggregate: transport planning decisions are taken using very detailed models that include the explicit representation of each segment of each main street. More strategic models – i.e. MARS – aggregate the city into a certain number of sectors (up to around 50), concentrating the attention on macro processes without losing each city's particularities. Our model treats the city as one homogeneous system, which leads to a representation which is more generic and simpler, but certainly not sufficiently accurate to be useful for particular decisions in concrete cities.

The current model is only conceptual; adequate quantification and validation will require an important amount of time. The MARS model – after a decade of development and multiple applications in cities across very different countries, is a good alternative, since it "only" needs the parameters of a city. Since many of the data it produces are compatible with our model's conceptual structure, the aggregate model might be able to use aggregate data from MARS.

It would make sense to develop a hierarchy of models at different levels of detail versus aggregation: big cities have to be looked at in the details of one subsystem (like transportation), but also at the aggregate level (where such subsystems interact). However, this is out of the scope of the current project and of this paper, too.

## Discussion

Leaving this particular project behind and turning towards the debate concerning qualitative system dynamics, two things can now be stated.

### *The validity of qualitative models*

There are at least two aspects of a model's structure that can be tested: each of the model's components (variable, link) must refer to an entity in the "real world" problem under study. Additionally, the units of measure have to be consistent across the model. The first of these tests can be performed even if the modeling effort uses causal loop diagrams as language. However, in such a case, since there are no equations, dimensional consistency cannot be checked for. In our case, as stated above, a stock-and-flow diagram was developed, and a tentative equation formulated for each variable. Even if these equations are preliminary, the arithmetic relationships they assume between the input variables have passed the test of expert inspection and they allow to check for dimensional coherence.

Since the modeling effort was conceived of as a qualitative one from the outset, and therefore a complete validation was not part of the activities (nor was it deemed necessary), the two tests gave the possibility to build trust in the model's conceptual structure.

### *Safe interpretation of model structure*

System dynamicists assume that behavior cannot be inferred from model structure without computer simulation; insofar as this model is medium-scale in its extension, we must resist the temptation to reflect on the variable's behavior over time. This does not mean that nothing can be derived from this model, though.

The choice of stock-and-flow diagramming has allowed to represent important entities in a way that avoids "static" thinking in the sense of immediate adjustment (Moxnes, 2004): adjustment time and slow adjustment of perceptions are explicitly part of the model, and the model reader is visually reminded of this fact. Therefore, even if reading a stock-and-flow diagram is more demanding than reading a causal loop diagram, the former helps avoiding mental errors (Schaffernicht, 2010).

Secondly, the model's structure clearly reminds that transport infrastructure decisions are taken in a zero-sum situation (where nothing can increase without equivalent decreases in some other part), and where multiple interdependencies tie virtually all the factors together. Also, the relative attractivity of public transport – main target variable for many decision makers – is clearly shown to be surrounded by balancing feedback loops, and it can be said without simulation that most adjustment processes in the transportation system will counteract efforts to change this relative attractivity.

The interdependency becomes very clear thanks to the reachability matrix (used for Table 2, p.8) and the loop membership visualization in Table 7, p. 12. It is conjectured that such tabular visualization like in this table can be easier to grasp than a causal loop diagram, even though such a diagram can be enriched (for instance by adjusting the character size to the number of loops a variable is on). It is also suggested here that model structure analysis (Oliva, 2004) could be a useful way to exploit a model's structure without simulation, thus giving qualitative system dynamics more tools for a rigorous use.

## Conclusions

This paper has reported from a qualitative modeling effort in the application domain of urban transportation systems, in which the available time was far too short to think of a full simulation modeling project. Even though a qualitative model cannot be simulated and therefore no policy recommendations based on the analysis of model behavior can be made, a deliberate effort has been made to deliver a model as trustworthy as possible, and the analysis of its structure has allowed to derive a series of characteristics:

- the transportation system cannot be separated from the land use system;
- any decision to change the street infrastructure contains lateral decisions that will counteract the intended effect (even though we cannot know how strong this counterpressure will be);
- any attempt to improve the relative attractiveness of public transport awakes counterpressures;
- the ongoing immigration of low income population reinforces the tendency of developers to build outside the city, thus expanding the city area, lowering public transportation relative attractiveness.

The recommendations derived call for a city-wide long range planning facility that will use transport system initiatives to influence the evolution of land use. A dynamics scorecard is needed, and it can be developed by transforming the qualitative model in a validated quantitative model.

In terms of qualitative system dynamics, it can be said that tools for structural analysis would be highly useful; especially tabular formats for representing (groups of) feedback loops. Even though such tools have been developed (Oliva, 2004), they are not widely diffused, nor readily usable in standard modeling software.

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