PARKING POLICY EFFECTS ON THE LEVEL OF SERVICE OF MOBILITY IN URBAN AREAS – A MODELLING APPROACH FOR DECISION MAKING

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ABSTRACT

Parking policy is the most directly available and widely used instrument to manage traffic and parking demand in cities. But the design of policy is subject to difficulties resultant from the complexity of the urban mobility system. Moreover, the emergence of new technologies offers new possible traffic management policy instruments theoretically more economically effective. For both reasons, tools to evaluate the effectiveness and optimal policy design are more needed than ever. This article presents a model framework, based on a System Dynamics approach, aimed to assess the effectiveness of parking policy and identify optimal design. We argue that the approach brings various benefits, and provide indications for its successful wide application in cities. An application to the city of Lisbon is developed, and results are discussed in face of their qualitative generalization and quantitative accurateness and robustness.

Keywords: parking policy, system dynamics, urban mobility, transport demand management

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INTRODUCTION

Parking policy in cities is widely applied as a policy instrument as a demand management instrument both directed at parking and traffic circulation demand. It has been widely applied in cities as a demand management instrument both directed at parking and traffic circulation demand. However, questions arise as to how to optimally design parking policies to meet the objectives that justify its use, and whether parking policy is an effective and efficient instrument as compared to other available policy instruments.

Without proper policy intervention, the development of urban areas leads naturally to an excessive use of private transport from the social welfare perspective, due to the presence of externalities like congestion, pollution and public space occupation. In line with economic theory, for the system to function efficiently from the collective perspective, all external costs should be internalized by the users, i.e. travellers should feel not only the private costs of their decisions but also the (marginal) costs that they impose on others. For that to happen, the price of travelling should reflect exactly the social marginal costs caused by the trip, i.e. all the costs inherent to the travel decision not faced by the user directly but also those imposed on third parties.

In practise, perfect social marginal cost pricing is far from being fully attainable, for a set of reasons including the technical viability and costs of practical implementation. Alternatively, second-best solutions can be applied, which, while not theoretically achieving a perfect equilibrium from a social welfare perspective, can still bring an outcome closer to it. Parking pricing is one of the possible second-best solutions, and has been the primary instrument adopted in cities worldwide for demand management purposes.

Identifying an optimal parking policy implies evaluating the extent to which it meets the established objectives. This way of measuring effectiveness is also useful when comparing the relative (dis)advantages against other possible policies, like road pricing. Theoretically, parking pricing is only perfectly effective in improving welfare in its role as an instrument of parking demand management. However, as a road traffic management instrument it is likely to be significantly less effective than other available means of demand management, since the parking price paid by travellers is only to a limited extent correlated to the costs caused to society only to a limited extent (see e.g. Verhoef et al, 1995a). For example, it does not introduce any incentive to through traffic.

The existence of scarcity of parking places without a proper reflection in a price holds three sorts of economic problems. Firstly, it does not allocate demand efficiently, i.e. it does not attribute the resource to those parties that most value its use. Secondly, the competition of users for parking places is centred on early arrival time. Travellers have to adjust their arrival time to a point where there are still free places, both in the morning at working locations (also humorously designated as the 'economics of sleep') as well as in the afternoon at residential areas. An extreme example is a shop worker who, in order to find a parking place, needs to arrive before the opening time of the shop and waste some minutes waiting inside his car before working time. A third and not less important type of inefficiency is the phenomenon of driving around for parking. When parking places are fully occupied, additional parking seekers need to cruise around until they find a place. This is resource wasteful both to them, who lose time and monetary resources while cruising, and to the other road users, who suffer additional congestion. Pricing for parking can be seen as the proper way to deal with these three types of problems. They are all related to the existence of scarcity of parking places. If there is a price regulating that scarcity and making parking demand meet the available supply, then from a theoretical perspective the problem can be economically solved to a socially desired equilibrium.

The same does not fully occur with parking policy as a road traffic demand management instrument. Although traffic demand choices have some correlation with parking time and parking place choices, it is probably far from one. For this reason, and in a time of emergence of new technological capacities allowing to realistically conceiving demand management schemes much more related to the sources of external costs, it is especially important to compare the effectiveness of parking policy with the other available instruments.

It should therefore be asked how effective parking policy can be in taking the mobility system to a more efficient level, and how to design urban parking policies in an optimal way, before a set of objectives?

As a contribution to these questions, not so much on the theoretical but more on the practical policy making level, this article presents a modelling framework based on the System Dynamics approach to assess parking policy at the urban level. The main goals of the model are to:

- Predict and measure the practical effectiveness of parking policies over the performance of the mobility system as a whole
- Identify optimal parking policy, at an aggregate urban level

The use of the type of aggregate, top down, model presented here is justified both from the technical perspective and from a pragmatic policy making perspective.

Ideally, parking policy should be designed to maximize welfare. Even if identification of perfectly optimal policy and its effects on welfare is a difficult and necessarily meticulous task, in the real world technicians and politicians seek pragmatic answers. For example, a politician may want to know the answer to a question as simple as "at which [average] parking price do we improve the level of service of our urban system to its best"? Obviously, there is no single answer, as an optimal solution might have numerous different prices across time, space and type of vehicle. But, in his decision process, the politician is not interested in such a detailed answer, and furthermore it might be not answerable in a very precise way due to the existing complexities. Both for politicians and, at least in a first stage, for experts, a more broader answer is required. As a matter of fact, city administrations commonly follow limited decision processes both regarding parking price level as well as its segmentation across time and space. Therefore, a methodology allowing the estimation of an optimal aggregate parking price or supply, within reasonable time and resources, is generally already a step forward compared to common practises.

But analysing parking policy at an aggregate level may also be required on technical grounds, as opposed to more micro level analyses of parking policy. The technical appropriateness of the use of either methodology depends fundamentally on the policy objectives behind its application. Indeed, if road traffic demand management is a policy objective of parking, Systems Dynamics is adequate both in terms of its aggregate level approach and its capability of capturing dynamic complex effects in a system. This argument is justified in detail in the methodological note below.

For the present task, parking policy is analysed as a stand alone policy, i.e. we analyse the results it brings in the absence of other possible demand management instruments, like road use pricing. However, for the reasons pointed above, an ideal maximization of the performance of the mobility system should comprise both parking policy (for parking management) and some other purposeful demand management policy (for traffic demand management). In future work, a comparative assessment of effectiveness of parking policy against other possible instruments of demand management could be performed.

The following section presents a methodological note on the application of the System Dynamics approach to the practical evaluation of parking policy in urban areas. Another chapter is dedicated to the description of the developed model, and its application to the case of the city of Lisbon. A third section discusses results of the model for the application in question, its robustness and transferability, indications for accurate use of the model, and its technical strengths and limitations

METHODOLOGY

System Dynamics is a modelling approach characterized by its capability of representing aggregate systems and capturing the dynamic complexity of their evolution. System Dynamics is also emphasised for its ability to deliver a comprehension of the systems structures (systems thinking) and for being a powerful communication tool. A detailed description on this modelling paradigm is not provided here, and the interested reader is referred to the work of Sterman (2000) or the several internet references on the theme.

The approach proposed here based on the System Dynamics modelling paradigm is justified as an appropriate tool to assess practical effects of parking policy on the performance of urban mobility systems for several reasons:

- Appropriate design and effectiveness analysis of parking policy directed at road traffic demand management must imperatively be carried out at an aggregate level.
- System Dynamics allows predicting dynamic effects not captured by common micro level traffic models.
- System Dynamics modelling can be a useful communication tool to decision makers and technicians.
- System Dynamics can be analytically more cost-effective than other analytical approaches.

This article concentrates on the first two elements. Additionally, it focuses on the issue of the ability of System Dynamics to provide reliable results for policy prescription.

Common static four-step traffic models, or dynamic micro-simulation models, are work intensive to implement and have limited analytical scope, particularly in capturing some feedback effects and in considering relevant variables. The System Dynamics approach, on the other hand, is appropriate to incorporate these. It allows capturing the complexity of the system by considering dynamic effects not foreseen by static or limited scope models. This need is pressed by the significant structural complexity of urban mobility systems, within which short and long-run feedback effects take place involving multiple factors and, for this reason, the prediction of policy effects is often not straightforward.

Additionally, the System Dynamics approach is justified by the possible need to assess parking policy at an aggregate level. This need depends on the precise objective of parking policy, which as described above can be used for parking demand management, for road traffic demand management, or both. Where traffic demand management parking is a goal of parking policy, an aggregate analysis at the urban level is essential. This is because a relationship cannot be directly established between the precise object of pricing – the parking place, at a given time – and the precise intended object of policy intervention – traffic flows, at given links in given time intervals. Unlike road pricing, where pricing in a given section could be designed exactly to meet the optimal congestion level at that same link, the same cannot be done if the policy instrument is parking pricing. The traffic in an urban road section is generated from and to multiple areas, and refers to parking use at a wide hourly distribution. Therefore, parking policy as an instrument to manage traffic circulation in an urban area must necessarily be conceived at aggregate rather than micro level, both in space and time. This need also highlights the advantages of using an aggregate modelling approach like System Dynamics. On the other hand, when the objective of parking policy remains local – the case of parking scarcity management – another appropriate analytical tool would be required be used to account for local phenomena.

The presented model is aimed at studying the effects of parking supply and pricing policies on the level of service of urban transport systems. It characterizes the aggregate system at the level of urban public transport and private car, and allows predicting the effects of changes in the parking policy with corresponding changes on modal split and resulting travel speed and cost. As an indicator of aggregate level of service in the mobility system, average speed is used. Other useful indicators included as outputs are average time per trip, average generalized cost per trip and congestion factor. The model accounts for short and medium term effects, while it does not consider long-term effects like variations of aggregate demand or car ownership.

The model is applied to the city of Lisbon, partly built on available local empirical data from the mobility system. We discuss the possible applicability of the model to reliably assess and design parking policy. To that end, we analyse robustness of results, discuss transferability of the application to other sites, and provide indications for model calibration.

MODEL

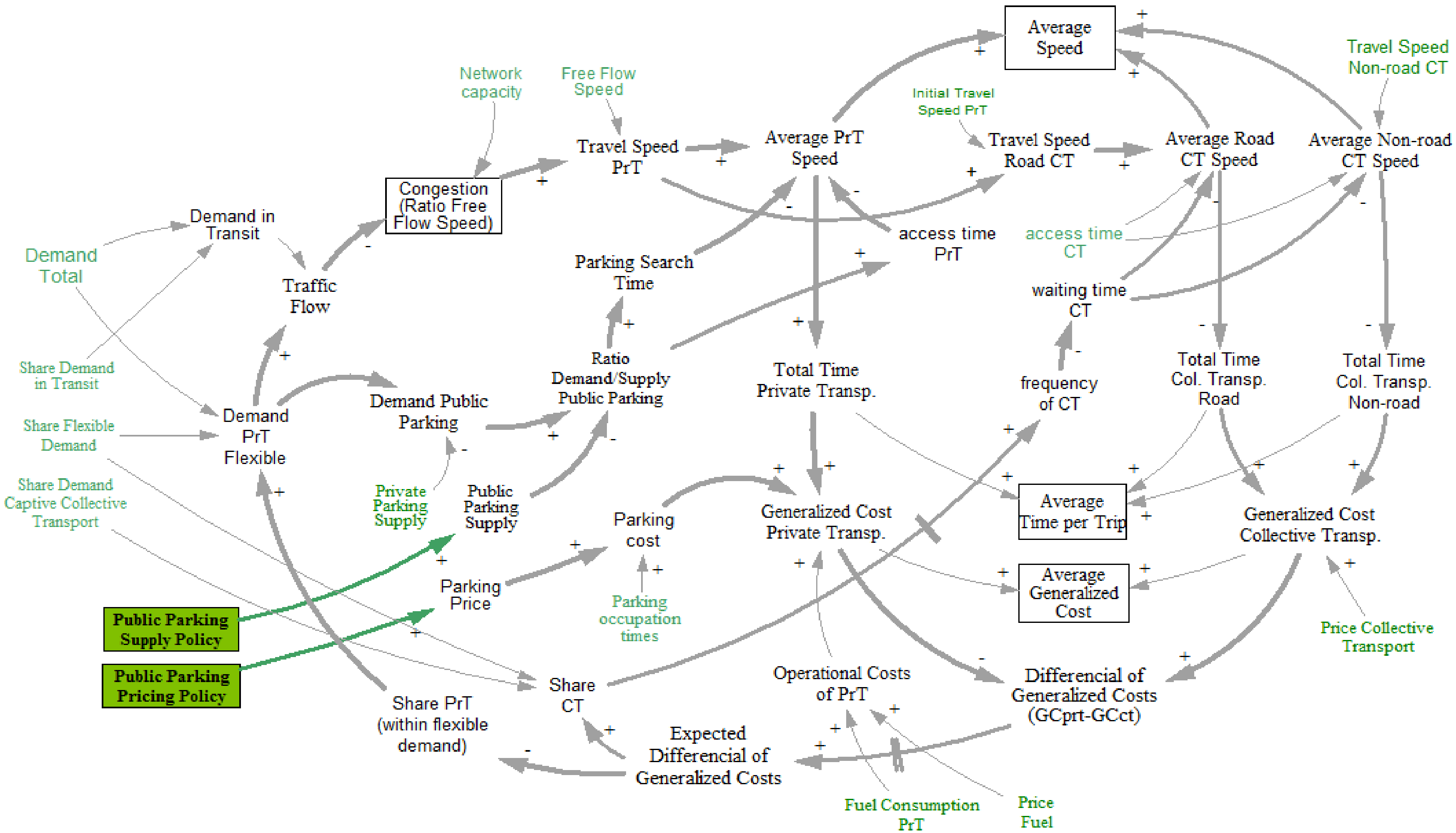
In its attempt to replicate reality at an aggregate level, the model structure is designed to cope with a set of crucial characteristics of the city and its transport system, such as the interdependence of flows between private and public transport, available types of parking, shares of demand segments according to potential use of parking, public transport supply segments according to infrastructure used, existence of road and parking congestion and public transport frequencies.

Some relevant external inputs of the model are demand, travel distances, initial parking times, public transport price and fuel price. Internal inputs are the policy types in question: parking supply and parking price.

The model broadly consists of three levels (described below in more detail):

- The input level – consisting of quantitative characterization of the policies tested over time
- The system level – consisting of all relevant interactions between system variables which directly or indirectly are affected by the inputs and influence the outputs
- The output level – consisting of system service and quality indicators

The scheme below presents a detailed structure of the model, representing the main variables and interactions taking part. A closer description of the model is provided in the following sections.



Notes: In line with the System Dynamics symbology, the signs in the relational arrows provide information on the direction of the interrelations between the pairs of variables in question. The tested policies are represented in green boxes. The most important indicators for quality and level of service are represented in blank boxes. External inputs are explicit in green.

Figure 1 – Detailed model structure

Detailed Description

Input level

The input level consists of the policy parameters that can be set by the relevant authorities, i.e. the types of parking policies covered in this work. Those policies are:

- Parking capacity
- Parking price level

As the model aims to test high-level policies, these variables are defined at city-level, i.e. they represent the average state of the variable for the whole city. This implies, for example, that changes in parking price level affect all private demand demand using parking.

The model simulates different policy scenarios. In particular, it is possible to test:

- Policy sizing – test effects of different "quantities" of each policy
- Multi-policy effects – test aggregate effects of policy sets consisting of more than one policy. When run simultaneously, policies may have counterproductive or synergic effects. Policies should not be designed individually but rather under a strategic framework targeting well defined objectives.
- Dynamic policy setting – i.e. a policy may be designed not only in its "quantity" but also in its timing. Different states of the system may ask for different policy sets over time, given a certain objective. It is also possible to simulate the system behaviour under the presence of state-responsive inputs, i.e. to simulate the effects policies which are dynamically responsive to the present state of its target indicators or other relevant variables of the system.

To the purposes of this article, only the first type of policy testing is essential and covered in the results presented in the following section.

System level

The system level consists of all the aggregate variables and interactions directly or indirectly relevant to the evolution of the state of the quality indicators. The scheme presented above maps relevant system variables and their qualitative inter-relations and illustrates how they lead to selected indicators of level of service.

Some of the most relevant external inputs of the model, i.e. variables not controlled in the simulation, and assumed fixed, are Demand, Travel Distances, Parking Times, Public Transport Price and Fuel Price.

The model is characterized by a set of structural elements and assumptions. They are described in detail in the following topics:

- **Demand**: three types of daily demand are considered, according to their flexibility towards the use on different modes and to their need to use parking:

a) Demand in transit; it has both trip extremes outside Lisbon, although it passes through the city during the trip. It is not affected directly by parking policy.
b) Captives of public transport; refers to travellers with no availability of private transport.
c) Demand with a potential use of parking; this refers to demand that is flexible towards mode (users choose private of public transport depending on their relative costs)

- **Parking scarcity effects**: as demand for public parking approaches parking capacity, **parking search time** and **access time** (the walking time from parking location to destination point) increase.
- **Road congestion**; average road speed practised depends on the daily traffic flow level.
- **Public transport types**: A distinction is made between Road Public Tansport and Non-road Public Transport. The former is affected in speed by road congestion while the later is not.
- **Total trip time**: Travel time, parking search time, access time and public transport waiting time, all account for total trip time and affect travellers' generalized costs.
- **Expectations**: The expectations on generalized costs made by travellers take time to meet changes of system conditions. Consequently, travellers only gradually adapt their choices to changes in level of service.
- **Frequency of public transport**: In the medium term, public transport operators adapt service frequencies to demand. The model assumes that in doing so they maintain a constant occupancy rate; therefore frequency is proportional to demand in the medium term. Frequency affects public transport waiting time.
- **Travel distances**: Demand mode split distinguishes between three groups of travel distances: short, medium and long distances.
- **Private parking price and demand**: It is assumed that private parking providers accompany their price level with the public price level in such a way that the occupancy rate of private parking is invariant to public parking price. In terms of model implementation, this translates into constant demand to private parking, independently of the demand for public parking.

Output level

The outputs of the model are a set of service level indicators. The central indicator analysed is Average Speed, which is an indicator for Level of Service. This variable accounts not only for the speed within the mode travel, but also for parking and access time, so it refers indeed to the speed of the whole door-to-door trip. Other indicators shown are Average Time per Trip, Average Generalized Cost per Trip and Congestion (real speed / free flow speed ratio).

Application

The assumption of relationships between variables and their quantitative parameterization makes it possible to simulate effects of policies over final policy goals. For example, the increase of parking supply would decrease parking search times, leading more travellers to choose private transport, which causes though a negative feedback through the decrease of travel speed. How that double-sided effect will affect policy goals, the simulation may tell. Supposing that this policy would lead to an excessive private and public transport speed decrease, one could test how that problem could be solved with the correct “dose” of parking pricing.

The model is applied to the city of Lisbon. A local characterization of the city is given, along with a more detailed specification of parameters used.

The parameters used are partly drawn from literature providing local empirical data. Other items are set arbitrarily with qualitatively plausible assumptions.

Local Characterization

Lisbon is a city with half a million inhabitants that is the centre of a metropolitan urban area of five times that population. The Lisbon area contains most employment in the region and attracts a mass of workers resident in surrounding cities. The share of those who travel by car is considerable and great pressure is put during the day both on the road network and parking supply.

The traffic situation in Lisbon is characterised by considerable road congestion in the morning peak, as a consequence of high private car use for commuting. Presently, about 400.000 vehicles enter Lisbon daily, while 180.000 of those are transit traffic without origin or destination in the area.

Since bus services often have to use the same infrastructure as private vehicles, road congestion also leads to slower speeds for bus transport. In addition, double lane parking is a considerable problem, leading to reduced capacity and slower speeds.

Official public parking places in the area comprise 200.000 spots. Nonetheless, the problem of parking space seems not to be an overall capacity problem but rather its management and spatial distribution. Scarcity of public parking on some spots, lax enforcement and low compliance rates are all common problems.

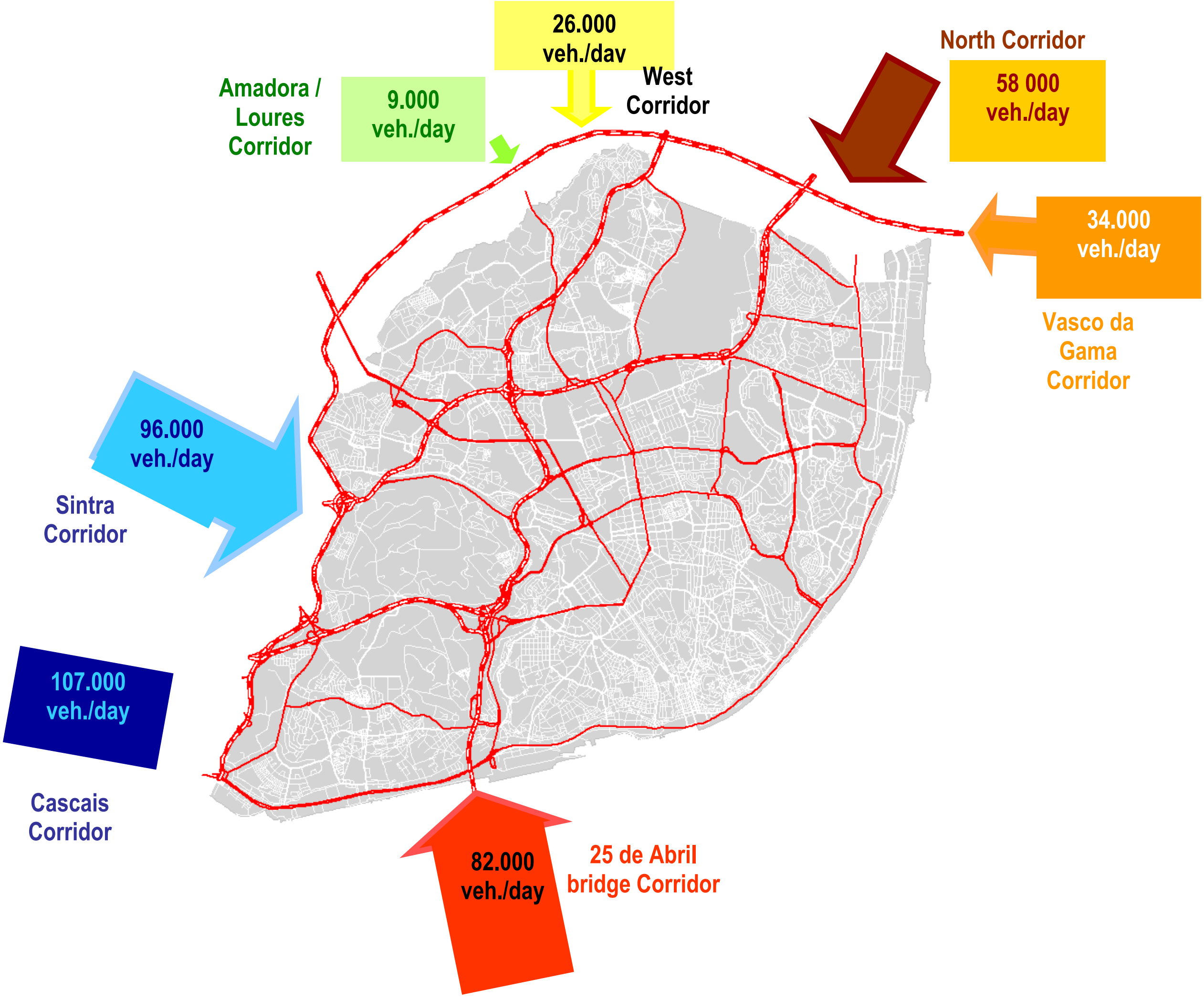


Figure 2 – Daily traffic entering the city of Lisbon

Parameterization

The parameterization of the model was mostly based on the information about the Lisbon transport system provided by the "Lisbon Mobility Plan" (CML, 2005). Several major inputs could be parameterized or calibrated on the basis of available data, like public parking supply, demand for public parking, total and type disaggregated demand, average travel speeds of bus, tram and metro, modal split shares, parking price or CT prices. Other parameters and relations were defined according to plausible assumptions.

The most important causal relationships are the congestion time degradation functions. For road traffic congestion, a common degradation function is used to represent the relation between aggregate traffic flow and average speed in the network:

$$\bar{s}(Q_a) = \frac{\overline{s_0}}{1+\alpha.\left(\frac{Q_a}{C_n}\right)^{\beta}}$$

with

$\bar{s}$ – Average speed in the road network
$\bar{s}$ – Average free flow speed in the road network
Q_a – Average traffic flow (vehicles/day)
C_n – Parameter for aggregate network capacity
α, β – Parameters

Parameters C_n, α and β could in principle be calibrated to the real case of Lisbon, provided availability and proper analysis of data.

The crucial time degradation relations are those related to parking search time and walking access time. The relation between parking demand and supply and parking search time considered is described by a function form similar to the exponential type[2]. A similar time degradation function describes the relation between the ratio of parking demand to parking supply and the access time (walking time) from the parking spot to the destination point. Existing and further research work could be used to calibrate these relations.

RESULTS

Scenarios

The model was simulated for several scenarios of public parking supply and pricing. Two scenarios were simulated for testing either a decrease or an increase in parking supply in relation to the present situation. Two other scenarios were simulated with different parking prices, the first with free parking and the second with the parking price that maximizes average speed in the network. These four scenarios compare to a business as usual scenario which assumes the maintenance of the present policies. The variations in policy parameters introduced in the first three scenarios were selected to represent realistic policies in a city. Scenario "Optimal Pricing" applies the pricing level that (approximately) maximizes average travel speed.

The inputs characterizing the scenarios are presented in the following table:

Table 1 – Scenario inputs

SCENARIOS	**Supply**	**Price (average)**
	(# places)	**(€/place.hour)**
0. Business as Usual (BAU)	203.800	1
1.1 Low Parking Supply	163.040 **-20%**	1,00 **0%**
1.2 High Parking Supply	244.560 **+20%**	1,00 **0%**
2.1 No Pricing	203.800	0,00

[2] An average park search time of 3,3 minutes is assumed when demand equals supply, in line with reported empirical results by Shoup (2006).

SCENARIOS	**Supply**	**Price (average)**
	(# places)	**(€/place.hour)**
	0%	**-100%**
2.2 Optimal Pricing	203.800 **0%**	2,75 **+175%**

The simulation results are used to analyse the effects of the tested policies on the targeted indicators. The main practical results were that:

a) Average trip speed could be improved up to 2,7 km/h in average in relation to the "business as usual" scenario by increasing parking price by 175% in relation to present level.

b) Increasing the parking supply could slightly improve the circulation conditions, decreasing average whole trip times. The opposite result would happen with a lower parking supply.

Both results depend greatly on some model assumptions, as we will see. The second, in particular, depends importantly on the trade-off between congestion at the road network and parking search times caused by excess parking demand. But, as is to be expected by theory, the use of pricing is essential to obtain the best circulation decisions, because it allows conciliating appropriate demand/supply conditions at the road network and parking infrastructure level, which is not achievable just by manipulation of supply.

Figure 3 shows the evolution of average speed in the road network for each of the scenarios. The table that follows outlines the average values for the indicators at equilibrium.

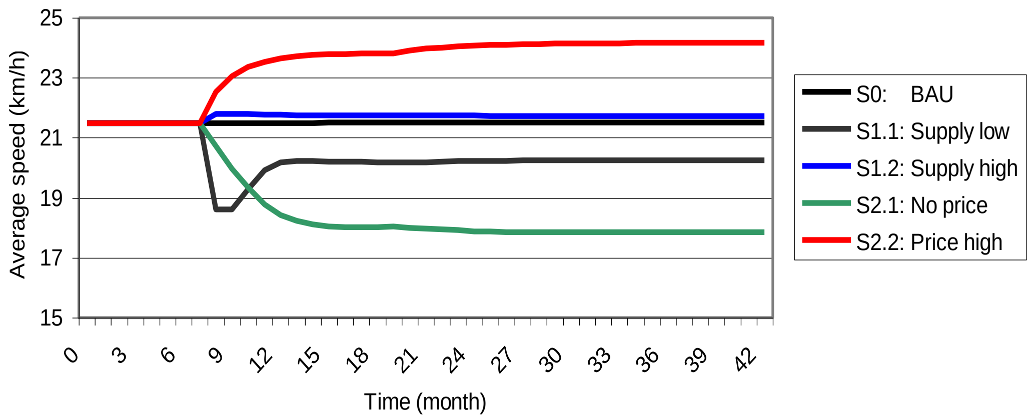


Figure 3 – Average speed results

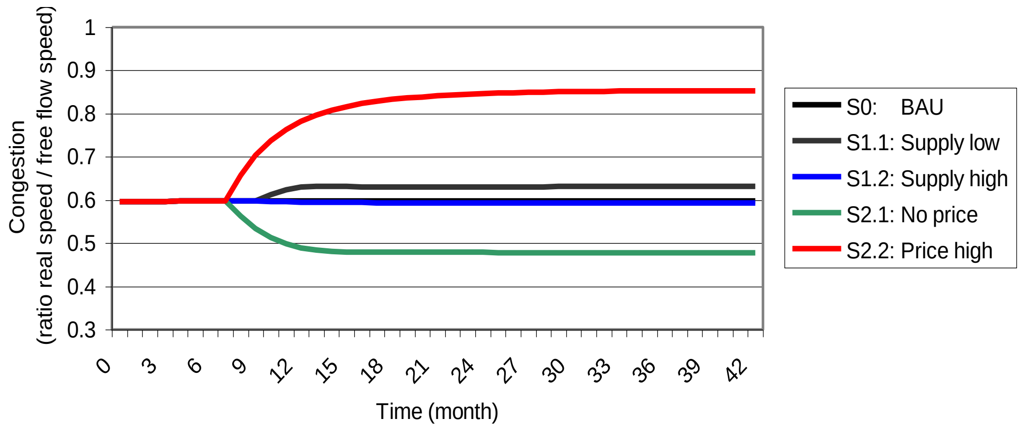


Figure 4 – Congestion results

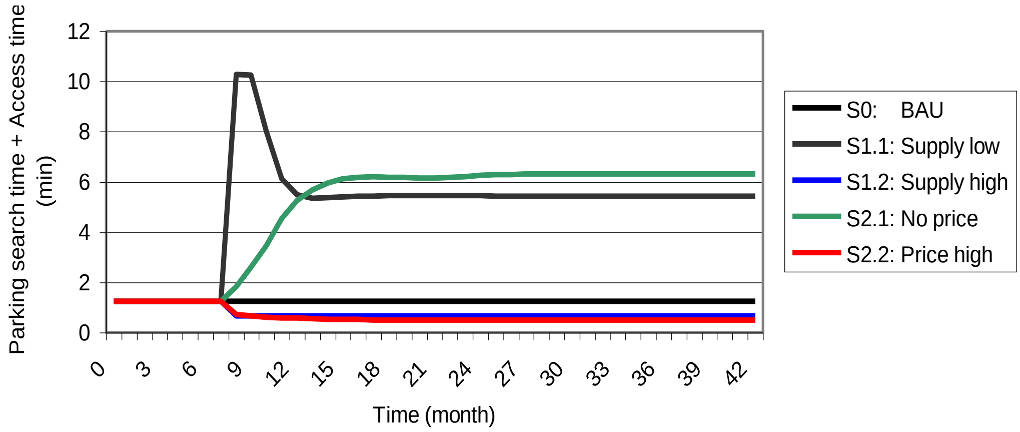


Figure 5 – Parking search time results

Table 2 – Indicator values at equilibrium under different policy scenarios

SCENARIOS		**Average Speed (km/h)**	**Average Time per Trip (minutes)**	**Congestion (real / free flow speed ratio)**	**Average Generalized Cost per Trip (€)**
0. Business as Usual	**S=1 P=1**	21,5	43,7	9,8	0,60
1.1 Low Parking Supply	**S=0,8 P=1**	20,2	46,4	9,9	0,63
1.2 Higher Parking Supply	**S=1,2 P=1**	21,7	43,3	9,8	0,59
2.1 No Pricing	**S=1 P=0**	17,8	52,7	9,6	0,48
2.2 Optimal Pricing	**S=1 P=2,75**	24,2	38,9	9,9	0,85

A detailed explanation of the results of the scenarios tested is described in the following commentary:

Scenario 0. - Business as Usual

In the "business as usual scenario" the transport system globally maintains its initial state, with circulation conditions at an average speed of 21,5 km/hour.

Scenario 1.1 - Lower Parking Supply

Decreasing public parking supply capacity has a negative effect on circulation conditions, increasing trip times. This negative impact is strongest in the short-run because the travellers do not immediately incorporate changes in the travel costs of the available modes into their travel decisions. This adaptation of expectations progressively takes place in the months following changes in generalized costs, which results in a partial recovery in average speed due to a gradual transfer of travellers from private to public transport.

Scenario 1.2 - Higher Parking Supply

The results of a higher parking supply scenario supply contrast with those of a lower supply. Circulation conditions slightly improve on balance due to lower parking search and access walking times achieved. The improvements in these elements is sufficient to offset a road congestion increase derived from a higher share of private transport.

Scenario 2.1 – No pricing

The scenario with no parking pricing produces the worst results for circulation conditions. The attraction of more private transport demand causes both an increase of road congestion and in parking search and access times. The time losses caused by these worsened conditions more than offset any time benefits acquired by the demand shifting from public to private transport. In the medium term, a significant further decrease of average speed is observed due to a reduction of public transport frequencies caused by a decrease of its demand, causing further time losses both at the level of access times and road congestion, following a negative Mohring effect.

Scenario 2.2 – Optimal Pricing

This scenario assumes a parking pricing that achieves an optimized level of the average speed in equilibrium. Optimal price is, according to the model, about 175% times higher than the BAU level. Such price policy allows both to reduce congestion and parking search and access times to levels that manifestly increase travel times. At this level, because the parking price is optimal towards travel speed, we know that marginal price effects on factors that improve average speed are equal to marginal price effects on factors that reduce average trip speed. A positive Mohring effect is visible in the medium term after an increase in public transport share, conducting into further speed improvement in the system.

Specific analyses

An analysis of sensitivity of results to assumptions is useful both to check if results are robust to uncertainty on the assumptions taken and to assess the transferability of results to other sites. The analysis includes five key elements:

- Parking price effects
- Optimal price under different parking supply levels
- Congestion parameters (β and Cn)
- Share Road / Off-road Public Transport
- Modal split logit parameter

The first two are directly related to the policies in question, while the later four relate to assumptions of the model

Parking price effects

This test assesses in full-length the performance of the mobility system before different possible parking prices (see Figure 6). As we had seen, the maximum average speed in the system reaches a maximum at a price of around 2,75 €/hour. In that scenario, the share of private transport is slightly above 30%.

The main result of this test is that, as already seen above, the use of pricing is essential to get the best performance in the mobility system. In this model, the losses in average trip speed incurred by not applying a price would amount to 26%.

One curious result is that the performance achieved is better with very high prices than with a zero price scenario. This means that the time burdens caused by excess private transport demand at zero price are higher than the time losses of caused by excess modal shift.

Another interesting result is that there is an interval of possible pricing at which the level of service achieved is very stable. Deviations from optimality of plus or minus 30% the optimal level do not produce losses of more than 2% in travel speed. Politicians aiming at optimizing the level of service of the urban mobility system and at the same time worrying about public acceptability of price levels, would prefer to keep the price at the lower level within that interval, although this would overlook other possible objectives like reduction of air pollution and occupation of public space.

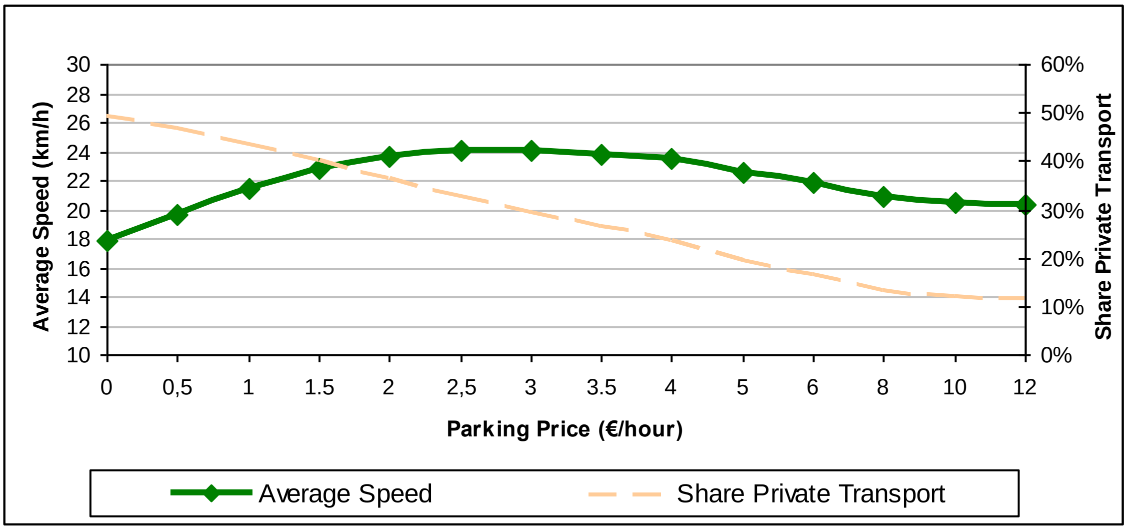


Figure 6 – Effects of parking price on average speed and share of private transport

Optimal price under different parking supply levels

The optimization of the price level under different public parking supply scenarios reveals that, after a certain supply level, the optimal price and speed are approximately constant. After that supply level, no matter how much more parking places are available, the optimal modal share remains constant, and therefore any extra parking places are not used. After that supply level is reached, it is simply ineffective to increase it further.

It is also possible to observe that, up to that supply level (in the model it lies at around -10% the BAU level), it is beneficial to increase supply, although with minimal marginal benefits.

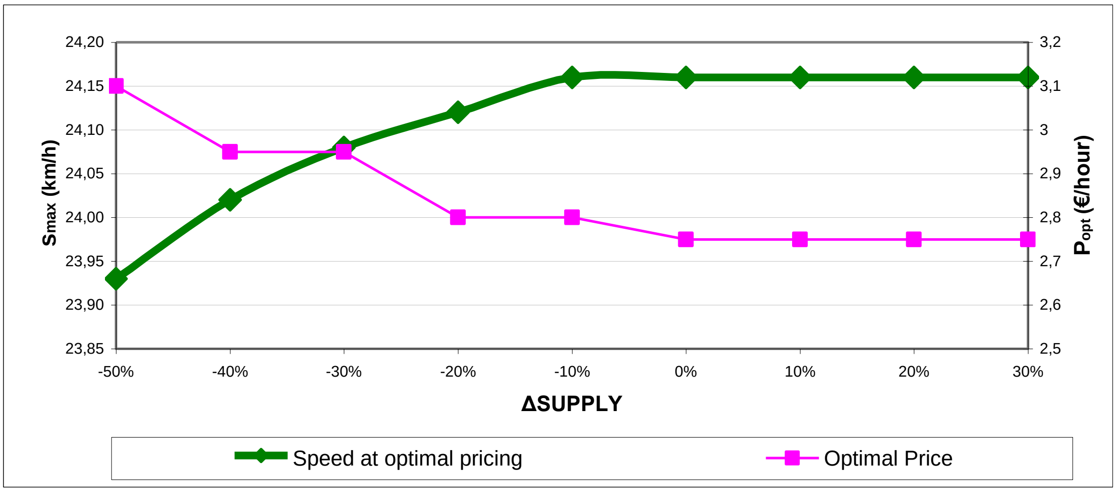


Figure 7 – Optimal price under different variations of parking supply to the BAU scenario

Congestion parameters

Important trade-offs in the model depend on the time costs incurred by pressure of private transport demand on the road network and the parking infrastructure. The precise sizes of those costs in relation to demand intensity are crucial parameters for the outcomes within the mobility system. This item analyses two of the three congestion parameters included in the road congestion function. They are the parameter β and the parameter for aggregate network capacity, C_n . The test performed in both cases refers to the speed losses from optimal level incurred from defining a price based on a wrong parameter assumption. Given the speed s^* obtained with a price policy designed with a certain parameter assumption, we calculate its percentage deviation Δs_{opt} in speed from maximum speed s_{max} that would be achievable through an optimal price defined with the correct parameter value. This allows anticipating consequences for policy of wrong model assumptions. The following equation defines this analysis:

$$\Delta s_{opt} = \frac{s^* - s_{\max}}{s_{\max}}$$

The negative consequences for policy of wrong β assumptions seem to be minor. For example, a negative deviation of 30% to the expected β level results in a negligible sub-optimal speed deviation of 0,6%.

Wrong parameter expectations seem to cause more impact on policy effectiveness with the parameter for aggregate network capacity. In this case, negative deviations above 20% cause very important errors in price setting with strong undesirable implications on the achieved system equilibrium.

Nonetheless, it is noteworthy that the adoption of wrong assumptions in such high extent is very unlikely under any soft check-up with reality. For example, a negative deviation of parameter C_n in 20% causes speed losses of 32%, which would hardly match with other known data the systemic level with other known data, like mode split or public transport commercial speed.

Modal split logit parameter

Mode split is defined in the model using a *logit* function, *where α* is a parameter and *ΔGC* is the generalized cost differential between private and public transport:

$$\frac{1}{1+e^{-\lambda.\Delta GC}}$$

Parameter λ defines the rigidity of demand towards differentials of generalized cost between the two modes. It could in principle be estimated at the local level, based on traveller behaviour data. Like in previous tests, a sensitivity analyses was performed to check for the effectiveness of pricing policy upon possible judgement deviations of this parameter.

The results show tenuous but non negligible effects of deviations of the mode split parameter on the effectiveness of pricing policy. E.g. a deviation in rigidity of demand provoked by a negative 20% variation of λ would result in a speed loss of around 0,8%.

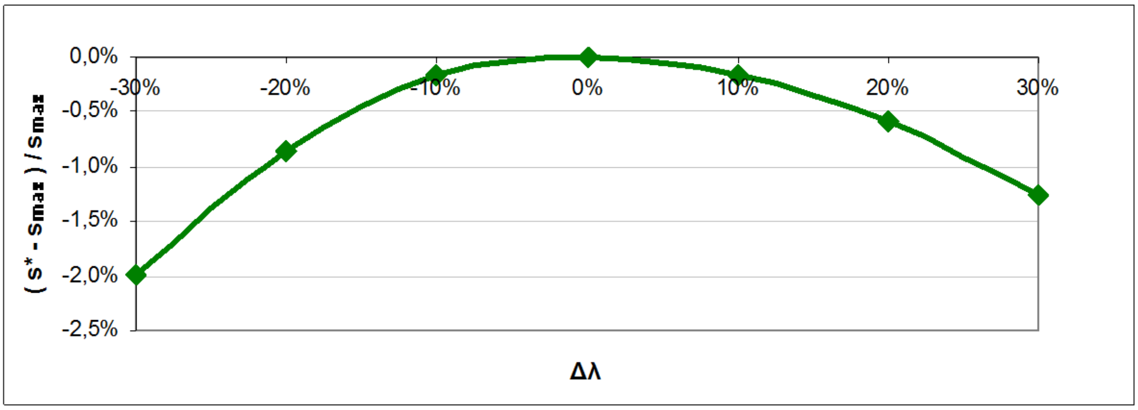


Figure 8 - Sensitivity analysis on deviations to optimal average speed from variations mode split parameter λ

Share Road / Off-road Public Transport

Public transport sharing road infrastructure with private transport is also affected by congestion. Cities have public transport systems of different nature, including the issue of infrastructure communality. The model accounts for this difference, and the consequences regarding policy are worth pointing out.

Apart from the baseline simulation with a 40% share of road public transport, the two extreme cases of 0% and 100% were tested. As would be intuitively expected, the higher is the share of road public transport over non-road public transport, the higher is the optimal price, since road public transport benefits in speed from the reduction of road congestion. Depending on the type of public transport system, optimal price may vary between 2,45 and 3,25 €/hour.

Table 3 – Effects of share of road public transport over total public transport demand on optimal price and speed

share	P_{opt}	s_{max}
0%	2,45	25,1
40%	2,75	24,17
100%	3,25	22,94

DISCUSSION

Synthesis of model results

The results of model simulations highlight the potential of the System Dynamics approach as an instrument to identify best parking policies at the city level. Results suggest that it is possible to measure and predict effects of policy on the aggregate performance of the urban mobility system, with proper model parameterization and calibration, as we argue below.

In particular, the simulations revealed that **parking pricing** may be used to obtain very significant mobility performance improvements, including parking demand management and traffic demand management, with results pointing to potential benefits in average trip speed up to the order of 35% to the system in question in relation to a scenario without pricing. The optimal average price level and the overall benefits it brings depend on several assumptions and particular city characteristics. Of these, we highlight the congestion function, the parking search time function, the rigidity of demand towards mode shift, the level of supply of parking places or the share of public transport coexisting in the private transport road infrastructure. A particularly relevant observation for the modelled system was that there is a reasonably wide price interval around the optimal price for which the mobility performance results vary little, which on one hand is a sign of model robustness on the result of mobility performance achieved (see also next topic) and on the other hand leaves policy makers with a margin to decide price on the basis of other criteria and still achieving favourable results at the mobility level.

Generally, **parking supply** used as a stand alone demand management instrument is seems to be rather ineffective policy. It was also seen that there is a level of supply after which the provision of more parking is useless from the system performance perspective and that in the system in question the reduction of supply below that level does not produce significant damage on its performance.

Robustness and transferability of results

The results of the application of the presented model can be trusted only if one believes that it is effective in reproducing real behaviour. To do that, not only must we believe that its structural assumptions are correct but also we need to have sufficiently reliable data to parameterize the model. As pointed below, there are reasons to believe that both premises are possible to achieve.

In relation to structural assumptions, generally it seems that they are not subject to major controversy or uncertainty. E.g. it is clear enough that average road travel times decrease with private demand level, that an increase in parking price reflects on the perceived costs of car use and consequently on its demand level, or that the flow of road public transport is negatively affected car demand. The same qualitative certainty could be mentioned of any of the model relations in question. Therefore the challenge lies not with the nature and direction of relations, but on their quantification.

Quantitative data on model parameters is in some cases directly available (including inputs like e.g. modal share, commercial speed of public transport, or demand per segments, or relational parameters like elasticity to price). Where it is not, it is in principle possible to obtain or estimate on the basis of available or obtainable empirical data. For example, parameterization of a congestion function (which deals with total demand and average speed) could be estimated on the basis of available speed-flow data on a representative sample of links within the city in question. The same is true, for example, for parking cruising time dependent on parking demand and supply relations (following work like that produced by Shoup, 2006). In both cases, data available for short time spans would have to be conveniently converted to meaningful relations on a daily basis, since the aggregate model works with average daily figures.

Either parameterization relies on solid data or is it estimated on the basis of subjective beliefs, it is relevant to assess the consequences of parameter uncertainty on the robustness of the model predictions. We have seen above that the sensitivity of model results to parameter variations does not seem severe in some cases, like congestion or modal split parameters. In cases like these, assuming values not relying on specific local empirical data might not undermine the certainty of the predictions. And like the general rule says, efforts to obtain better data should focus primarily on parameters for which the model gives *a priori* reasons to believe that their wrong assumption can lead to severe mistakes in prediction.

Analyses on the influence of variations of specific parameters also allow providing indications on the transferability of results of a model application to another. The example of the share of road public transport over non-road public transport points out how results can differ from city to city, depending on specific characteristics.

Examination of parameters and calibration

To apply the model as a real policy assessment instrument, it thus should preferably be subjected to a detailed quantitative scrutiny of its relationships and parameters. The Lisbon model application produced interesting results, but their trustworthiness could be improved through more detailed analysis than the one carried out so far, which basically consisted of taking all possible data from the Lisbon mobility plan and setting most other model parameters on the a subjective *best guess* basis.

For that task, we outline a set of relationships that seem to be particularly important to analyse from the perspective of an aggregate model like the one presented:

- Aggregate congestion function
- Parking search / walking access time functions
- Aggregate mode split function (elasticity of demand)
- Road congestion effects on public transport

As made evident in the description of results, these were relationships of particular importance in the development of trade-offs crucial for the model outcome. On the other hand, some seemed to have a low interference with the successful identification of effective policy, and could thus be subject to softer examination efforts.

Also important are particular local characteristics, like demand in its various segments, average real and free flow speeds, parking supply per segments, modal share or value of time.

Technical strengths and limitations

Aggregate VS local analysis

Using an aggregate urban model has advantages and disadvantages. The main disadvantage refers to its inability to account for local phenomena, both physically and dynamically. This limitation is especially important when the goal of parking policy is parking demand management, because the scarcity of parking places is a quite local matter. There are parts of the city area where scarcity is very high compared to demand, while in others it may be low. In the first case, the optimal price directed at parking demand management should be high, whereas in the second it might even be zero. These different scarcity levels may take place not only physically but also dynamically across the time of day. To account for these local specificities, System Dynamics should be complemented by micro level analysis, which should account for parking scarcity locally across space and time.

In contrast, as explained above, the use of parking policy as a road traffic demand management instrument (to control road network congestion or local pollution) must be designed in an aggregate rather than local perspective, since the physical relationship between network congestion and parking use is disperse. Therefore, in the field of road network demand management, the aggregate modelling approach is the most appropriate analytical tool.

The best approach in designing parking policy directed both at parking demand management and road network demand management is to complement aggregate modelling with local parking scarcity assessment. However, local administrations often take decisions on parking policy based more on political than technical concerns. For example, in Lisbon, until recently the parking price was set at the same level in all covered areas of the city, which reveals limited technical insight taking part in the price decision. This may occur for various reasons, like concerns of political nature, low regard for technical capabilities or scarcity of budget or time for their use. It may be thus be too optimistic to expect the departure to large-scale technical policy analyses. As a first step, the use of more aggregate models seems to be the best approach, since they are capable of giving a wide insight, while they are comparatively economical in the resources necessary for its application.

Insight on economic efficiency

The notion of economic efficiency applied to mobility is based on the notion that the use of the available resources produces the highest value. Given the approach used in the model of evaluating the performance of the urban mobility system by the average speed achieved, one may question if it is adequate from the perspective of economic efficiency.

Improving average speed is certainly good, but is the way how it is achieved fully in line with the notion of value maximization? Not necessarily, since the value of mobility depends not only on the time spent to access the point desired, but also on the value put by the travellers on that time (among several other factors relatively independent of parking policy and thus not covered here). Mobility management policy should thus also take into account the value of time of individuals. And parking policy does not succeed to do it, when applied as a traffic demand management instrument. By way of pricing parking only, it excludes or over-considers segments of demand depending on the time of their parking time use. Some segments of demand do not use parking at all (through traffic) while others use it all day; the first are totally excluded from the parking pricing system, while the second are possibly overburdened, before a traffic management goal. As a consequence of this imperfect relationship between object of price and the fundamentals of value, the goal of economic efficiency is damaged. In the case of parking policy, the effect may be that subjects with very high value put on travel time may still be excluded from the use of private transport, while some subjects with low value to travel time (or with a good alternative at hand) may remain on it. Therefore, even if parking policy is effective in increasing travel speed at constant aggregate demand, theoretically it may still be economically harmful if the market distortions it introduces produce even higher costs.

The model may be extended to account for these market distortion phenomena. This is possible particularly by considering different demand segments according to their parking time (which is partly done by the model described by considering demand in transit) and their value of time. And, besides using solely travel speed as an indicator for economic performance, one would also consider the matter of value creation. This model upgrade would also be particularly useful to compare parking pricing with other possible traffic demand management instruments.

SUMMARY AND CONCLUSIONS

Nowadays, the emergence of new technological possibilities are putting in question the use of parking-based policy instruments as the core means to deal with urban problems of congestion and pollution. From the political perspective, it becomes more relevant than ever to assess the ability of parking to solve problems in an effective and efficient way, in comparison with other means.

Given that congestion taking place in particular road links is generated from traffic with multiple origins and destinations, parking policy as an instrument to manage road traffic demand in an urban area must necessarily be conceived at aggregate rather than micro level, both in space and time. On the other hand, the mobility system is complex, and the actual effects of policies are not always evident. These two technical arguments, along with the need to offer meaningful and costs-effective analytical approaches to policy makers, raise the need of practical modelling approaches capable of capturing aggregate and dynamic effects, as a way to identifying optimal parking policy and assessing its effectiveness. The System Dynamics modelling approach seems to be a proper one for the purpose.

In this article, we presented a modelling framework, based on the System Dynamics approach, designed to assess effectiveness of parking policy and formulate optimal its design. In broad lines, the policies introduced in the modelled system – parking supply and parking pricing – affect the way transport users evaluate mode choice alternatives, which in turn influence the performance of the transport system in various ways: the level of private transport demand affects road congestion, parking search times and walking access times; road public transport is partly affected by road congestion, and; public transport demand affects medium and long-term frequencies of the services. The key variable determining the average speed of trips in the system is modal split. The model is supposed to capture short and medium term effects of policy, so aggregate demand is assumed to be constant.

The model allows determining optimal parking policy directed at a given objective, like the maximization of the level of service (or average speed) within the mobility system. Results of the model application to the city of Lisbon have shown that pricing, contrary to parking supply control, is an effective instrument to improve level of service.

The results obtained could be more trusted at a quantitative level if the model were fully calibrated with real empirical data, which is conceivably possible with additional data gathering and analysis. Analysis of robustness of results to deviations in key parameters has shown that imprecise assumptions on some variables produced minor impacts on the effectiveness of prescribed policy, while others justify additional efforts for a precise valuation to avoid significant errors in policy prescription. The model is in principle applicable at any city, while results obtained for a given may not be fully quantitatively transferable to other sites due to the importance of specific local characteristics, like the common use of road infrastructure between private and public transport.

Extensions of the model may also be useful to evaluating the relative effectiveness of parking policy in relation to other possible demand management instruments. There are *a priori* reasons to believe that road pricing achieves a better mobility system performance, since it can be more connected to the causation of externalities from car use. The price of parking faced by users cannot be appropriately related to length, time and place of travel. It is, to a relevant extent, inefficient in bringing an optimal demand management both from the perspectives of network congestion and environmental prejudice. But in the coming years, experts and politicians in cities will face the dilemma of choosing between keeping parking pricing as the core demand management policy or shifting to travel-based pricing schemes, with the possible implementation costs and acceptability barriers posed by the later option. An informed decision needs to take into account the effectiveness of those policies over the performance of the mobility system. This article provides a framework for an evaluation and optimal design of the former.

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