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Abstract:

This paper describes the development of a model architecture based on systems dynamics and econometrics. The purpose of the system of models is to simulate the medium- and long-term effects of urban transport policies with reference to sustainable travel. Three models are presented successively with some results from simulation. The first model relates to the regulation of public transport finance and allows for the constraint of the scarcity of public funds. The second is a modal split model based on price-time modelling. The third is a combined assignment and time of departure choice model based on a queuing representation of congestion. Finally, the coupling between the last two models is described.

1 INTRODUCTION

This paper describes the development of a model architecture based on systems dynamics and econometrics. The purpose of the system of models is to simulate the medium- and long-term effects of urban transport policies with reference to sustainable travel.

The traditional econometric approach to travel behaviour has a number of limitations, essentially because the available data (surveys of observed behaviours) only express the final state, which from the aggregate standpoint, appears as an equilibrium: x% of parking spaces are permanently occupied every day, there is a traffic peak between one a time of day and another, etc. Using such data, which relates to expressed demand, econometric modelling attempts to reproduce the final equilibrium as well as possible.

However, analysis of travel behaviours shows that the stability which appears from an aggregate standpoint conceals considerable variation in individual behaviours (see for example Cairns et alii, 1998). Furthermore, these changes in behaviour in response to various stimuli are not instantaneous but take place with a delay, as can be seen by the fact that the empirically calculated elasticities differ for the short and long terms (Goodwin, 1992). This has led Goodwin (1998) to announce “the end of equilibrium”.

It is theoretically possible to introduce dynamic interactions into the traditional four stage modelling process, although this requires a hypothesis of equilibrium in order to achieve coherence (Ortuzar and Willumsen, 1994). However, the introduction of this type of feedback is usually not considered because the unwieldy nature of the calculations results in excessive complexity (Stopher et al, 1996).

These considerations – the interaction between feedback loops, the complexity of reaction mechanisms, non-linear relationships between variables – justify the use of systems dynamics simulation tools. The dynamic modelling of urban systems achieved some prominence more than 20 years ago with the work of Forrester. Systems dynamics has been widely used in transportation, particularly for aggregate long-term situations, for economic trip forecasting scenarios or for modelling the interaction between transport and land use (readers are referred to Abbas and Bell, 1994, for a survey of this field). It has been used more recently for strategic transport modelling at European level in the framework of the ASTRA project (1998-2000).

The approach we are proposing involves constructing a system of models which makes use of simulation techniques derived from systems dynamics and various elementary components obtained from econometric models.

The architecture of our modelling platform consists of seven major blocks. These are the block describing "demographic and economic change" in the conurbation; the "urbanization" block that describes land use and the locations of activities; the block that describes the "internal travel demand" in the conurbation which deals with trip generation by purpose, time of day, origin and destination; the household "car ownership" block; the "external travel demand" block that deals with inflowing, outflowing and through traffic; the "transportation" block which compares supply with the demand mentioned above and, lastly, the "evaluation" block that produces socioeconomic and environmental appraisals.

The paper concentrates on three models in the "transportation" blocks which are presented successively with some results from simulation. The first model relates to the regulation of public transport finance and allows for the constraint of the scarcity of public funds. The second is a modal split model based on price-time modelling. The third is a combined assignment and time of departure choice model based on a queuing model representation of congestion. Finally, the coupling between the last two models is described.

2 A MODEL FOR REGULATING THE FINANCING OF PUBLIC TRANSPORT

The model that deals with the regulating the financing of public transport aims to simulate the impact of the scarcity of public resources and the consequences this has on the operation of public transport. We shall begin by describing the structure of the model and then give a few results from simulation.

2.1 Structure of the model

This model restricts itself to the financing of public transport: only aspects which are linked to public transport supply and demand are considered and, for the time being, any interactions with private transport supply are ignored. In particular, this model does not consider the effect of congestion on the speed of buses in non-exclusive lanes: the speed of buses is therefore assumed to be constant. Furthermore, this simplified model considers a fixed distance link.

Therefore the only component of the duration of public transport trips that varies is the waiting time.

The principal relationships in this model are displayed in Figure 1.

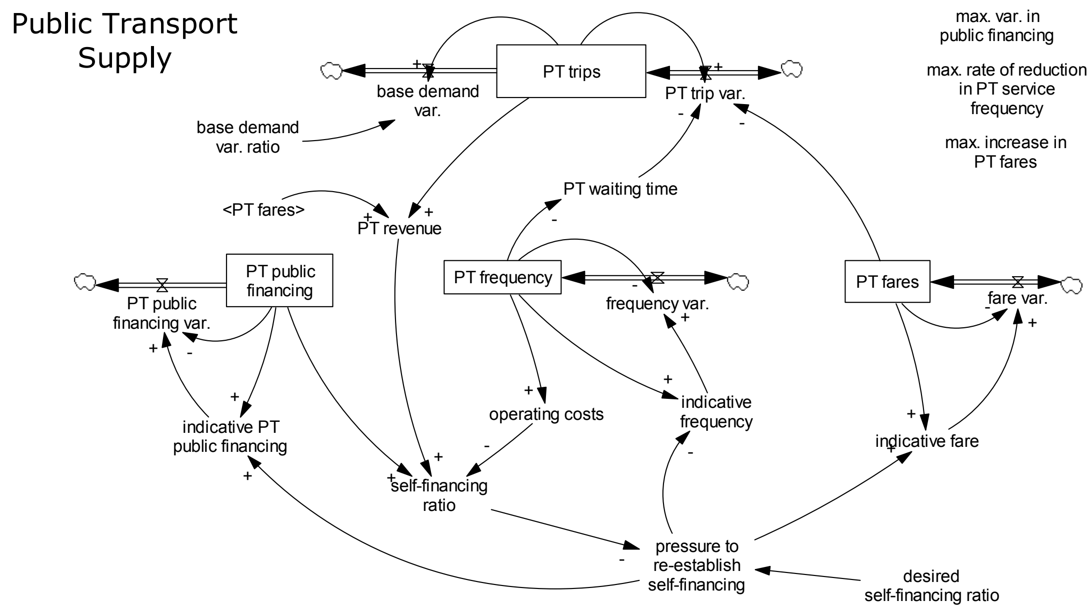

Figure 1 : A simplified representation of the public transportation regulation model

Public transport (PT) supply is represented here by two fundamental parameters, the trip duration and the monetary cost of trips for the user. For trip durations, as we have assumed constant speed, the only factor that varies is the *frequency* of public transport services. The monetary cost of the trip is equal to the *fare* that is charged. These two supply parameters determine the *operating costs* which vary directly with the service frequency, and the *revenue* which depends on the fare and demand.

The third fundamental parameter is the need for *public financing* which may allow the self-financing constraint to be relaxed, by making it possible to increase frequencies or reduce fares.

Revenue and public funding on the one hand and operating costs on the other, determine the *self-financing ratio*. One of the objectives of the organizing authority is to maintain finances in a state where a *desired self-financing ratio* is achieved. Normal practice is for this to be around 0.25 and not fall below 0.20. Once the ratio diverges from the target value of 0.25 *pressure to re-establish self-financing* will act at the level of public finance, frequencies and fares, and indicative values will be determined for each of the three parameters. They will then be adjusted, but not instantaneously because the organizing authority needs time to recognize the need for adjustment and spread it over time: for example, during each step of the model, the level of PT fares includes a variation which is calculated as the difference between the *indicative fare* and the current fare divided by the fare adjustment time. Furthermore, these variations can be blocked in the simulations, that is to say that the organizing authority can refuse to increase funding, to reduce frequencies or increase fares. The variations can also be bounded by an annual maximum rate of variation selected by the organizing authority, as shown by the *maximum variation in public financing*, the *maximum rate of reduction in PT service frequency* and the *maximum increase in PT fares*. The pressure to re-establish self-financing is therefore a mechanism that regulates the levels of public financing, service frequencies and fares.

PT trip demand is itself dependent on the two supply parameters of trip duration and trip cost to the user. In this model, this influence on demand (*PT trip variation*) has been modelled by a price elasticity and a duration elasticity, which vary according to the ratio between the current level of demand and the reference level of demand: the higher the current demand, the higher the elasticity and vice-versa. Lastly, PT trip demand can drop under the influence of a variety of factors which tend to reduce the size of the captive clientele: possible examples are socio-demographic factors such as a reduction in the number of schoolchildren, or economic factors such as a rise in income and hence car ownership.

2.2 Some results from simulations

The simulations described below illustrate the interaction between the supply of public transport services and trip demand through the impact of the levers of fares, service frequencies and public funding.

The time step of the model is annual and the forecast horizon is 20 years. The price elasticity values (-0.7) and the duration elasticity values (-0.4) were adapted from values found in the literature (Goodwin, 1992, TRACE, 1998). The reference values (or initial conditions) for PT trip demand, public financing, service frequencies and fares were fixed at an equilibrium level. The results are shown as variation with respect to a base of 100.

All the scenarios which are described below occur in a situation where basic demand decreases by 5% per year, under the combined effect of increasing car ownership and demographic ageing.

The purpose of these scenarios is to investigate whether it is possible or not to maintain the public transport system in financial equilibrium under the constraints of moderate changes in public financing, fares and service frequencies. We shall begin by presenting separately the effects of the levers of fares then frequencies. Next we shall examine the simultaneous effect of fares, frequencies and public financing.

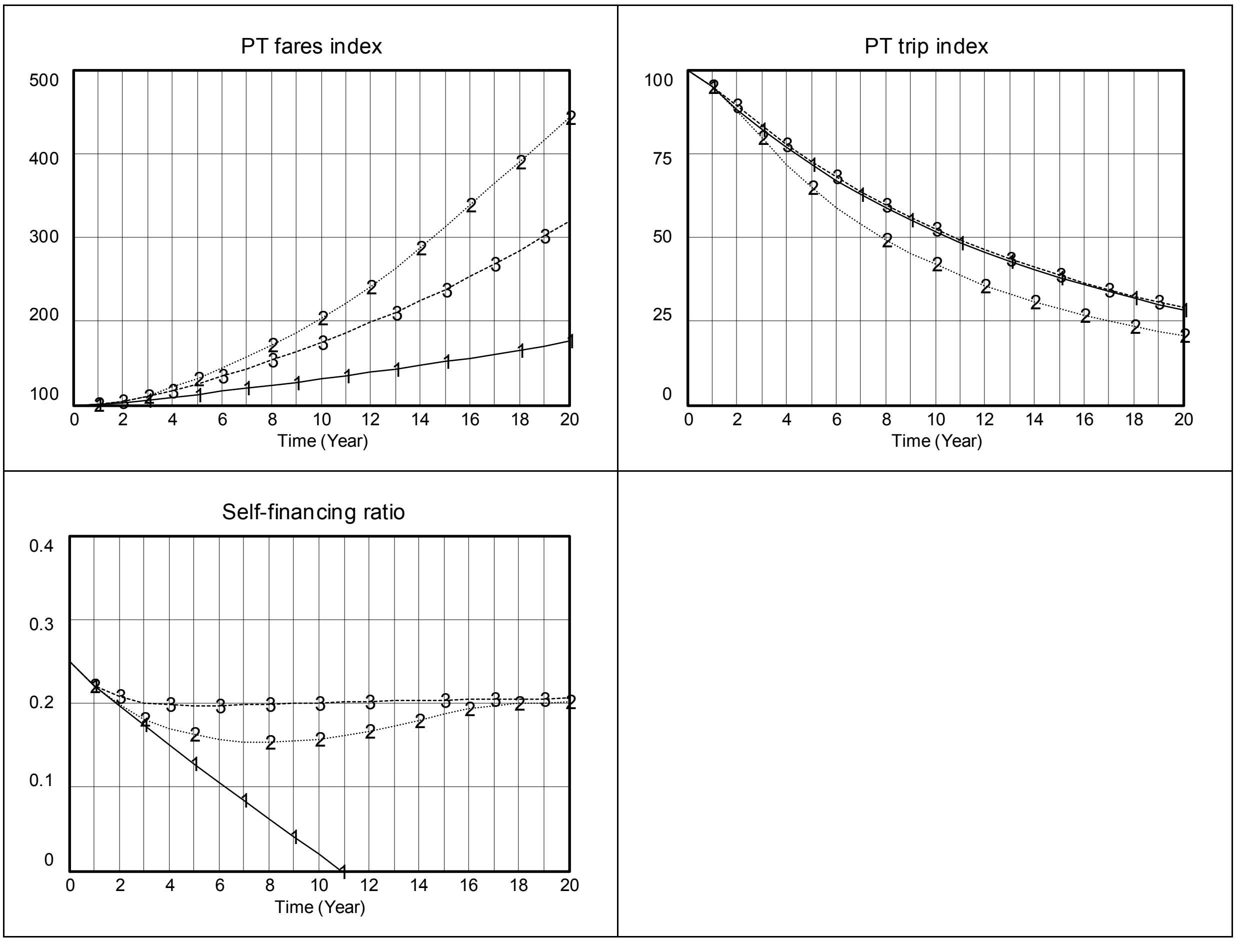

Figure 2 : The pricing change scenarios

In the pricing scenarios (see Figure 2), the level of public financing and the service frequency are fixed at their initial value. A first scenario (*1)* in which the maximum annual fare increase is 3% shows that it is not possible to compensate for falling revenue which results from a drop in demand: the self-financing ratio falls to dangerously low levels and becomes negative after 10 years. Only with a maximum annual fare increase of 9% (scenario *2*) can the self-financing ratio be raised to acceptable values (of the order of 0.20) after fifteen years. However, these results are dependent on the price sensitivity of demand. If instead of taking the value of –0.7 for the reference elasticity, which is considered in the literature as appropriate for long-term elasticity, we take a value of –0.3 (scenario *3*), the rise in fares can be more moderate (a maximum annual increase of 7%): fares increase “only” by a factor of 3 over a 20 year period, demand does not fall more than it does in the first scenario and the self-financing ratio is kept permanently at an acceptable level of 0.20.

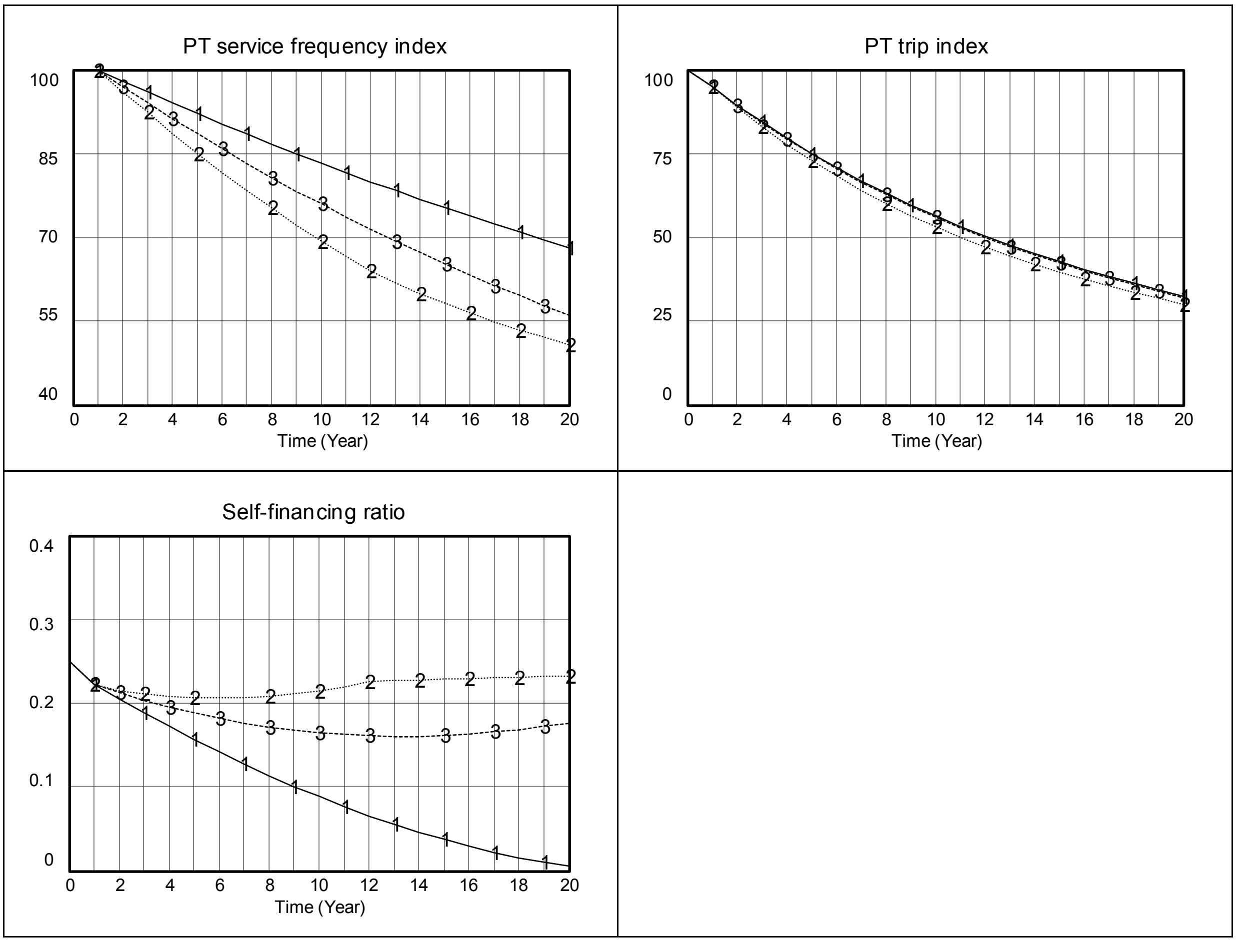

Figure 3 : The service frequency variation scenarios

In the frequency scenarios (see Figure 3), public financing and fares are fixed at their initial values. An initial scenario (*1*) in which the maximum annual reduction in frequencies is 2% shows that with this reduction in frequency it is not possible to maintain an acceptable self-financing ratio: the reduction in operating costs which results from this reduction in service frequencies is insufficient to compensate for revenue losses that result from the fall in demand. Only a maximum annual reduction in service frequencies of 4% (scenario *2*) can maintain the self-financing ratio at an acceptable level of over 20%. Here too, the results are dependent on the sensitivity of demand to waiting times. If instead of taking a reference elasticity of –0.4, we take a value of –0.3 (scenario *3*), the maximum permitted reduction in service frequencies can be reduced to 3% per year and the self-financing ratio can be brought back to an almost acceptable value after 20 years.

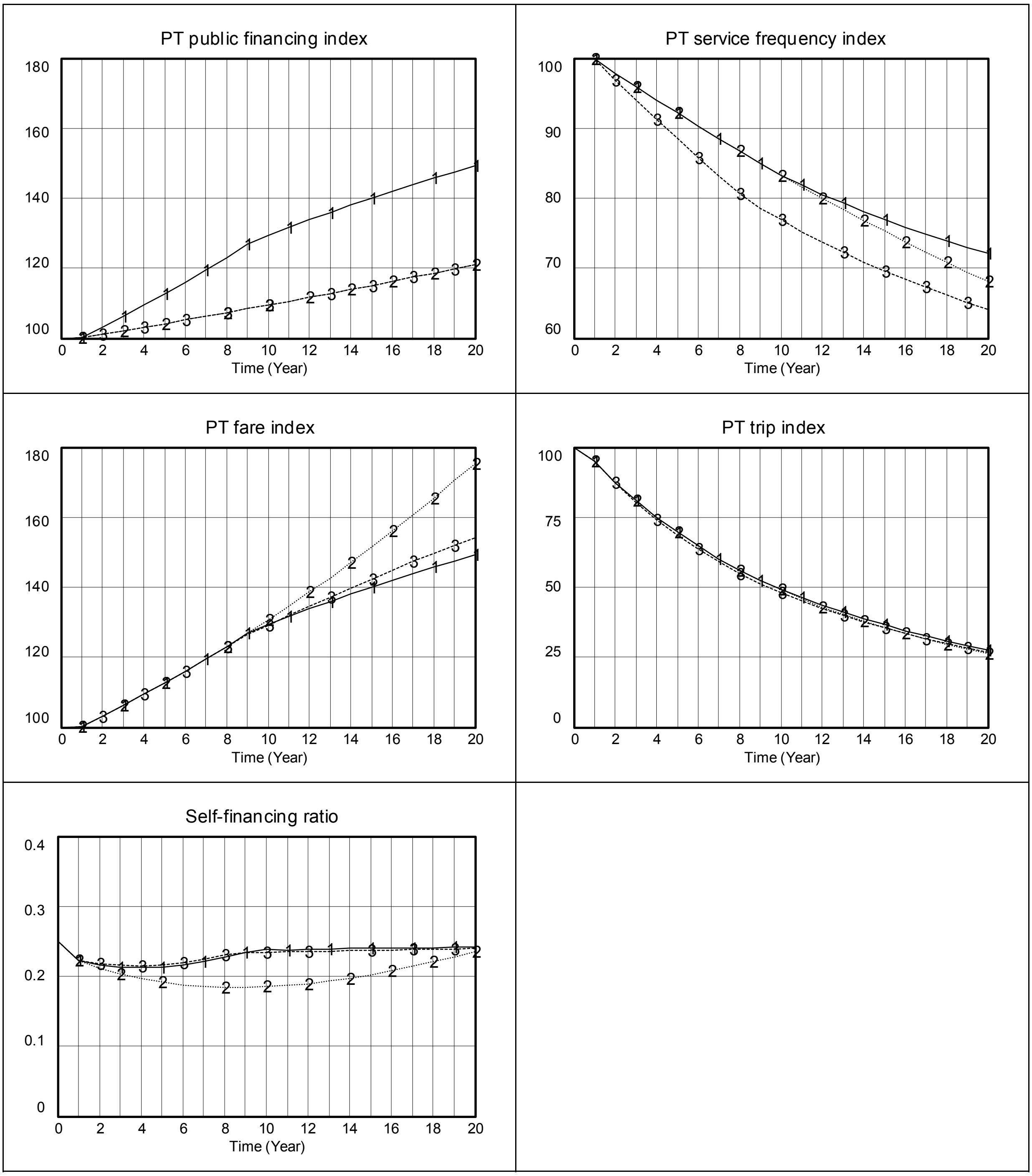

Figure 4 : The scenarios in which funding, fares and frequencies are modified simultaneously

The last scenarios bring into play simultaneously the effect of the levers of financing, pricing and service frequencies (see Figure 4).

In the first scenario (*1*) the maximum annual rates of change are as follows: a 3% increase in public financing, a 3% increase in fares and a 2% reduction in service frequencies. By simultaneously varying these three levers, an acceptable financial solution can be achieved as the self-financing ratio falls to about 20% and approaches 25% in less than 10 years: this equilibrium is obtained with a 28% reduction in service frequencies and a 49% rise in fares and public financing after 20 years.

If we make a comparison with other scenarios, we can see that the same objective as regards the self-financing ratio can be achieved with a different combination of policies. If, on grounds of budgetary rigour, the maximum annual increase in public funding is restricted to 1% (scenario *2*, with an annual maximum reduction of 2% in service frequencies and an annual maximum fare increase of 3%), the self-financing ratio falls dangerously but returns to acceptable values after about 15 years: this is at the cost of a 32% drop in service frequencies and a marked rise in fares of 75% over 20 years. If the maximum annual rise in public financing is restricted to 1% with a maximum annual reduction in service frequencies of 3% (scenario *3*), the behaviour of the self-financing ratio resembles that of the first scenario: the reduction in service frequencies is more pronounced (36%), the increase in fares is less pronounced (54%) and the increase of public funding is almost identical with the level in the first scenario (21%).

2.3 Conclusion

This model allows us to show and quantify the effect of the interaction between supply and demand, principally via the two supply parameters of fares and frequencies. These two parameters influence respectively the revenue and the cost of producing the service: in combination, they also influence the level of demand which ultimately affects revenue. The model also includes a regulatory mechanism by means of the pressure to re-establish self-financing which affects the levels of public financing, service frequencies and fares.

The simulations described above show that this type of model could be used to investigate the conditions for maintaining the financial equilibrium of public transport supply in a context where the competitiveness of this mode of transport deteriorates.

This model can next be interfaced with a model that deals with the formation of congestion: congestion affects the commercial speed of buses and therefore the quality of public transport supply and its operating costs. It can also be interfaced with a modal split model which reproduces the competition between the private car and public transport on the basis of trip duration and user cost for each mode: this model is described below.

3 THE “PRICE-TIME” MODAL SPLIT MODEL

As we shall see, the modal split model is essentially based on a price-time model. We shall begin by explaining the theoretical reasons for this choice. An analysis of our survey data emphasizes the fundamental role of the availability of a car and paid parking in modal choice decisions. Furthermore, we have represented spatial characteristics in a particular way. We shall also describe calibration of the model and its results. Lastly, the structure of the simulation model is briefly explained.

3.1 The choice of the price-time model

In order to select the type of model, we had to consider several criteria: whether to adopt an aggregate or disaggregate approach, how detailed the representation of supply and demand should be, what determinants should be favoured and what functional form should be adopted for the specification, etc.

Discrete choice models have a relatively sound theoretical basis. If we adopt the hypothesis of random utility, an additive specification and distribution of error terms (Weibull distribution) we arrive at a logit model, which is by far the most frequently used because it is so easy to calibrate.

In their basic form, such models pose two major difficulties, one of which relates to the consideration of individual socio-economic data such as income, and the other to the problem of measuring individuals' choice sets.

The simplicity of the model has a price (Jara-Diaz, 1998), namely that income cannot be introduced into an additive linear specification of choice: the choice between two modes is independent of income. This seems particularly false if we wish to represent adequately modal choice behaviours in the presence of alternatives with very different costs, in particular if we consider the increasing prevalence of charging for car use (by pay parking or tolls). Attempts to introduce the effect of income into the discrete choice model for transport mode have not been very convincing (Jara-Diaz and Videla, 1989; Viton, 1985; de Palma and Fontan , 2001).

This is why we have selected a "price-time" model. This specification is based on the hypothesis that the choice between two transport modes depends on the value-of-time for the individual in question and the cost and travel time characteristics of each mode. The comparison is made on the basis of the generalized cost of each mode: the generalized cost is expressed as a combination of the cost of using the mode and the cost of the travel time as assessed on the basis of the individual's value-of-time. The model employs the general theoretical framework of consumer utility maximization, with the consumer selecting the mode with the lowest generalized cost.

By specifying a distribution of values-of-time we are able to take into account the variability of individual behaviours. In addition, the income effect is also included because the distribution of values-of-time is derived from the distribution of incomes.

The "price-time" model has been applied widely and successfully in the area of interurban transportation, in particular for modelling the modal split between planes and trains. However, to the best of our knowledge it has not been employed before in this form for urban transportation. However, the central hypothesis of a lognormal distribution of values-of-time in urban areas is supported by the results of other studies (for example, most recently, de Palma and Fontan, 2001; Segonne, 2001). This justifies the choice of this type of model for our application.

We can provisionally resolve the issue of the level of disaggregation of demand (individual behaviours) if we consider that the level of disaggregation is conditioned by that of supply (costs and journey times): in practice, the average time and the cost (or the distance in the case of the private car) are measured with reference to a geographical zone which will be as small as possible in order to limit the dispersion of real values around the averages. However, the spatial characteristics of supply have been treated in a particular way (see below).

The development of the model is based on data from the 1994-1995 Lyon Household Travel Survey.

3.2 The availability of a private car

In our model, separate treatment is given to the availability of a private car (which is considered before modal split) and its actual use. We have made the hypothesis that the cost of using the private car is equal to the marginal cost of fuel and any parking or toll charges that are incurred. We have assumed that the maintenance cost does not influence the decision to use a car or not for daily trips.

The model we have used to compute the modal split between the car and another mode has therefore been calibrated using the sample of trips made by individuals with a choice, that is to say individuals to whom a car is available. In the observed sample, this population was reconstituted by aggregating two categories: (1) those who actually drive and (2) those who use another mode, own a driving licence and who had a car available (i.e. not used by another member of the household) at the time of the trip.

The modelling technique for modal split consists of segmenting the sample on the basis of individuals' possibilities of modal choice then developing separate models for each of the segments.

3.3 The fundamental role of pay parking

In view of the fact that we have limited the cost of using the car to fuel and parking costs, the comparison with fixed fare public transport tends to be to the detriment of the latter *in the absence of pay parking*. For example, on the basis of the fares charged in 1995, in order for public transport to be competitive *in monetary terms,* a person needs to travel more than 10 kilometres between two central zones (zones 1 to 15) and more than 17 kilometres between other zones. In fact 89% of trips are less than 10 kilometres and 96% are less than 15 kilometres.

However, if we take account of travel times, the competitive situation can be reversed: public transport can be faster than the car, particularly in the case of central journeys using high capacity systems or vehicles that are protected from traffic congestion.

This situation must be taken into account when modelling modal split between the car (with pay or free parking) and public transport.

3.4 From zoning to distance and speed classes

The representation of transport supply depends on a trade-off between the need for accuracy which encourages the smallest possible scale of zoning, and a statistical difficulty which relates to the low number of observations when one considers individual transport modes and individual origin-destination pairs. We have got round this problem by replacing conventional zoning by a division based on classes of distance and speed. The observed trips have been grouped together on the basis of combinations of distance and speed classes for the different modes.

3.5 Model calibration

At present, the modal split model only deals with home-to-work trips.

In the case of individuals who are able to choose to travel by car, an econometric analysis of the observed data has led us to conduct separate modelling for walking trips and motorized trips. The conclusion we have drawn is that for trips of less than 4 km, the modal share of walking is independent of the conditions of competition with other modes and depends only on distance. This modal share becomes non-existent above 4 km. The remainder of trips are considered as being a set of motorized trips to which the price-time model is applied in order to assess the respective shares of private car and public transport.

The parameters of the lognormal distribution for this price-time model are a median value-of-time of 13.1 €/h and $\sigma = 1.39$. This means that our value-of-time distribution is more asymetrical, both more concentrated on low values and more drawn out towards high values than the values-of-time found by de Palma and Fontan (2001) for car and public transport users in the Greater Paris Region: however, it is difficult to compare values from models with different specifications.

The relative prediction errors for modal shares are acceptable: between –8% and +6% for walking, between –5% and +8% for the private car and between –5% and +13% for public transport.

However, with regard to the trips made by individuals who are not able to choose the car, our attempts to calibrate a price-time model with this data were unfruitful, for at least two reasons: it is not easy to ascribe a cost to a trip made by a car passenger; the quantities of observed trips are quite small in spite of the distance and speed class groupings we have made, which make it difficult to detect tendancies. Consequently, we have used a very simple but robust model which calculates public transport's modal share on the basis of the distance travelled and the speed of public transport. Improvement is obviously possible here, but will depend to a major extent on the observed data.

3.6 The simulation model

The simulation model (see Figure 5) is a direct expression of the structure of the models and the econometric equations that have been developed previously. The model deals with home-to-work trips, one origin-destination link, a given preferred arrival time and a given departure time. It will be generalized to several O-D links, preferred arrival times and departure times when the modal split model is coupled with the departure time and assignment model.

The model firstly separates trips where the individual is able to choose the private car and those where the individual is not, as a function of the level of car ownership (considered here as an exogenous variable). These two bundles of trips are then treated separately using the econometric models developed previously. The overall modal shares are then aggregated to form the variables *total PT trips, total PC trips* and *total walking trips.*

It should be noted that the cost of time for the two modes (PT and PC, private car) explicitly includes a cost for the travel time and costs for early or late arrival, consistently with the departure time choice model (see below).

Furthermore, the dynamic is introduced by means of a delay in the consideration of changes in the value-of-time threshold: the price-time model produces potential PT demand towards which the real PT demand will tend (this being the average potential PT demand over a *reaction time for modal change*). This reaction time has been fixed at 4 weeks, considered as a minimum to take modal changes fully into account (in this context we are considering those persons who are able to make a modal choice between the car and public transport).

The hypothesis we have made is, in fact, as follows: new perceptions of journey times and the costs for different modes lead to a re-assessment of modal choices. But even in the event actual behaviour not being optimal with regard to the conditions of competition, the agent does not immediately question his/her habits with regard to transport mode use: a certain period of time is required for this (see Goodwin, 1984, 1992).

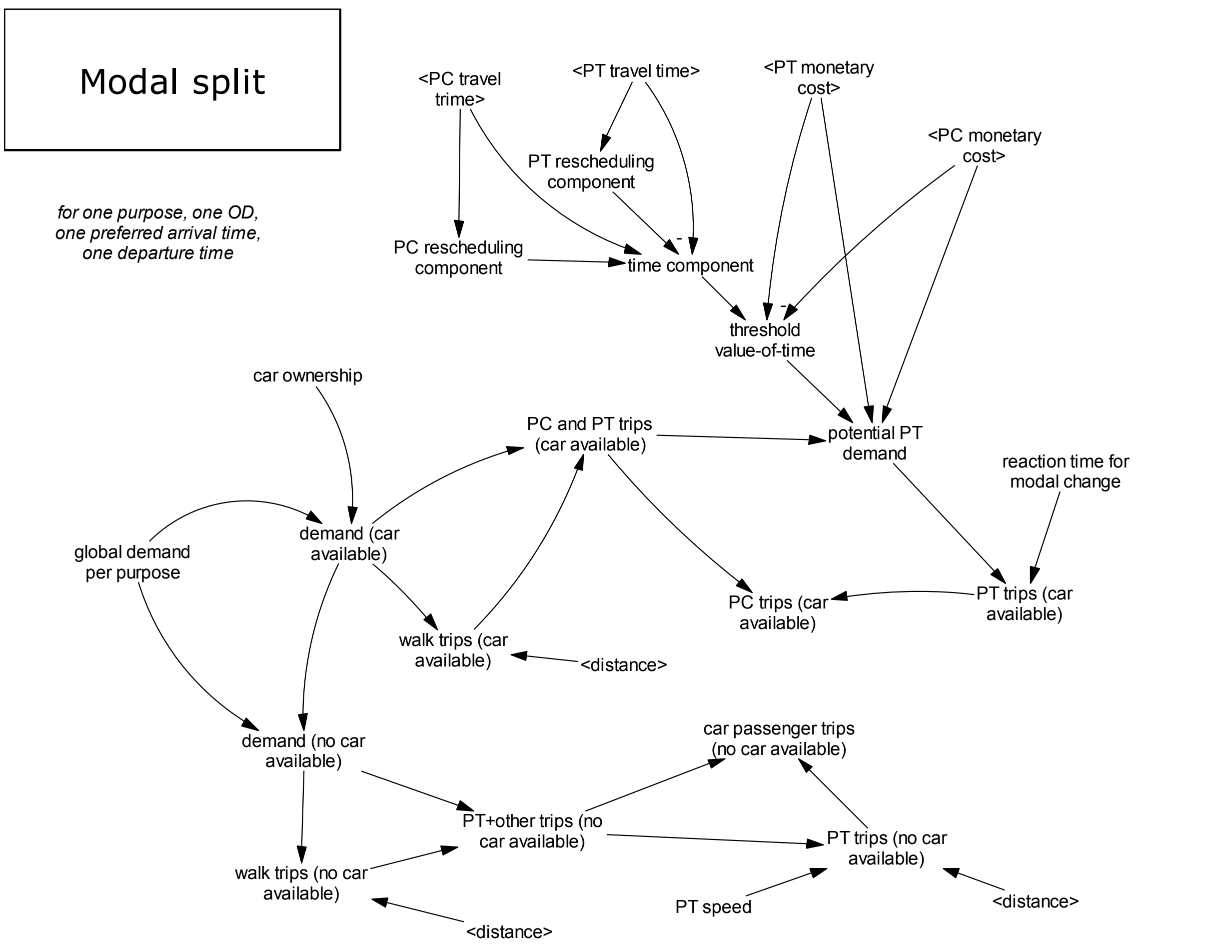

Figure 5 : Structure of the modal split model

3.7 Conclusion

We have developed a modal split model derived from theoretical principles of microeconomics and essentially based on the determinants of price and time.

The central core of the model is a price-time model which was calibrated on the basis of behaviours observed in 1994 and 1995. In particular, by using distance classes, this allows us to dispense with ad hoc zoning. It also makes use of private car and public transport speed classes: this means that the model should be readily transferable to other agglomerations.

By analyzing observed behaviours and the characteristics of transport supply we have also been enable to specify a modelling method which distinguishes between different groups on the basis of real availability of a car at the time of the trip and which deals separately with walking on the basis of distance classes.

We shall now turn to the question of congestion, assignment on the network and choice of a departure time.

4 THE COMBINED ASSIGNMENT AND DEPARTURE TIME CHOICE MODEL

The combined assignment and departure time model is based on a representation of queuing that employs a bottleneck model: the assignment phase employs a shortest path algorithm, which has been adapted for the bottleneck model. Lastly, the departure time choice model takes into account the concepts of lateness and earliness cost.

4.1 The representation of congestion by means of a bottleneck model

The bottleneck model of road capacity is particularly appropriate for a representation of queue formation, unlike a static speed-flow diagram: this is because it can take account of the spreading of departure times that occurs as a result of congestion, and allows us to calculate speed on the basis of the number of vehicles wishing to gain access to the road, and to represent the dynamic of congestion formation. The bottleneck or queuing model was originally developed by Vickrey (1969). The economic analysis of a single bottleneck model was conducted by Arnott et al (1993).

However, in the case which concerns us, we are dealing with a road network, therefore a network made up of bottlenecks: the economic analysis of such a network has not been undertaken and would only seem possible empirically by simulation. For this reason, we take as our starting point the single bottleneck model described in Small (1992), which we shall then extend to the entire network.

According to Small (1992, pp. 72 et seq.) we can express the average waiting time $\overline{T}_D$ for passing through a bottleneck with a capacity V_K at instant *t* by:

$$\overline{T}_D = 0 \qquad \text{if } V_a \leq V_K$$

$$\overline{T}_D = \frac{1}{2}\left(\frac{V_a}{V_K} - 1\right)dt \qquad \text{if } V_a > V_K$$

with $V_a(t)$ being the demand to enter the arc at *t*, assuming that the bottleneck is empty before the period *dt*

The total journey time is the sum of the waiting time and the time taken to pass through the bottleneck in the absence of congestion.

When congestion is present, a queue will form which will not necessarily have dissipated by the next time period.

In order to generalize this model to several time periods, we discretize the time interval into periods, we make the hypothesis that demand is a constant piecewise function and we take account of whether or not there is congestion remaining from the previous time period. An algorithm is then used to compute the average queuing time in each time period. The day is therefore divided into time periods and it is possible to compute the travel times *for each departure time*, according to the traffic on the network.

The travel time calculation uses a road network assignment model, which has been adapted from that used for the strategic model for the Lyon conurbation (Lichère, 1997). This assigns traffic by slice and conducts route search and shortest path assignment during each iteration. However, instead of using a static speed-flow diagram we shall use the bottleneck model described above.

4.2 Choice of departure time

We shall start by describing the microeconomic optimization program on which the user's choice of a departure time by one mode or another is based. After this, we shall give a brief description of the algorithm which resolves this program.

If we adapt the formulation put forward by de Palma and Marchal (2001), the generalized cost of using mode *m* during the time period *h* is written as follows (for a given route)

$$Cg_{mh}(t) = \alpha T_{mh}(t) + \beta \max[(hap - \Delta) - (t + T_{mh}(t)), 0] + \gamma \max[(T_{mh}(t) + t) - (hap + \Delta), 0] + C_{mh}$$

where $T_{mh}(t)$ represents the journey time at departure time *t*,

α is the unit cost of the journey time (classical value-of-time),

β is the unit cost of early arrival time,

hap is the preferred arrival time and Δ the permitted earliness or lateness,

γ is the unit cost of late arrival time,

C_{mh} is the monetary cost of using mode *m* during the time period *h*.

We have made the hypothesis that the transport user (PC or PT) attempts to minimize the generalized travel cost by combining the cost of the journey time and the cost of late or early arrival.

In the absence of specific measurements for Lyon, the values have been adapted from those found in the literature (Small, 1982; de Palma and Fontan, 2000).

In view of the fact that we have considered a distribution of values-of-time for modal split (see above), as a first approximation we shall use unitary values for the cost of early and late arrival which are proportional to the value-of-time for the journey. It seems reasonable to consider that the cost of lateness is higher than the cost of earliness.

$\beta = k_\beta \alpha$ where $k_\beta = 1/2$ and $\gamma = k_\gamma \alpha$ where $k_\gamma = 2$

where α is the distribution of values-of-time that has been calibrated for modal split.

The structure of the distribution of flows with reference to the time of departure is calculated after a number of iterations during which the agent attempts to reduce the generalized cost of the trip for a given activity at a given destination, for a preferred arrival time and a given transport mode. During each iteration, the minimum journey time, starting at a certain departure time, for each mode and for each origin-destination pair is calculated. Then, for each mode, the users change the departure time if this can lower the generalized cost for them.

We have made the hypothesis that the distribution of trips according to departure time is the outcome of a learning process in which only a fraction of users attempt to change each day. The attempt to find a better departure time involves leaving earlier and earlier until a reduction in the generalized cost is achieved; if no solution is found the user tries leaving later. In addition, the change is only made if the gain is sufficient.

Our tests have shown that the model accurately reproduces the spread of departure times when demand increases at constant capacity and, conversely, that departure times tend to draw closer together and closer to the preferred arrival time when capacity is increased.

4.3 Conclusion

The model includes a more realistic representation of the formation of congestion on a road via the formation of queues based on the use of a bottleneck model. The bottleneck model is combined with a shortest path (in generalized time) search algorithm that assigns traffic on the network and computes the corresponding journey times. Furthermore the model endogenizes the choice of departure time with respect to a preferred arrival time by including the costs of early or late arrival.

We shall now describe the coupling between this assignment and departure time choice model and the modal split model.

5 THE COUPLING BETWEEN MODAL SPLIT AND DEPARTURE TIME CHOICE

In this section, we shall couple the two models which deal, on the one hand with modal split, and on the other with the choice of a departure time and assignment on the network.

We shall present the model in the first section, and then in the second section go on to describe some validation tests. At the present time this model only deals with home-to-work trips.

5.1 The simulation model

The two models in question, one dealing with modal split and the other with the departure time choice have been coupled, after a few modifications to make them compatible with each other.

The departure time choice optimization procedure produces a distribution of trips by mode, departure time, preferred arrival time and origin-destination pair, in other terms “optimized motorized trips”, and on the other hand the journey times for the same dimensions, in other terms the “instantaneous private car journey times” and the “instantaneous public transport journey times”.

When making a comparison between modes, agents do not consider these instantaneous times but an exponential smoothing of the accumulated data: the smoothing is conducted with an average delay, i.e. the “delay for journey times to be taken into account”. We have made the hypothesis that a change in journey time from one week to another is initially seen as temporary. It is the accumulation of congruent modifications which may cause the agent to re-evaluate the information perceived regarding the characteristics of the different modes.

In the causal chain, work-related trips, for each time and mode, obtained from the modal split procedure (see Figure 5) are used as the input to the departure time optimization procedure: this is conducted separately for each mode. The output “optimized motorized trips” are subjected to exponential smoothing to take account of the fact that time changes do not take place immediately. The product of smoothing is aggregated for the two modes in order to provide the work-related trip demand for each departure time. This is used as an input for the modal split procedure (the variable *total demand for each purpose,* see Figure 5): at the moment, this is an equality, but other factors may affect overall demand in later versions of the model, for example change in the size of the working population or the number of jobs in each origin or destination zone.

5.2 Some results

To illustrate the capacities of the model we have deliberately very much simplified the application context. The data for this context is as follows: the day has been divided into 15 minute time slices and the studied period consists of 5 of these. We have considered two zones, all car trips are subject to pay parking, public transport service frequencies and fares have been specified, there are no exclusive lanes for public transport vehicles. Initial demand has been uniformly distributed over the studied period (5 slices): this has been fixed at 250 trips for each of the two modes, for each of the 4 origin-destination pairs, for each departure time and for each preferred arrival time (i.e. a total of 50,000 trips).

We shall analyse the behaviour of the model by observing the change in the demand to travel from zone 1 to zone 2 which attempts to arrive at the preferred arrival time *5*. Simulation was conducted over a period of 20 years (i.e. 1040 weeks) in order to reveal any long-term discontinuities.

5.2.1 Changes with increasing car ownership

We have kept demand constant but increased car ownership at a rate of 5% a year, which means that in the course of the 5th year all the agents who wish to make a home-to-work trip will own a car (week 280).

The trip distributions on the basis of departure time for the private car (see Figure 6, left) show an oscillation between the departure times *3* and *4*.

We can understand these oscillations on the basis of an increase in private car trips (see Figure 6, right), as a result of increasing car ownership: the increase in trips in departure times *3* and *4* is rapid. Later, the increased private car traffic increases private car journey times which results in departure times changes.

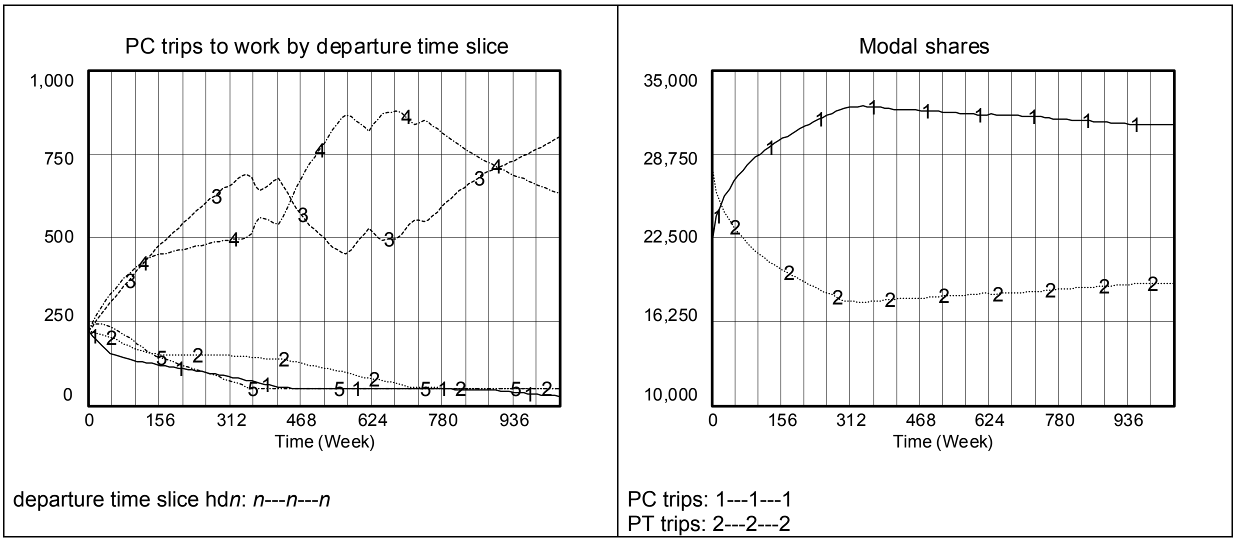

Figure 6 : Results of the increasing car ownership scenario

Rising car ownership increases the number of private car trips: the resulting rise in congestion is counterbalanced by a spreading of departure times. Simultaneously, the modal share of public transport falls.

5.2.2 Changes when the congestion constraint is relaxed

In order to simulate a relaxation of the congestion constraint, for example caused by an increase in road capacity over time[1] we have assumed that demand decreases over time (in this case a 90% reduction over 20 years) with the starting point as initial uniform demand of 800 trips for each mode, departure time, preferred arrival time and origin-destination pair.

Public transport traffic falls more quickly than private car traffic over time (see Figure 7, left), which results in a reduction in the modal share of public transport, from 55% at the start to 45% at the end of the period.

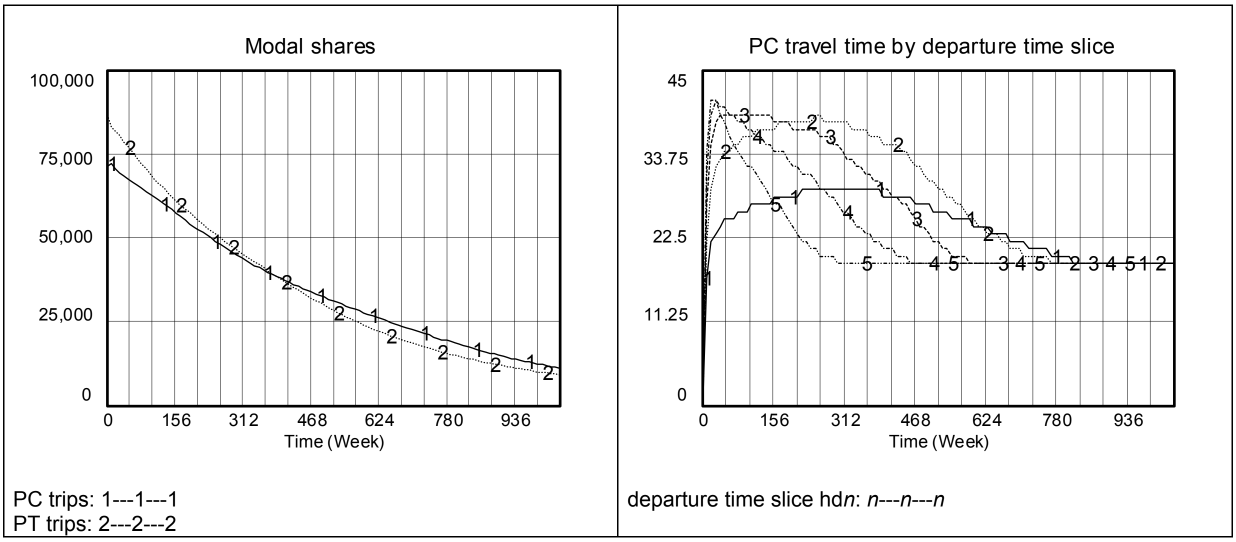

Figure 7 : Results of the congestion relaxation scenario

This change is adequately explained by the gradual easing of traffic flow that takes place, as witnessed by the private car journey times which converge towards the same value of 19 minutes (see Figure 7, right). The competitiveness of the private car in relation to public transport achieves a maximum level (in view of the fact that parking charges remain constant).

5.3 Conclusion

We have developed a combined model that deals with modal split, departure time choice and network assignment. By conducting tests on limited configurations of supply and demand, we have been able to validate the model's behaviour in relation to congestion and changes in car ownership levels. One of the results from the model is that the rise in car ownership leads to an increase in private car trips, in spite of the rise in congestion that it generates: this rise in congestion is counterbalanced by a spreading of departure times. At the same time, the modal share of public transport falls. Conversely, an increase in road capacity permits the car to retain its advantage over public transport and result in more uniform travel times by car.

The dynamic of this system has three origins:

[1] The model does not yet include this parameter

- delay in changing departure times,
- delay in taking account of journey time information, and
- delay in changing modal choice practices.

In the absence of empirical data, the values of these delays have been fixed in a somewhat arbitrary manner. The difficulty is that we only have qualitative information about these delays, as is apparent from the literature on observed behaviours, and this results in, for example, the differences between short-term and long-term elasticities. The full-scale calibration of these parameters of inertia therefore still remains to be done.

6 OVERALL CONCLUSION

We have developed a model that deals with the regulation of the financing of urban public transport. This model allows us to illustrate and quantify the interaction between public transport supply and demand, through the impact of the parameters of fares, service frequencies and public funding. This model also includes a mechanism for regulating self-financing which simultaneously modifies public financing, service frequencies and fares. We have shown that this type of model can be used to investigate the conditions for maintaining the financial equilibrium of public transport supply.

The theoretical basis of the modal split model which we have constructed is derived from microeconomics, and uses the determinants of price and time. The price-time model was calibrated on the basis of behaviours observed in Lyon in 1994-1995. The spatial representation of transport supply on the basis of classes of speed and distance provides a means of avoiding the problem of zoning and means that the model should be readily transferable to other agglomerations.

The model has employed a more realistic representation of the formation of congestion based on a bottleneck model. This bottleneck model has been applied in a traffic assignment model. It also allows us to endogenize the choice of a departure time with regard to a preferred arrival time, by including the costs of early or late arrival.

Lastly, we have coupled the modal split, departure time choice and network assignment models. The dynamic of the system has three origins: delay in changing departure times, delay in taking account of journey time information, and delay in changing modal choice practices. In particular, the model shows that increasing car ownership results in an increase in car trips, in spite of the increased congestion it generates: this congestion is counterbalanced by a spreading out of departure times. Conversely, an increase in road capacity will permit the car to retain its advantage over public transport, and result in more uniform travel times by car.

These three models therefore provide a sound basis for the achievement in the future of an urban trip simulation system based on a systems dynamics approach.

7 REFERENCES

Abbas, K.A., Bell, M.G.H. (1994) System dynamics applicability to transportation modeling. *Transportation Research A*, Vol 28A, n° 5, pp. 373-400, 1994.

Armoogum, J. Bussière, Y., Madre, J.-L. (1995) Demographic dynamics of mobility in urban areas : a case study of Paris and Grenoble. *World Conference on Transportation Research Proceedings*, Sydney.

Armoogum, J., Madre, J.-L. (1996) *Motorisation et mobilité des Franciliens aux horizons 2010-2020*. Rapport INRETS n° 209.

Arnott, R., de Palma, A., Lindsey, R. (1993) A Structural Model of Peak Period Congestion : a Traffic Bottleneck with Elastic Demand. *American Economic Review* 83 (1), pp. 161-179.

ASTRA (2000) *Assessment of Transport Strategies*, Final Report for the European Commission, 48 p. (http://www.iww.uni-karlsruhe.de/ASTRA)

ATN (2002) Simulation de scénarios d'évolution prospective de la mobilité urbaine à 20 ans. Application à l'Aire Urbaine de Lyon. Rapport de résultats. Octobre 2002, 44 p.

Berthier, J.P. (1998) Congestion urbaine : un modèle de trafic de pointe à courbe débit-vitesse et demande élastique. *Les Cahiers Scientifiques du Transport*, n°34/1998, pp. 3-29.

Bonnafous, A. (1985) Simulation du financement du transport urbain : le modèle QuinQuin. *Transports urbains*, n°54, GETUM, Paris.

Bouf, D. (1989) *Un nouvel instrument d'analyse stratégique pour la RATP : le modèle Gros QuinQuin*. Thèse de l'Université Lumière-Lyon2, Lyon.

Bouf, D., Gargaillo, L. (1985) Les modèles QuinQuin. *Transport, Urbanisme, Planification,* vol.7, Paris.

Cairns, S., Hass-Klau, C., Goodwin, P. (1998) *Traffic Impact of Highway Capacity Reductions: Assessment of the Evidence*. Landor Publishing, 1998, 261 p.

De Palma, A. Fontan, C. (2000) *Enquête MADDIF : Multimotif adaptée à la dynamique des comportements de déplacements en Ile-de-France*. Rapport de recherche pour la DRAST. 147 p.

De Palma, A., Fontan, C. (2001) Choix modal et valeur du temps en Ile-de-France. *Recherche Transports Sécurité*, n° 71, pp. 24-48.

de Palma, A., Marchal, F. (2001) *Real cases applications of the fully dynamic METROPOLIS tool-box: an advocacy for large-scale mesoscopic transportation systems*. Unpublished paper. 28 p.

Gallez, C. (1995) Une nouvelle perspective pour la projection à long terme des comportements d'équipement et de motorisation. *Recherche Transports Sécurité*, n°48, pp. 3-14, Septembre 1995.

Golob, T., Kitamura, R., Long, L. (eds) (1997). *Panels for Transportation Planning*. Kluwer, Dordrecht, The Netherlands.

Goodwin, P.B. (1984) Evolution de la motivation des usagers en matière de choix modal, *Rapport de la 68ème table ronde,* CEMT, Paris.

Goodwin, P.B. (1992) A Review of new demand elasticities with special reference to short and long run effects of price changes. *Journal of Transport Economics and Policy*. Vol XXVI n°2, pp. 155-169.

Goodwin, P. (1998) The End of Equilibrium. In : *Theoretical foundations of travel choice modeling*, T. Gärling, T. Laitila, K. Westin, eds, pp. 103-127. Pergamon, Oxford, 1998.

Jara-Diaz, S.-R. (1998) Time and Income in Travel Choice : Towards a Microeconomic Activity-Based Theoretical Framework. In Garling, T. Laitila, T. and Westin, K. (eds.), *Theoretical Foundations of Travel Choice Modelling*. Pergamon, 1998, pp. 51-73.

Jara-Diaz, S.-R., Videla, J. (1989) Detection of Income Effect in Mode Choice : Theory and Application. *Transportation Research*, 23B, 393-400.

Karsky, M. Salini, P. (1999) *Le modèle Simtrans*. Rapport de recherche PREDIT. 50p. + annexes, Septembre 1999.

Kitamura, R. (1990) Panel analysis in transportation planning : an overview. *Transportation Research*, vol.24 A, N°6, 1990.

Lichère, V. (1997) *Développement d'un modèle stratégique de simulation des déplacements. Présentation générale*. SEMALY-LET, 28 p. + annexes.

Mas-Colell, A., Whinston, M.D., Green, J.R. (1995) *Microeconomic Theory*. Oxford University Press. 981 p.

Mougeot, M. (1989) *Economie du secteur public*. Economica, 485 p.

Raux (C.) (1998) *Modèle stratégique de déplacements de l'agglomération lyonnaise. Tests de sensibilité, erreurs et incertitudes liées à la prévision*, LET, SEMALY, janvier 1998, 64 p.

Raux (C.), Masson (S.), Godinot (C.) (1997) *Modèle stratégique de déplacements de l'agglomération lyonnaise. Vingt ans de rétrospective à travers les enquêtes-déplacements de l'agglomération lyonnaise (1976-1986-1995)*, LET, SEMALY, février 1997, 181 p.

Raux, C. (2002) Uncertainties in Forecasting: The Role of Strategic Modeling to Control Them. In H.-S. MAHMASSANI (ed), *In Perpetual Motion. Travel Behavior Research Opportunities and Application Challenges*. Pergamon, Elsevier Science, Oxford, 2002, pp. 505-526.

Raux, C., Tabourin, E. (1992) Congestion et crise du financement des transports à Lyon : vers un péage urbain ? In *La mobilité urbaine : de la paralysie au péage ?* Raux, C. et Lee-Gosselin, M. (ss la direction de). Editions du Programme Rhône-Alpes Recherches en Sciences Humaines, Lyon, pp. 41-63.

Segonne, C. (2001) Choix d'itinéraires et péage urbain. Le cas du tunnel Prado-Carénage à Marseille. *Recherche Transports Sécurité*, n° 71, pp. 3-23.

SEMALY, LET (1997) *Développement d'un modèle stratégique de simulation des déplacements. Présentation générale*. Février 1997, 28p. + annexes.

SEMALY, LET (2000) *Modélisation des contraintes de stationnement*. Rapport pour la DTT (à paraître).

Small, K.A. (1982) The scheduling of consumer activities : work trips. *American Economic Review*, vol. 72.3, pp. 467-479.

Small, K.A. (1992) *Urban Transportation Economics*. Harwood Economic Publishers, Luxembourg, 185 p.

Stopher, P.R., Hartgen, D., Li, Y. (1996) SMART : simulation model for activities, ressources and travel. *Transportation* 23 :293-312, 1996

Tabourin, E. (1988) Un modèle de simulation du financement public des transports collectifs urbains à l'horizon 2000 : le modèle QuinQuin. *Transport, Environnement, Circulation*, n°87, Paris.

Tabourin, E. (1989) *Un modèle de simulation du financement des transports collectifs urbains à l'horizon 2000 : le modèle QuinQuin. Application à l'agglomération lyonnaise*. Thèse de l'Université Lumière-Lyon2, Lyon.

TRACE (1998) *Review of existing evidence on time and cost elasticities of travel demand and on value of travel time*. Report for the European Commission, Directorate General for Transport. May 1998, 100 p.

Vickrey, W.S. (1969) Congestion Theory and Transport Investment. *American Economic Review* (59) pp. 251-260.

Viton, P.A. (1985) On the Interpretation of income Variables in Discrete Choice Models. *Economics Letters* 17 (1985) 203-206.

Wiel, M. (1999) La transition urbaine. Pierre Mardaga Editeur. Liège. 149 p.