

# **MOBILITY RIGHTS FOR URBAN ROAD PRICING: A MODELLING ANALYSIS WITH A SYSTEM DYNAMICS APPROACH**

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## **ABSTRACT**

One criticism concerning road pricing concerns undesired equity impacts on low income groups, especially when transport alternatives (e.g. public transportation) are missing or poor. A promising approach to tackle this criticism is setting quantified physical constraints in the form of “mobility rights” evenly allocated to travellers and granting the permission to transfer these “rights” to other agents. This way, low mobility groups, often correspondent to low income groups, can enjoy a monetary benefit from higher mobility groups. In the year 2005, a strategic system dynamics model was developed to provide quantitative estimations of the impact of alternative road pricing and mobility rights schemes in the case of the city of Genoa (Italy). The model is now being extended and refined within the European research project DEMOCRITOS. This paper, after providing the key theoretical elements under the mobility rights concept, provides details on the features of the model, with special reference to the simulation of travelling choices concerning overall individual mobility in a given time span instead of a decisions related to single trips. The modelling of long-term impacts, in particular land-use, is also addressed.

*Keywords: Road Pricing, Mobility Rights, System Dynamics, Strategic Modelling*

## **INTRODUCTION**

Road pricing is increasingly perceived as a policy instrument to manage private transport demand. Urban road pricing has been applied for several years in cities like Singapore, Stockholm, Trondheim and, more recently, in London and Milan (Bielefeldt et. al, 2008). Inter-urban road pricing (for duty vehicles) is one of the policy measure included in the EC Greening transport Package (European Commission, 2008).

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Road pricing has been applied for different goals. Urban road pricing has been usually conceived as a congestion charge (e.g. Singapore, London) but in Milan it has been applied as a pollution charge. The approach followed by the EC for the inter-urban road pricing is social marginal cost pricing (SMCP), aiming at adding the value of external costs to the marginal cost of transport (internalisation) in order to achieve a fair competition between modes and an efficient level of transport activity.

Whatever the rationale for road pricing come from, one of the major criticism raised against this measure concerns the undesirable equity impacts on low income population groups, especially when transport alternatives (e.g. public transportation) are missing or poor. A proposed approach to address this criticism is the distribution of “mobility rights” evenly to travellers, while at the same time granting the permission to transfer these “mobility rights” to other agents. Under this approach, low mobility groups, often correspondent to low income groups, can enjoy a monetary benefit by selling unused mobility rights to higher mobility groups, often correspondent to higher mobility groups.

In the year 2005, an explorative study towards the application of the mobility rights principle was carried out for the Municipal Authority of Genoa (Italy) (Evidenze, 2006). Within this study, a strategic system dynamics model was developed to provide quantitative estimations of the impact of alternative road pricing and mobility rights schemes. This model is now being enhanced and refined within the European research project DEMOCRITOS, undertaken for the 7<sup>th</sup> Framework Programme of the European Commission.

The enhanced model is aimed at providing more detailed results (e.g. in terms of origin/destination trips rather than just in terms of number of generated trips) and at simulating behavioural decisions in a more general way (e.g. fully simulating mode choice rather than just estimating car trips shifted to public transport). Furthermore, the enhanced model is expected to allow interlinking with a land-use module where long term impacts on households and activities locations are simulated and demand activity patterns are endogenously generated.

The paper introduces the model and it is organised as follows. First, the basic concepts of the mobility rights are presented. Second, an overview of the model is provided with special reference to the assumptions adopted to translate the concept of mobility rights in a way that can be addressed by the model. Third, the internal modelling process to simulate the mobility rights is described in some detail. Fourth, the modelling of long term effects through the linkage with the land-use model is explained. Conclusions end the paper.

## **THE CONCEPT OF MOBILITY RIGHTS**

The idea of mobility rights can be seen as one version of the wider concept of transferable permits. This concept combines economic incentives and regulation by quantity (Raux, 2008) based on the theory of property rights allocation (Coase, 1960). An early proposal of using mobility rights in the transport sector to address congestion was made by Prof. Jose Viegas (Viegas, 2001). Since the year 2005 the principle of Mobility Credits has been developed by the Italian firms Evidenze and Rightstrategy with the support of Fondazione Italiana Accenture (owner of the trademark “Crediti di Mobilità”<sup>TM</sup>).

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In its essential terms, the application of mobility rights to the transport case is based on the definition of a “sustainable” level of (mainly private car) transport demand and its translation into an overall mobility budget to be evenly distributed across individuals under form of a certain number of rights. Trips exceeding the mobility budget are charged while, at the same time, individuals whose mobility needs are below the sustainable threshold can sell unused rights, thus activating a distributional effect.

It can be readily understood that this principle needs plenty of specifications in order to be applicable. Just to make some examples, elements to be defined include:

- How to define the sustainable level of mobility (e.g. based on some physical measure or using individuals willingness to pay for better urban conditions, etc.).
- What is the reference population for the even distribution of the mobility rights correspondent to the sustainable mobility threshold (e.g. all people in age, all car owners, only residents in the urban area or also commuters, etc.).
- Which rules define the correspondence between one trip and the consumption of mobility rights (e.g. whether each trip is equivalent to the same amount of rights or trip conditions – such as the vehicle used or the zone of destination – make a difference).
- Under which institutional setting, individuals can sell and purchase rights (e.g. additional rights can be purchased only within the sustainable limit, i.e. until someone is willing to sell unused rights, or the public authority can sell additional rights).

Whatever is the response to these questions, the basic concept of mobility rights is to use pricing to manage transport demand, but only beyond a certain threshold of mobility. Within such a threshold individuals are not discriminated for their payment capacity. Beyond the threshold people that can and want to limit or avoid the use of private car can enjoy a monetary benefit.

Therefore, at least in theory, the advantage of mobility rights compared to ‘pure’ road pricing is twofold. First, allocating mobility rights increase social equity of the economic measure. Second, also as a consequence of the larger equity, acceptability of road pricing measure is improved. Recent results from a survey in Austin (Texas, USA) showed that acceptability of a pricing scheme based on mobility rights can be actually higher than usual pricing schemes (Kalmanje and Kockelman, 2003). Modelling simulations (again based on the Austin case) suggested that benefits in terms of welfare can be achieved as well (Kalmanje and Kockelman, 2004).

The role of the strategic model developed for the case of Genoa is to allow simulations of alternative mobility rights based schemes and analyse impacts against multiple criteria like mode split, average transport costs, households expenditure, authority revenues, travel times and emissions (both in linkage with a transport network model), population and activity location choices (in linkage with the land-use module).

## **OVERVIEW OF THE GENOA MOBILITY RIGHTS MODEL**

### **Methodological assumptions**

As mentioned above, the implementation of the mobility right principle requires the definition of several aspects. Many of these aspects have to be defined also for a model simulation of a mobility right scheme. Some other assumptions concern simplifications needed to reduce the complexity of the system and allow a synthetic representation through a model. In the following, both types of assumptions adopted in the Genoa model are presented.

The key assumptions concerning the implementation of the mobility right principle are the following:

- In the Genoa Mobility Rights Model (GMR model from now on), mobility rights are allocated with reference to private motorized trips (i.e. cars and motorcycles, since the latter are quite relevant in the Genoa area) and are distributed to all adult individuals in the study area (setting the threshold at the minimum car driving age, i.e. 18 years).
- The level of sustainable mobility is not fixed but can be changed, thus allowing the simulation of alternative definitions of sustainable mobility threshold.
- The initial allocation of mobility rights to each individual correspondent to the mobility threshold is defined on a quarter basis. However, quarters do not have a correspondence with actual months, i.e. education, working and holiday trips are represented in the same proportion in each quarter.
- Rules of consumptions that define the correspondence between rights and trips are based on the following elements: vehicle type, zone of destination, public transport service level for the O/D pair, time period of the day (peak or off-peak). For instance, a trip made off-peak using a small EURO-V car to reach a zone with a poor public transport service consumes less mobility rights than a trip made in peak hours using a large EURO-II car to reach a zone well served by public transport.
- Individuals can purchase additional mobility rights to cater for their mobility needs even if in such a way the overall number of rights in the area grows beyond the estimated sustainability threshold. However, the model is capable to simulate scenarios where rights can be purchased only as a result of trading of rights between individuals, thus only within the sustainable mobility threshold.
- The price of additional mobility rights does not depend on a demand/supply equilibrium but is defined in advance according to the following rule: within a certain number of additional rights their price is fixed, then it increases slowly and, after a second threshold, it grows much faster. This rule is used to deter individuals with a large purchasing power to keep their mobility habits unchanged.

The main assumptions adopted to reduce modelling complexity are:

- The initial allocation in terms of number of rights available in one quarter is converted into free trips allowed in the same period. This conversion is made by using the rules of consumption defined above, in order to use always “trip” as the unit of measure of mobility across the whole model. Also the purchase price of additional rights is

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expressed in terms of cost of additional trips (using the same rules of consumption) for the same reason.

- GMR model is an aggregated one. Analysis is made by population group and not by individual. In theory, individuals are endowed with  $n$  mobility rights for one quarter and, given the rules of consumption and their mobility behaviour, they consume mobility rights, purchase additional rights if needed and adjust their behaviour (e.g. suppressing some trips, using public transport for some other trips and so on). The Genoa model does not simulate the behaviour of each individual, but segments of individuals with a comparable mobility pattern. For instance, since mobility rights consumption depends on the vehicle type, the fleet composition of each origin zone is considered to estimate the average number of free trips correspondent to the initial endowment of mobility rights or to estimate the cost of an additional trip starting from each zone.

## **Model framework**

The GMR model is a System Dynamics model implemented in Vensim®. System Dynamics is an academic discipline started in the 1960s by Jay W. Forrester of the Massachusetts Institute of Technology (Forrester, 1969). System Dynamics was originally rooted in the management and engineering sciences but has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological, and ecological systems. In the field of System Dynamics, a system is defined as a collection of elements that continually interact and the term “dynamics” refers to change over time. A dynamic system is therefore a system in which the variables interact to stimulate changes over time and System Dynamics can be defined as a methodology used to understand how systems change over time.

The choice of setting up a System Dynamics model has two main justifications. First, this methodology is capable of modelling feedback effects and simulate adaptation over time rather than just provide an estimation of an equilibrium at a given time point. Second, the structure of a System Dynamics application is inherently open to further developments, addition of new modules, etc. Indeed, the GMR model is an evolution of a previous tool to which additional elements have been added or modified to provide a more detailed simulation of trips and of mobility right policy impacts.

The model is calibrated for the year 2006 (starting year of the simulation) and run for 10 years on a quarter basis.

The GMR model deals with the mobility to/from/within the urban area of Genoa. Genoa is the capital of the Liguria region in the North-West part of Italy and one of the major ports in the Northern Mediterranean sea, for both goods and passengers. With the sea on its front and Apennine close on its back, Genoa has experienced a peculiar development, extending in length much more than in width.

In the model the urban area is segmented into 25 zones corresponding to urban districts for which socio-demographic data is available. 3 additional zones group the municipalities belonging to the metropolitan area. 4 ‘external’ zones are used to represent origins and destinations of longer distance trips. Such ‘external’ zones are treated differently in the

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model. For instance, they are considered outside the area where mobility rights are allocated and they are also not included in the land use module.

In the GMR model only passenger demand is simulated. Such a demand is the result of trips generated by 8 main different population groups, identifying various combinations of income and working conditions. A further split of each group is made according to the car availability. Population groups are used for endogenous transport demand generation, based on average trip rates by six different trip purposes: commuting, education, business, shopping, personal business and others. Mobility of each group is kept separated through the various steps of the model because different behavioural parameters are associated to groups to simulate the impact of mobility rights schemes. Destination choice is modelled according to a gravitational-type algorithm where average generalised travel cost is used as impedance and different measures of zone attractiveness are defined according to the trip purpose.

Three different daily matrices are computed within the model: an average working day matrix, a Saturday matrix and a Sunday matrix. Such matrices are the result of generated home-based trips in four time periods – AM peak, AM off-peak, PM off-peak, PM peak – and the correspondent return trips (which can occur either in the same time of the day or not). Trip chains are not modelled.

Mode split is carried out on the home-based trips only (return trips are assumed to use the same mode) by means of a logit algorithm based on the generalised cost of alternative modes. Four modes are modelled: car, bus, rail (including metro) and motorbike (which are widely used in Genoa). Non-motorised trips are not modelled.

The Genoa model does not include a transport network, but data on generalized cost comes from a transport network based model (see the following paragraph).

The modelling process within the GMR model is shown in figure 1 below. The input information consists of the base O/D matrix resulting from the steps mentioned above and of the mobility rights scheme to be simulated. The base O/D matrix concern the overall number of trips in one quarter and is obtained by expanding the daily matrices of the average working day, Saturday and Sunday. The mobility rights scheme is defined by means of three main elements.

First element is the set of *rules of consumption* of the mobility rights. The number of rights consumed for one trip depends on: vehicle type used for the trip, zone of destination, public transport service level for the O/D pair, time period of the day (peak or off-peak). For each of these elements, the model needs to know how the consumption of rights change. The user defines that e.g. using a Euro-I car is two times 'more expansive' than using a Euro-V car or that travelling in off-peak time a 25% discount is applied.

Second element is the *pricing policy* for the mobility rights. As mentioned above, it is an assumption of the GMR model that after a first threshold purchasing additional rights is more and more expensive according to a linear increment and after a second threshold the linear increment is faster. It is up to the user to define the initial cost, the two thresholds and the two linear increments. Since the GMR model works with trips rather than with mobility rights, as mentioned above, the user does not define the cost of the mobility rights, but the cost of

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additional trip. However this is only for sake of simplicity, since the correspondence between trips and number of mobility rights needed to make them is fixed by the rules of consumption. So there is no any significant difference between the information that one additional mobility right costs X Euros and the information that an additional trip (which requires a certain number of mobility rights) costs X Euros.

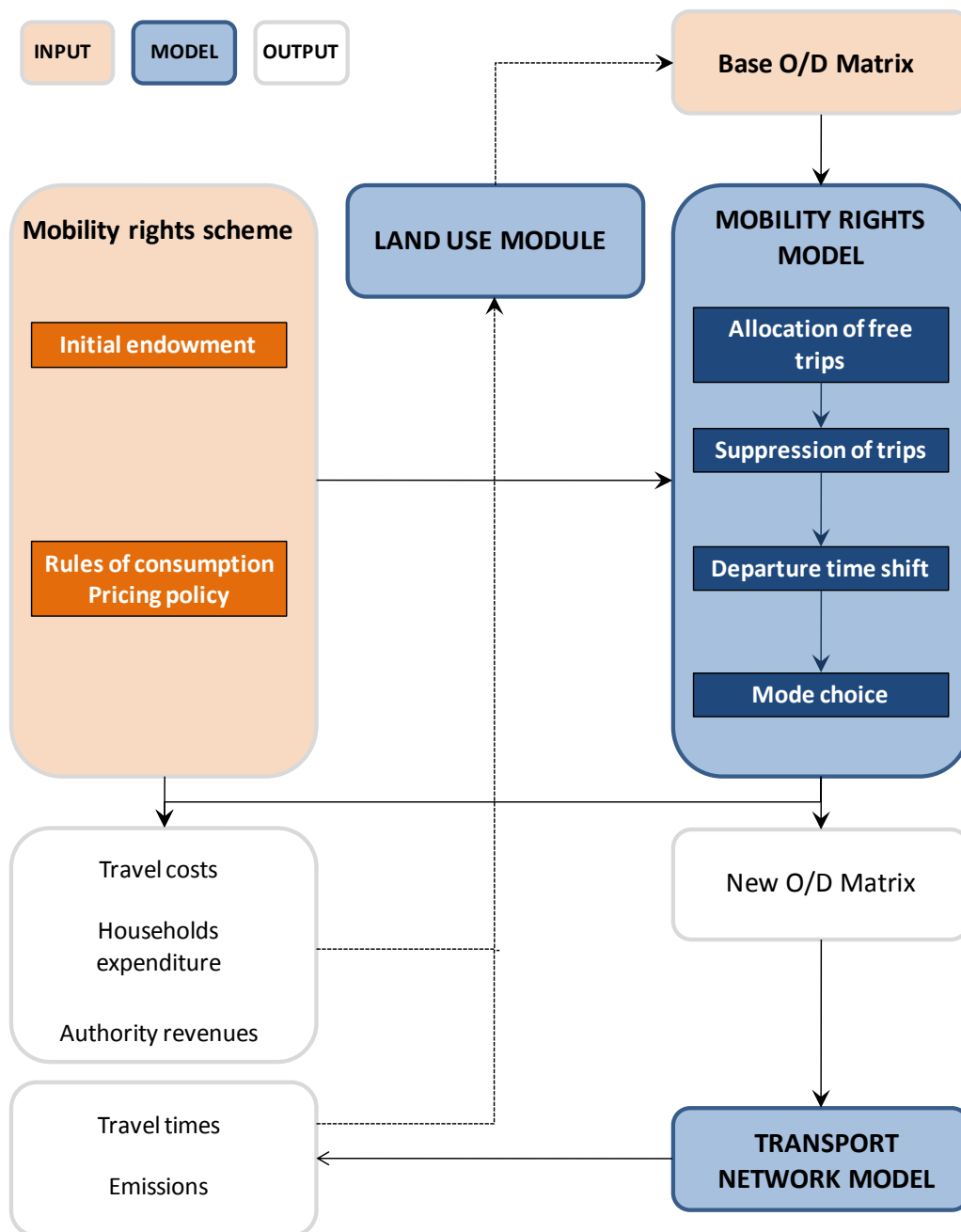


Figure 1 – Modelling process

Third element is the *initial endowment of free rights* evenly allocated across individuals. As explained above, since it works in aggregated terms, the model does not use directly these number of mobility rights but it computes the number of free trips for each demand segment (population group) corresponding to the number of free rights, given the average mobility pattern (fleet composition, distribution among destinations and among times of the day, etc.) and the rule of consumptions.

Using the input information, the GMR model starts a sequential process where the first step is the allocation of free trips among alternative trip purposes. The second step consists of estimating the number of suppressed trips. The third step is the estimation of trips shifted to an alternative time of the day (from peak to off-peak). The final step is mode choice to make the remaining trips (i.e. those not covered by the free endowment, not suppressed and not shifted to another time). These steps are described in some detail in the following chapter. The final outcome of the process consists of a new O/D matrix and of several summary indicators like travel costs, the household travel expenditure (distinguishing different population groups and especially low income and high income) and the authority revenues (provided that the mobility right scheme simulated includes this possibility). The new O/D matrix, translated back to the appropriate time span (e.g. peak time of an average working day) is transferred to a transport network model, which addresses the assignment of trips and comes up with additional indicators like travel times and road transport emissions. More details on the linkage between the GMR model and the transport network model are provided in the next section.

## **Linkages with a transport network model**

The GMR model does not include a transport network and works on an O/D basis. Yet, some impacts of a mobility rights scheme can be better appreciated on a link level, in particular travel times and emissions can be estimated with a greater detail if a network assignment is available. For that reason, the GMR model is conceived to work in linkage with the transport network model used at the municipality level to support transport planning at the urban level. This transport network model performs route choice of private and public road modes (separately) and is built using the VISUM software. A specific additional module is available to compute road emissions. The transport network model has 330 zones, of which the 28 internal zones of the GMR model are an aggregation.

The linkage between the GMR model and the network model does not consist of just breaking down (from 28 to 300 zones) and transferring the modified matrices of trips from the former to the latter, but it is more complex. First of all, the network model provides initial elements for the calibration of the GMR model: the reference base O/D matrices as well as the initial travel times and travel costs for each O/D pair. Travel times for the public transport are also used to classify O/D pairs in terms of quality of service, which is one of the elements that affect the consumption of the mobility rights.

Second, since one of the expected impacts of implementing a mobility rights scheme is the reduction of private transport activity, the mobility pattern in the area can be changed. On the one hand, a lower congestion can modify the attractiveness of the zones of the model, thus



leading to a different trips matrix. On the other hand, car can become attractive, despite the larger monetary cost, thus smoothing the initial mode shift towards alternative modes. In order to consider these impacts, the two models work according to an iterative approach as follows:

- The GMR model simulates the first-order impact of the mobility right scheme and provides new matrices (AM peak and PM peak) to the network model for two future years (the assumed first year of application of the scheme, e.g. 2014 and the final simulation year 2019).
- The network model performs the assignment of the new matrices for the two future years and provides the GMR model with new travel times for each O/D pair.
- The GMR model is given the trend of travel times by interpolating the values provided for the two future years (travel times at the base year will be unchanged since it is assumed that the scheme is applied in the future). Using new travel times, and taking into account new travel costs (i.e. including the cost of the mobility rights) the O/D matrices are re-estimated. If the linkage with the land use module is activated, also long term impact on households and activity relocation is taken into account. A new version of the O/D matrices for the two future years are forwarded to the network model.
- The network model performs the assignment of the new matrices for the two future years and provides final link-based results.

In principle, this approach could be iterated until a sort of convergence is achieved, but for the time being this is not envisaged to keep the simulation time shorter.

## **SIMULATION OF MOBILITY RIGHTS APPLICATIONS**

In this chapter, the sequential estimation process carried out by the GMR model to transform the initial O/D matrix is described. First of all it should be explained why the model uses a sequential process to address this task. Traditional four steps models treat trips like independent entities each subjected to some utility maximisation choice. However a mobility rights scheme intrinsically requires to consider the overall mobility activity of one individual in a given period of time (one quarter in this case). Decisions are required with reference to the whole mobility because the conditions faced for one trip depends on the decisions taken on previous trips. For instance, one trip can be made without charge provided that the endowment of free trips has not been consumed. Or the cost charged for one trip depends on how many mobility rights have been already purchased.

Furthermore, the responses available at the individual level are diverse: suppressing trips, shifting to a different mode, shifting to a different time of the day. Also in many traditional models, even without the complication of the dependency of choice conditions on previous decisions, such different reactions are dealt with in separate steps: demand generation, model choice, travel time choice.

Thus, even if the possibility of writing a complex algorithm capable to treat the whole problem in terms of a single optimization problem cannot be completely ruled out, the use of a sequential process seems an easier and more understandable solution.

At the same time, however, even if in principle one should follow how choice conditions evolve trip by trip (for each individual or for groups of individuals sharing the same mobility patterns) this is unfeasible and an aggregated treatment is needed at some point. In the following it will be clarified where and how such an aggregated treatment is used in the GMR model.

### **Allocation of free trips**

The first step of the sequential simulation is the allocation of available free trips among the different trip purposes. The assumption here is that individuals plan how to consume their initial amount of mobility rights. For instance, if the overall number of motorised trips in one quarter for one individual is 800 and the initial endowment of mobility rights is equivalent to 500 trips, it is implicitly assumed that the individual chooses in advance to use the available free trips to make some trips (e.g. all commuting and shopping trips plus some personal business trips) and then, for the remaining trips, choose among the available alternatives: give up some trips, shifting on another mode, purchase additional rights.

The user can define the hierarchy within the trip purposes. For example, it can be assumed that the following hierarchy applies:

- commuting,
- business,
- education,
- shopping,
- personal business,
- other purposes.

Then the model proceeds as follows (separately for each population group).

1. The total number of commuting trips ( $T_c$ ) in a quarter is compared to the amount of free trips available ( $FT$ ). If  $T_c < FT$  then all commuting trips are assumed to be made for free; otherwise  $FT$  commuting trips will be made for free and the remaining part is pending;
2. If in the previous step the whole amount of free trips has been used, all remaining trips in the quarter for any other purposes will be pending. Otherwise, the number of business trips ( $T_b$ ) is compared to the remaining number of free trips ( $FT - T_c$ ): If  $T_b < (FT - T_c)$  then all business trips are assumed to be made for free; otherwise ( $FT - T_c$ ) business trips will be made for free and the remaining part is pending;
3. So on for the remaining trip purposes.

Different hierarchies of trip purposes can be defined in the model since the ranking can change across population groups. However, the difference is at least partially reflected in the different number of generated trips. For instance, the population group “students” will not have commuting or business trips in the top of the hierarchy, but at the same time, this group will not generate such kind of trips and therefore education trips will be considered first even they are not in the first place of the ranking.

Another assumption is that the allocation of free trips does not depend on their characteristics. It could be thought that individuals try to maximise the number of trips they

can make using their mobility rights endowment. Or individuals could choose to use rights for those trips they want to do by car, irrespective of their purpose, because they need departure time flexibility or for any other reason. If one of these criteria are applied, some trips for each purpose could be selected, rather than all trips for some purposes. However, decision rules depending on the nature of trips cannot be modelled without simulating trips in much more detail than feasible in the GMR model.

### **Estimation of suppressed trips**

The second step of the sequential simulation is the estimation of the number of trips suppressed. The assumption is that individuals may not be willing to stick on their motorised private mobility habits when using their car (or motorbike) becomes more expensive and that part of the trips are not shifted on public transport but just avoided (or transferred on non-motorised modes, not considered in the GMR model). Actually, a revision of the private mobility behaviour is one of the goals of the mobility rights approach.

In the GMR model the trips suppressed are estimated on the ground of a fixed travel (generalised) cost budget. Already in the 1960's it was suggested that people dedicate a fixed amount of resources (money and time) for travelling. Evidence supporting this assumption is not conclusive, but travel expenditure and travel time are generally quite stable across time and space (Schafer, 2000). At the level of detail of the GMR model, a fixed budget dedicated to motorised trips can be accepted as a reasonable assumption to simulate individual behaviour.

The cost of making the private motorised trips not covered by the free mobility rights endowment is compared to the reference travel budget (a different budget is defined for each population group). The budget is exogenous but it can be modified if average travel time changes in order to reflect that if e.g. travel speed increases, a smaller part of the fixed budget is spent under form of travel time. However, since travel time also affect the trip distribution phase, a faster travel speed can also lead to larger travel distances. Furthermore, it will be explained later that the concept of a fixed budget is used also in the land use module, where travel expenditure is compared to housing expenditure. Therefore, improving travel speed can also have an impact on residential choices (e.g. living in a more central zone where floorspace rent is higher).

The budget is compared to the cost of making the residual trips. According to the pricing policy, additional trips have a certain cost until a certain threshold, beyond such a threshold the cost is increasing. Making reference to figure 2 below, the cost for making  $N$  additional trips is the integral of the curve from 0 to  $N$ . Integrals cannot be computed in the model, nevertheless approximated formulae based on the area of the trapeziums described by the curve. Namely, given the symbols of the figure, the cost of making  $N$  additional trips can be estimated as follows:

If  $N \leq A$ , the total expenses for the additional trips is:

$$C = K * N \quad [1]$$

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Where:

K is the base price for one additional trip (depending on the cost of mobility rights).

A is first threshold of the pricing policy.

If  $A < N \leq B$ :

$$C = \left( K * A + \frac{[2K + r * (N - A)] * (N - A)}{2} \right) \quad [2]$$

Where:

B is the second threshold of the pricing policy.

r is the slope describing the price increase in the second phase of the pricing policy.

If  $N > B$ :

$$C = \left( K * A + \frac{[2K + r * (B - A)] * (B - A)}{2} + \frac{[2K + 2r * (B - A) + s * (N - B)] * (N - B)}{2} \right) \quad [3]$$

Where:

s is the slope describing the price increase in the third phase of the pricing policy.

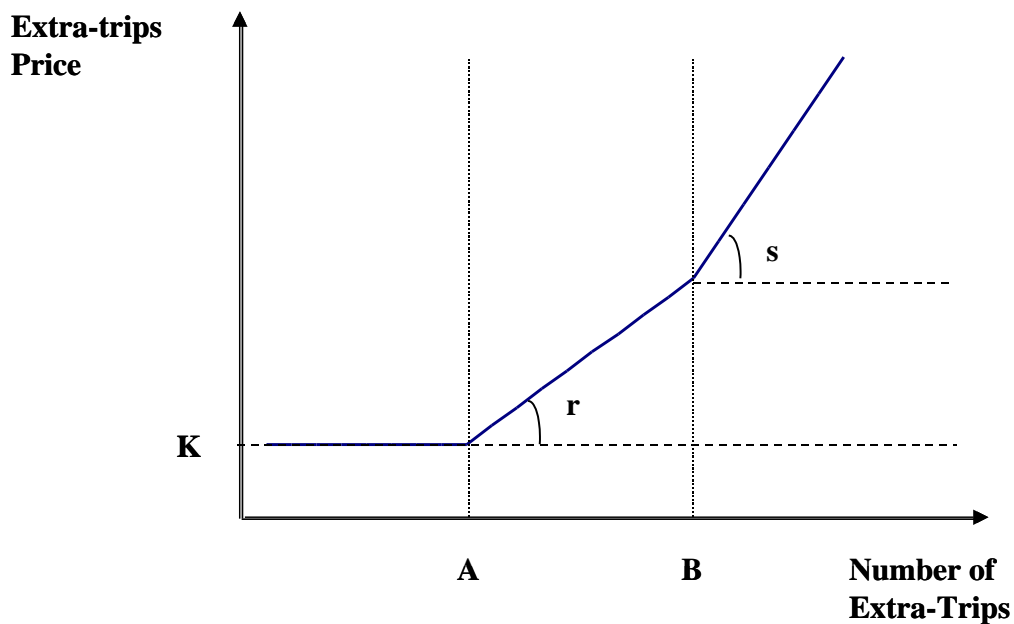


Figure 2 – Pricing Policy

Using the appropriate formula, given the total available expenditure (budget Bu), the corresponding number of trips can be estimated. When the formulae [2] and [3] above are rewritten with N as the unknown term they become quadratic equations. In such cases the largest root is taken, computed as follows.

Bu<sub>A</sub> and Bu<sub>B</sub> are defined as the budget corresponding to A and respectively B Extra-trips, . Then:

If  $Bu_A < Bu \leq Bu_B$ :

$$N = \frac{- (K - rA) + \sqrt{(K - rA)^2 - 2r \left[ KA + \frac{(-2KA + rA^2)}{2} - C \right]}}{r} \quad [4]$$

If  $Bu > Bu_B$

$$N = \frac{- [K - r(B - A) - sB]}{s} + \frac{\sqrt{[K - r(B - A) - sB]^2 - 2s \left[ -B \frac{(2K + 2r(B - A) - sB)}{2} + KA + \frac{(-2K + r(B - A))(B - A)}{2} - C \right]}}{s} \quad [5]$$

The value of  $N$  estimated with the formulae [4] and [5] is not taken as such in the model. A slightly higher number is used instead to take into account that individuals can decide to shift some trips to the public transport or to a different time of the day and so they can make those trips at a lower cost. However, departure time change and mode choice are modelled in separate steps for sake of simplicity so the potential number of motorised trips available for a given budget is corrected upwards in this step.

Like for the allocation of free trips, and for the same reasons already explained, the nature of the trip is not considered in the estimation of suppressed trips. The formulae provide the number of feasible trips given the available budget irrespective of their purpose or distance or zone destination. However, it would be unreasonable to assume that working trips can be suppressed as easily as leisure trips can. For this reason, the model checks that the expected number of commuting, business and education trips can be made given the available budget. If not, the number of trips is increased. The difference between base trips and feasible trips according to the budget (i.e. suppressed trips) are subtracted proportionally to all other purposes and to all destinations.

A further check can be activated if the mobility rights scheme is assumed to allow individuals to purchase additional mobility rights only if some other individuals are willing to sell part of their endowment. In other terms, this means that the total number of private motorised trips cannot exceed the number of trips equivalent to the initial distribution of mobility rights. So the model has to check whether this condition is satisfied, otherwise the number of suppressed trips is increased to meet this exogenous requirement. Again, a tolerance is applied to take into account that part of the private motorised trips will be shifted on public transport and therefore will not make use of mobility rights.

## **Departure time change**

The estimation of private motorised trips shifted from peak time to off-peak (the opposite has no reasons to occur) is estimated by simply applying cost elasticities. Elasticities are applied

to the cost difference between peak and off-peak according to the rules of consumption. Elasticity parameters are different in the model according to population groups and to trip purpose. Commuting and education trips are considered totally inelastic since their departure time is generally not an individual choice.

## Mode split

The mode split step is basically a repetition of the same calculation made to estimate the base O/D matrix with the only difference that generalised cost of private modes is modified to take into account the additional expenditure for the mobility rights. Given the pricing policy, this additional expenditure is increasing after a certain threshold. However, it would be obviously unfeasible to repeat the mode split for each additional trip. Therefore the average additional cost per trip is estimated in two steps:

1. An initial average additional cost is computed by using equations [1] to [3] divided by  $N$ .
2. This cost is therefore smoothed (i.e. revised downwards) to take into account that the first step estimation is influenced by the larger price of last trips, while for an initial number of trips the extra-cost would be much lower.

Table 1 below includes some simplified numbers to explain the need for this second step.

Table 1 – Example of generalised costs

Trip N°	Generalised cost				Mode choice
	Car base cost	Car Extra cost	Car total cost	Bus cost	
1	5	1	6	8	Car
2	5	1	6	8	Car
3	5	1	6	8	Car
4	5	1	6	8	Car
5	5	1	6	8	Car
6	5	2	7	8	Car
7	5	3	8	8	Car
8	5	4	9	8	Bus
9	5	8	13	8	Bus
10	5	12	17	8	Bus

Let's assume that car and bus are the only two alternative modes and that mode choice is made for 10 trips. Base generalised cost of car is 5 Euros, while base generalised cost of bus is 8 Euro. However, since mobility rights have to be purchased for using car, there is an additional cost. Given the pricing policy, the additional car trip cost is 1 Euro for the first five trips, then the cost increases up to 4 Euro for the eighth trip and finally reaches 12 Euros for the tenth trip. If each trip is examined separately and if the mode with the lowest generalised cost is chosen, car should be selected for first seven trips and bus for the last three trips.

If we want to use a logit formula to estimate mode split for the whole ten trips, we can compute the average additional cost, which is 3.4 Euros. This means that the logit formula will provide the share of car and bus using 8.4 Euros (5+3.4) as the average generalised cost

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of car and 8 Euros as the generalised cost of bus. Quite clearly, the share of car will be much lower than the 70% (7 trips out of ten) that the trip by trip analysis suggested. This is the reason why the average cost has to be smoothed before to apply a logit model. The size of the smoothing is the result of empirical tests also given the parameters of the logit formula.

The outcome of the mode split step consists of the new O/D matrices. After the required transformations in terms of period of time, they can be sent to the network model for the link based analysis.

At the same time, after the mode split is completed, the model is able to compute the travel expenditure for each population group as well as the revenues of the public authority if this is allowed to sell additional mobility rights.

## **MODELLING LONG TERMS EFFECTS**

### **Outlook of the land use module**

The land use module is conceived to simulate the location of households and activities in the study area (the 28 internal zones of the GMR model). The aim is to fully integrate this module in the GMR model, but so far it has been developed as an external module especially for reasons of computing size.

The module simulates endogenously both demand and supply side of land use. Demand is represented by 20 households groups and 6 economic sectors. The households groups are defined according to employment status of adult components, presence of underage components, income and house availability (property or rent). The economic sectors cover the retail sectors as well as services and manufactures, but large private activities like malls or big factories as well as public services like schools or hospitals are modelled separately (i.e. they affect location decisions, but their own location is entirely exogenous).

The supply side consists of five different house types while non-residential floorspace is not segmented.

The land use module manages three main tasks:

- Estimate the number of households and activities (for each segment) located in each zone in each simulation period,
- Estimate the supply of floorspace (for each type) and its price in each zone in each simulation period,
- Estimate (motorised) transport demand O/D matrices to be used in the GMR model.

The land use module works in an aggregate manner, so it estimates how many households of one segment leave one given zone X and how many households of one segments locate in another zone Y, but it cannot provide any information about how many households move from zone X to zone Y.

The relationships implemented in the module take some inspiration from other urban model built in System Dynamics (Steer Davies Gleave, 2002; Büttner et al., 2003; Haller et. al.

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2007). On the demand side, the module estimates the number of households and activities that want to leave their residence building upon various elements like the overall floorspace supply (the more houses available the more likely that some households want to move) or the share of rented houses (households living in rented dwellings move more easily) or the average floorspace price level in the area (if the price increases some households might be in need of moving because they cannot afford to pay the rent). Outward and inward migration is also modelled.

Households and activities that want to move choose a destination zone according to elements like floorspace availability, floorspace price, zone accessibility, environmental quality of the area. Accessibility is defined as a function of average generalised cost to move in or out the zone and of attractiveness of the zone in terms of e.g. jobs, shopping opportunities, public services (for different households groups, different elements are considered, for instance, schools are included in the attractiveness of households including underage components but not for the other segments). If the housing cost in one zone plus the average transport cost from that zone is larger than a maximum budget defined for the household (different households types have different budgets) the attractiveness of the zone is set to a very low value. This way less affluent households are pushed away from zones where floorspace becomes very expensive.

On the supply side, the stock of floorspace in each zone is the result of the inflow of new buildings and the outflow of demolished buildings. New buildings depend on available land, average zone accessibility and demand pressure in the zone (demand/supply ratio). Accessibility and demand/supply ratio are also factors determining floorspace rent, together with environmental quality and one exogenous variable reflecting the use of savings at the macroeconomic level. This variable accounts for rent changes not depending on the dynamics of study area but nevertheless of great importance. In fact, at least in Italy housing rents have increased dramatically over the last twenty years because a large share of savings have been invested in the estate market. Differences across zones due to local conditions (accessibility, demand pressure, etc.) has remained but the base level has grown in general and this is the effect that the exogenous variable try to capture. It should be mentioned that the absolute rent is used in the module (rather than e.g. differences between zones) to allow the comparison of housing plus transport expenditure to the household budget as explained above.

The population groups used for the endogenous generation of transport demand are 'produced' by the households groups in the land use module. Each household segment 'gives rise' to a certain number of individuals of given population groups. For instance, one high income household with two or more occupied adults and some underage components 'produces' employed individuals, self-employed individuals and students. Therefore, the location choices modelled in the land use module are directly reflected in the mobility demand.



## **Linkages between Mobility Rights model and land use module**

The main purpose of the land use module when linked with the GMR model is to allow for the simulation of long terms impacts of the implementation of mobility rights schemes. The introduction of a mobility rights policy has the primary effect of changing personal travel costs. This change affects the results of the land use module through three main mechanisms.

The first mechanism is the modification of the attractiveness of zones as destination for trips. This mechanisms works in the distribution phase rather than in the overall land use modelling and can be considered a medium term effect. The attractiveness changes because different costs are needed to reach zones and, in general, cost variation will be not the same for all zones especially if the consumption rules set out that travelling to some areas (e.g. city centre) is more 'expensive'. Through the interaction with the transport network model also travel times can change (e.g. due to lower congestion on some links), thus affecting accessibility – that depends on generalised cost – and, in turn, attractiveness.

The second mechanism is the modification of zones attractiveness for the location choice algorithm. Accessibility is one of the elements that enter in the index of attractiveness used in the land use module to select the new living zone for households willing to move. One difference with respect to the impact of accessibility on destination choice, where all trips are influenced at the same time, is that in the land use module only a fraction of households are affected by the new accessibility, so the location changes occur more gradually over time.

The third mechanism is the modification of the transport cost summed to housing cost and compared to households budget to define whether dwellings in a given zone are affordable. Given the mobility rights mechanism, transport cost changes differently across population segments, namely high income households should face a cost increase, while low income households could receive a compensation.

The combination of these three mechanisms gives rise to long term modifications in locations: therefore, transport demand patterns and transport impacts like congestion or pollution can be different from the short term effects of the mobility right scheme.

## **CONCLUSIONS**

This paper describes the Genoa Mobility Rights (GMR) model, a system dynamics model aimed at simulating the impact of the implementation of a mobility right scheme in the urban area of Genoa. The model uses a sequential procedure to estimate the change of personal motorised mobility in one quarter as result of a the introduction of a given endowment of free mobility rights distributed to all people in age coupled with a pricing policy for purchasing additional rights (or selling unused rights of the initial endowment). The key features of the policy (i.e. number of free rights distributed, cost of additional rights, etc.) can be set by the user to test alternative design of the scheme. When Linked to the transport network model used to support transport planning in Genoa, the GMR model can provide link based result,

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while the linkage with a land use module, also developed in Vensim®, allows for the simulation of long term impacts.

The GMR model is the enhancement of a previous model developed in 2005. It is being developed as one activity of the European project DEMOCRITOS, whose results are expected for late 2011. In the course of the work, one crucial task will be the revision of the elasticity parameters used in the model to simulate behavioural responses. Such parameters had been estimated partially from literature and partially from direct surveys for the previous model, but a larger set of values is needed. Furthermore, not all the elasticity values used in the previous model were satisfying and therefore improvements are desirable on this side.

Once calibrated, the GMR model will be used to simulate a set of alternative mobility rights schemes that will be defined in the DEMOCRITOS project and will be also simulated, with different tools, in other three case studies in Europe: Craiova, Stuttgart and Lisbon.

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## **REFERENCES**

- Bielefeldt C., L. Persia, G. Giustiniani, J. Knockaert, P. Bonsall, T. Tretvik, H. Condie, M. Maher, A. Martino (2008). User Reaction and Efficient Differentiation of Charges and Tolls - Results from Urban Case Studies. Deliverable D9.1 of the DIFFERENT project for the European Commission. Edinburgh.
- Büttner J., K. Spiekermann and M. Wegener (2003). Review Report on Environment Land Use Feedback, Deliverable D2 of the PROPOLIS project for the European Commission. Dortmund.
- Coase, R. (1960). The Problem of Social Cost. *Journal of Law and Economics*, 3, 1-44.
- European Commission (2008). Proposal for a Directive of The European Parliament and of The Council amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures. Brussels.
- Evidenze (2006). Il Modello dei Crediti di Mobilità - Progetto Crediti di Mobilità per Genova. Milano.
- Forrester J.W. (1969). *Urban Dynamics*. Pegasus Communications, Waltham, MA.
- Haller R., G. Emberger and P. Pfaffenbichler (2007). National Scale Land-Use and Transport Modelling: The MARS Austria Model. Paper presented at the European Transport Conference 2007, Leeuwenhorst.
- Kalmanje S. and K. M. Kockelman (2003). Credit-Based Congestion Pricing: A Policy Proposal and the Public's Response. *Transportation Research Part A*, 39, 671-690.
- Kalmanje S. and K. M. Kockelman (2004). Credit-Based Congestion Pricing: Travel, Land Value and Welfare Impacts. *Transportation Research Record*, 1864, 45-53.

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- Raux, C. (2008). How Should Transport Emissions Be Reduced? Potential for emission trading Systems. JRC Discussion Paper No 2008-1, OECD-ITF.
- Schafer A. (2000). Regularities in Travel Demand: An International Perspective. *Journal of Transportation and Statistics*, 3 Vol.3, 1-31.
- Steer Davies Gleave (2002). The Urban Dynamic Model. Technical note.
- Viegas, J. (2001). Making Urban Road Pricing Acceptable and Effective: Searching for Quality and Equity in Urban Mobility. *Transport Policy* 8 (2001), pp. 289-294.