A MICROECONOMIC TRIP GENERATION EQUILIBRIUM MODEL

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1. MOTIVATION AND OBJECTIVES

The basic feature of the trip generation phenomenon is that trips are derived from activities demand, which is well known according to Domencich and McFadden (1975). However, it has not been properly incorporated into a theoretical framework and actual models. They try to explain the trip generation without explicitly considering that a trip is only a requirement for the individual to perform an activity. The trip itself has no explanation, it is justified by the wish or need of going shopping or performing social visits, working, studying or having fun. This characteristic of mobility is one of the main research matters of the activity base approach (Kitamura, 1988).

These remarks show an alternative approach to study the trip generation, similar to that used in the on the activity based approach, but with traditional modeling elements : instead of a direct study to reproduce generation of trips, we first study the phenomenon of activities demand and then derive the trip generation. Although the study of activities demand is a complex task, fortunately a microeconomic model of the kind have been developed which will be used for our purpose . Once the activities demand is known, it is possible to calculate the corresponding travel demand, by introducing the activity chaining concept which is concerned with the concatenation of activities in one trip chain. This concept, however, only makes sense at an individual level where equilibrium of choices take place, which is the reason to maintain that disaggregation level throughout the framework. In other words, we leave home as the basic unit of analysis for the trip generation, although it maintains its role to describe socioeconomic characteristics.

The objective of this work is to develop a framework in order to study the trip generation in order to obtain a better theoretical understanding of people's mobility a an operational model. A better understanding means to know the variables which influence on the phenomenon and how it is affected; particularly, it is important to know what is the role of the transportation- land use system and the role of socioeconomic characteristics of the individual in the travel demand. This paper does not present the operational model of trip generation.

The paper is organized so that in the next chapter the theoretical approach is developed and, in the following one, the obtained results are commented emphasizing the methodological contribution of the approach

2. DEVELOPMENT OF THE THEORETICAL APPROACH

The theoretical approach is composed by two main elements; a model of activities demand and a conditional model of trip demand. These two elements are then linked in order to produce a new trip generation model.

2.1 Activities Demand

In order to study the individual participation in activities, the microeconomic behavioral model developed by *Jara-Díaz et al.* (1994) is used. Here, the individual welfare come from performing activities described by three attributes : time spent and the quality of each activity, plus duration of the trip to reach that activity. Under the assumptions of the consumer's theory, the individual tries to maximize his/her welfare taking into account that he/she has a limited period of time and budget plus the fact that activities are somehow distributed in the space which restrains the quality of activities available at each site.

Jara-Díaz et al. paper assumes that the individual's behavior is represented by the following consumer optimization problem :

$$
\begin{aligned}
&\underset{q,t,x}{Max}\; U((q,\tau),tv) \\
&sa \\
&\sum_k \tau_k + \sum_k tv_k \le TT \\
&p \cdot x + \sum_k c_k \le I + \sum_k \omega_k \tau_k \\
&R(x,q,\tau,z) = 0 \\
&f_k \ge f_k^{min} \quad \forall k = 1,\ldots,K
\end{aligned}
\tag{1}
$$

where q, τ y tv denote activities quality and time spent and travel time, associated to every type of activity (k), x the vector of goods consumed by the individual and p the vector of prices of these goods, TT the total time available in the modeling period, I the individual's fixed income in the TT period, ω_k the wage rate of the k-th activity. R represents the *spatial constraint*, which is a technological relationship between goods, quality, time and zone characteristics where activities are carried out. It states that, in order to be able to perform activities with a certain quality level and duration (q, τ), it is necessary to consume certain quantity of goods (x) and that the zone where the activity is to be performed needs to have certain characteristics (z), which insure the feasibility of performing activities with q quality. For example, to enjoy a concert, it is required a good theater which will be only available in certain places and it is also required to buy a ticket and spend time.

Additionally, the following conditions are defined :

$$\left.\begin{aligned}\tau_k &= f_k\overline{T}_k\\ B_k &= B_k(f)\\ tv_k &= B_k\bar{t}_k\\ c_k &= B_k\bar{c}_k\end{aligned}\right\}\quad \forall k = 1,\ldots,K \tag{2}$$

The first one expresses the total time devoted to activity k (τ_k) in terms of visits, as the product of its performing frequency (f_k) times its average duration $(\overline{T}_k)$. The second condition explicitly states the derived character of transportation demand, by defining the number of trips associated to the activity k (B_k) as a function of the frequency of performing all activities, allowing the possibility of chaining activities in one round trip. Finally, travel time and cost of trips associated to each activity is expressed in terms of the average trip travel time $(\bar{t}_k)$ and the average trip cost $(\bar{c}_k)$ for each activity k.

It is important to mention that following *Jara-Díaz et. al*'s framework trips destinations and mode choices are assumed to be known, therefore, $\bar{t}_k$ and $\bar{c}_k$ correspond to the weighted average (by the number of trips) of the trip time and cost associated to the activity. The same assumption holds for the frequency and the number of trips. Consequently, in this work trip generation is analyzed assuming destination and mode choice as known or, in modeling words, given the trip distribution and the mode share.

According to the above mentioned optimization problem, every individual chooses the activities set (time spent and quality and goods) which maximize their utility and satisfy the time and income availability restraints. In order to solve this problem, the Lagrange method with the optimization variables (q,τ,x) yields the following system of $(3K+2J+2)$ equations :

$$\begin{aligned}
&q_k\frac{\partial L}{\partial q_k}=0\,,\quad \tau_k\frac{\partial L}{\partial \tau_k}=0\,,\quad \eta_{f_k}\frac{\partial L}{\partial \eta_{f_k}}=0 \qquad \forall\, k=1,\ldots,K\\
&x_i\frac{\partial L}{\partial x_i}=0\,,\quad \alpha_i\frac{\partial L}{\partial \alpha_i}=0 \qquad \forall i=1,\ldots,J\\
&\mu\frac{\partial L}{\partial \mu}=0\,,\quad \lambda\frac{\partial L}{\partial \lambda}=0
\end{aligned} \tag{3}$$

where $\{1,\ldots,K\}$ is the set of available activities, $\{1,\ldots,J\}$ is the set of consumption goods and L is the Lagrange function of the consumer problem :

$$\begin{aligned}L &= U((q,\tau),tv)+\mu(TT-\sum_k\tau_k-\sum_k tv_k)+\lambda(I+\sum_k\omega_k\tau_k-p\cdot x-\sum_k c_k)\\ &\quad+\sum_i\alpha_i R_i(x,q,\tau,z)+\sum_k\eta_{f_k}(f_k-f_k^{min})\end{aligned} \tag{4}$$

with μ, λ y η_f the Lagrange multipliers that represent the gain in utility produced by a marginal relaxation in the time, income and minimum frequency constraints, respectively. α_i is the multiplier associated to the i-th spatial constraint and its value is always different from zero ; it may be interpreted as the potential benefit of changes in land use.

From equations (3) :

$$q_k \frac{\partial L}{\partial q_k} = q_k [\frac{\partial U}{\partial q_k} + \sum_i \alpha_i \frac{\partial R_i}{\partial q_k}] = 0 \qquad \forall k = 1,\ldots,K \tag{5}$$

$$\begin{aligned}\tau_k \frac{\partial L}{\partial \tau_k} = f_k \frac{\partial L}{\partial f_k} &= f_k [\frac{\partial U}{\partial f_k} - \mu \overline{T}_k - \mu \sum_j \frac{\partial B_j}{\partial f_k} \overline{t}_j + \lambda \omega_k \overline{T}_k + \\ &\quad - \lambda \sum_j \frac{\partial B_j}{\partial f_k} \overline{c}_j + \sum_i \alpha_i \frac{\partial R_i}{\partial \tau_k} \frac{\partial \tau_k}{\partial f_k} + \eta_{f_k}] = 0 \qquad \forall k = 1,\ldots,K\end{aligned} \tag{6}$$

$$x_i \frac{\partial L}{\partial x_i} = x_i [\sum_j \alpha_j \frac{\partial R_j}{\partial x_i} - \lambda p_i] = 0 \qquad \forall i = 1,\ldots,J \tag{7}$$

To simplify these equations we assume that the minimum frequency restrictions are not active ($\eta_{f_k} = 0, f_k > f_k^{min}$) and time and income restrictions are bounded according to the non local saturation condition (Varian, 1992, Chapter 7).

Therefore, we have a system of $(2K + J + 2)$ equations with the same number of unknowns (q, f, x, μ, λ). After a some algebra, one can obtain from equations (5) to (7) the individual's theoretical optimal quality and frequency for each activity. The expressions are :

$$q_k^* = q_k^o \, exp[\frac{\lambda}{V \varepsilon_{q_k}^U} \Delta(p \cdot x)] \tag{8}$$

$$f_k^* = \frac{V \varepsilon_{f_k}^U}{CG_k} \tag{9}$$

where q^o and $\Delta(p \cdot x)$, represent, for some observed equilibrium situation, the quality level, and the variation in goods expenditure . $\varepsilon_{q_k}^U$ and $\varepsilon_{f_k}^U$ are the elasticity of the utility regarding the quality and frequency of the k-th activity, and $V \equiv U(q^*, \tau^*, tv^*)$ is the indirect utility function at the optimum activities choice, i.e., the maximum utility that could be reached considering the individual's constraints.

The term $CG_k = \lambda[\overline{T}_k (M_k - \omega_k) + \sum_j \frac{\partial B_j}{\partial f_k} \overline{c}_j] + \mu[\overline{T}_k + \sum_j \frac{\partial B_j}{\partial f_k} \overline{t}_j]$ is the generalized marginal net cost associated with performing activity k. The first term is the monetary cost, with $M_k = \dfrac{\partial (p \cdot x)}{\partial \tau_k}$ the marginal increase in the expenditure due to an increase in the dedication ; then, the monetary cost includes the change in income (expenditure minus wage rate) plus the change in transport cost due to the increase in frequency. The second term is the time cost, including that spent in performing the activity and extra travel time.

It is important to mention that in equations (8) and (9) all functions are implicitly evaluated at the optimal. To obtain more explicit expressions of the optimal quality and frequency, it is necessary to have a particular utility function and a relationship between activities and trips.

2.2 Travel Demand

In this section the relationship between activities performed and required trips is developed. Hautzinger (1981) work proposes a statistical model assuming non residential activity as known and forecasts the expected number of trips necessary to perform those activities. Here we use combine the this model with the consumer optimal activities model to generate the final trip generation model.

One of the main variables of Hautzinger's model is the number of cycles (return trips) that the individual performs from home to carry out his/her activity pattern. This activity chaining study is the main objective of the Hautzinger work. A cycle is defined as a temporal and spatial sequence of activities, where the first and the last activity are performed at home. Denoting the number of cycles by C, the total frequency of performing non residential activities by f and number of trips by B, the following condition holds :

$$B = f + C; \quad 1 \le C \le f \qquad \forall f \ge 1 \tag{10}$$

Therefore, $f + 1 \le B \le 2f$. The minimum number of trips is reached when the individual performs all the activities within a single cycle and the maximum is reached when the individual returns home after each activity. This reasoning also justifies the constraint on the number of cycles. Please note that the number of cycles is equal to the number of leaving or return home trips, then the relationship between B, f y C is compatible with usual differentiation of trips in known trip generation models, which distinguish home based (BH) and non-home based (NBH) trips. Then, it is easy to deduce that (Goulias *et al.*, 1990) :

$$\begin{aligned} BH &= 2C \\ NHB &= B - BH = f - C \end{aligned} \tag{11}$$

On the other hand, the number of cycles is related to the frequency level. For instance : if $f = 1$, then $C = 1$; if f is big then C must tend to be small in proportion to the frequency because otherwise the number of trips requires to much expenditure in time and cost ; forcing to the individual to perform short duration activities and to spend most of his/her available time traveling.

Following Hautzinger work, uncertainty in the individual's behavior leads to assume that the frequency and total number of cycles are discrete non negative random variables ; therefore, the number of trips is also a random variable. Particularly, the conditional expected total frequency is :

$$\begin{aligned} E(B|f) &= f + E(C|f) \\ &= f + f\,\overline{p}_f \end{aligned} \tag{12}$$

where $\overline{p}_f$ is the average conditional probability of return trips, i.e. an aggregated measure of the probability to return to home after performing any activity, if f activities are performed.

Hautzinger shows that an empirically suitable expression for $\overline{p}_f$ is :

$$\overline{p}_f = e^{-\alpha(f-1)} \tag{13}$$

where α is the individual's propensity to chain activities. So, considering an α value, the individual will return home more often the lower the frequency. On the other hand, having a frequency value, the individual will return home more often the lower of his/her propensity value.

Finally, the expected number of cycles, conditional on the total frequency value, becomes $E(C|f) = f\,e^{-\alpha(f-1)}$. Replacing this result in equation (12) the conditional expected number of trips is obtained :

$$\overline{B}(f) = E(B|f) = f(1 + e^{-\alpha(f-1)}) \tag{14}$$

It is clear that the number of trips is bounded by $f \le \overline{B}(f) \le 2f \quad \forall f \ge 0$, as it is shown in Figure 1. This figure allows to see that $\overline{B}$ function exactly reproduces the number of trips for two particular values (but very important ones) of the total frequency : 0 and 1, whose corresponding trips values should be 0 and 2. This is so, because if off-home activities are not performed, then it is not necessary to travel and if only one activity is performed, two travels are required, because it is assumed that the individual returns home at least once during the modelling period. The importance to the correct forecast in these two cases is found on that the they represent the most common values of total frequency in real data.

As the decision variable of the above behavior model is the frequency disaggregated by type of activity, it is necessary to extend the Hautzinger work to calculate the number of trips associated to each activity type or trip purpose. A simple alternative is to consider that :

$$\begin{aligned} \overline{B}_k(f) &= E(B_k|f) = f_k + \delta_k E(C|f) \\ &= f_k + \delta_k f\, e^{-\alpha(f-1)} \end{aligned} \tag{15}$$

where $\sum_k f_k = f$ y $\sum_k \delta_k = 1$. The variable $0 \le \delta_k \le 1$ allow us to associate to activity k a proportion of the return trip to each visited activity in the cycle, so as to spread the costs of the return trip between visited activities. Also, by construction $\overline{B}(f) = \sum_k \overline{B}_k(f)$.

It is very important to emphasize that the presence of the total frequency in equation (15) the trips demand by activity (or purpose) is dependent on other activities trips demand, which is reasonable since activities share a finite time budget and affects a common utility.

2.3 Travel Generation Model

In order to derive an operational trip generation model, assume that the direct utility function has the *Cobb-Douglas* form, i.e. :

$$U((q,\tau),tv) = \rho \prod_k q_k^{\upsilon_k} \tau_k^{\beta_k} tv_k^{\gamma_k} \tag{16}$$

which has the main properties required by utility functions. If other type of function is used, different results with regards to functional form swill be obtained but the main theoretical concepts remain.

As $tv_k = B_k(f)\bar{t}_k$, the utilities elasticities regarding quality and frequency are the following :

$$\begin{aligned} \varepsilon_{q_k}^U &= \upsilon_k \\ \varepsilon_{f_k}^U &= \beta_k + f_k\left(\frac{\gamma_k}{B_k} + \psi\eta\right) \end{aligned} \tag{17}$$

Additionally, if we assume that the number of trips may be modeled by its conditional expectation, $B_j(f) = \overline{B}_j(f)$, we can obtain from the equation (15) the following equation :

$$\frac{\partial B_j}{\partial f_k} = 1_{k=j} + \delta_k \psi \tag{18}$$

where $1_{k=j}$ is 1 if $k = j$ and 0 in other cases, and $\psi = f\, e^{-\alpha(f-1)}[\frac{1}{f} - \alpha]$ is the derivative of the conditional expected number of cycles with respect to total frequency.

Replacing equations (16) and (18) in equations (8) and (9), after some algebra work, we obtained :

$$q_k^* = q_k^o \, exp[\frac{\lambda}{V\upsilon_k}\Delta(p \cdot x)] \tag{19}$$

$$f_k^* = \frac{V\,[\beta_k + f_k(\frac{\gamma_k}{B_k} + \psi\eta)]}{\lambda[\bar{c}_k + \bar{c}\psi + \overline{T}_k(M_k - \omega_k)] + \mu[\bar{t}_k + \bar{t}\psi + \overline{T}_k]} \tag{20}$$

where $\eta = \sum_j \frac{\gamma_j \delta_j}{B_j}$, $\bar{c} = \sum_j \bar{c}_j \delta_j$ is the weighted average of the travel cost associated to all the activities and $\bar{t} = \sum_j \bar{t}_j \delta_j$ is the weighted average of the travel time. Here, the influence of the transportation costs (time and money) over the activity frequency becomes evident. The effect of the other activities is produced by the activity chaining model since this defines an explicit relationship between all the trips.

The first order conditions of the consumer optimization problem (equation 3) allows to obtain λ and μ values, which represent the marginal utility of income and time, respectively. It is possible to show that their approximated expressions are the following :

$$\begin{aligned} \lambda &= V[\frac{\rho_{\lambda 1}}{I} + \frac{\rho_{\lambda 2}}{TT}]\sum_j \varepsilon_{f_j}^U \\ \mu &= V[\frac{\rho_{\mu 1}}{I} + \frac{\rho_{\mu 2}}{TT}]\sum_j \varepsilon_{f_j}^U \end{aligned} \tag{21}$$

where ρ is a vector of unknown parameters ; two associated to λ and other two associated to μ.

When replacing equation (21) in equation (20), we obtain the optimal (maximum utility) activity frequency :

$$f_k^* = \left\{ (\frac{\rho_{\lambda 1}}{I} + \frac{\rho_{\lambda 2}}{TT})[\bar{c}_k + \bar{c}\psi + \overline{T}_k(M_k - \omega_k)] + (\frac{\rho_{\mu 1}}{I} + \frac{\rho_{\mu 2}}{TT})[\bar{t}_k + \bar{t}\psi + \overline{T}_k] \right\}^{-1} \frac{\varepsilon_{f_k}^U}{\sum_j \varepsilon_{f_j}^U} \tag{22}$$

From equation (22) we can study the effect over the activity demand of small changes in variables that intervene in the model. First note that marginal utilities are, by definition, positive ($\lambda, \mu > 0$). Therefore, if cost and/or travel time increase, then the frequency decreases ; the same happens with the average dedication although its impact is less negative if the activity is remunerated ($\omega_k > 0$). On the contrary, the frequency increases if : the dedication time elasticity increases (β_k), the travel time elasticity decreases (γ_k), and if the wage rate (ω_k) increases.

The optimal trip demand is obtained by the expected conditional number of trips evaluated at the optimal frequency. That is, replacing the optimal frequency into equation (15) :

$$B_k(f^*) = E(B_k \big| f^*) = f_k^* + \delta_k f^* e^{-\alpha(f^*-1)} \tag{23}$$

This equation represents the trip generation model developed in this work, obtained from joining an activity demand model and a trip chaining model. Thus, the main characteristic of the transportation demand is taken : it is directly and explicitly derived from the demand for performing activities.

Equation (23) establishes that the number of trips associated to activity k is equal to the number of times that the activity is performed (since every time it is performed requires a space movement or one-way travel) plus a proportion of the number of cycles. The number of cycles is equals to the number of home return trips. These trips cannot be associated to a specific non residential activity since they were not generated by anyone in particular but by all of them. The goal of a home return is to allow the individual to develop residential activities, such as : rest, gardening, interact with other members of the family, etc. In this work the return trips associated to non residential activities through δ_k, which can be defined according to certain criterion, for instance, in proportion to time spent at each activity.

If we replace equation (22) in equation (23), the explicit function for the trip generation model is obtained. In generic terms this function is :

$$B = h(\overline{c}, \overline{t}, \overline{T}, I, TT, \upsilon, \beta, \gamma, f, \alpha, \delta) \tag{24}$$

which states that the trips demand is a function of the same variables that the activity frequency function, including variables from the transport and land use, but they are also complemented with variables from the trip chaining model (α, δ). Equation (24) defines a new approach to analyze the trip generation phenomenon, with a solid microeconomic and statistical foundation, with provides the theoretical support for trip generation models.

2.4 RELATION BETWEEN THE TRIP GENERATION FRAMEWORK AND ACCESIBILITY

The optimum frequency (equation 22) can be interpreted as the result of the individual maximization of his/her integral accessibility (acc_k), defines as the net benefit obtained from performing activities considering the alternative options (destinations) available to do so (Martínez, 1995). The net benefit may be expressed as the difference between utility of performing a set of non residential activities minus the transport cost, then $acc = U - CG$, where U is the utility obtained from those activities and $CG = \lambda(p \cdot x - \sum_k \omega_k \tau_k + \sum_k c_k) + \mu(\sum_k \tau_k + \sum_k tv_k)$ is the total generalized associated to perform these activities which is associated with the previously defined marginal

marginal activity cost by $CG_k = \frac{\partial CG}{\partial f_k}$. Equation (9), defined for the optimum set of activities so $U = V$: $V\varepsilon^U_{f_k} - f_k CG_k = 0$, with $\varepsilon^U_{f_k} = \frac{\partial V}{\partial f_k}\frac{f_k}{V}$, may be expressed as

$$f_k \frac{\partial acc}{\partial f_k} = 0 \qquad \forall k = 1,\ldots,K \tag{25}$$

where $\frac{\partial acc}{\partial f_k} = \frac{\partial (V - CG)}{\partial f_k}$ is the variation of the net benefit due to a change of the activity k frequency. Equation (25) states the usual equilibrium condition for activity frequency choice : frequency increases up to a point where net benefit (accessibility) is exhausted.

It is worth noting that V incorporates quality which in turns depends on availability of associated infrastructure, therefore it depends on land use. The second order optimization conditions of the behavior model assure us that the solution of equation (25) is a maximum, therefore, the optimal demand of the activity is produced when the associated net benefit is maximized.

The interest of the relationship between generation and access lies beyond the interpretation of theoretical results, since it concerns to practical issues. Indeed, accessibility has been defined as the microeconomic link between the transportation and the land use systems. Indeed, following Martínez (1995) the household location choice takes into account a measure of household accessibility acc_h obtained from adding the expected net benefit of individual members (denoted by n) and their activities (acc^n_k) :

$$\underbrace{acc_h}_{\substack{\text{Residential}\\ \text{location}}} = \sum_{n,k} acc^n_k = \sum_n \sum_k \int \underbrace{\frac{\partial acc^n_k}{\partial f^n_k}}_{\substack{\text{Trip}\\ \text{generation}}} df^n_k \tag{26}$$

This approach was successfully applied in the model of the Santiago City called MUSSA (Martínez and Donoso, 1995).

Thus, as the frequency determines the number of trips, equation (26) allows that mobility decision of individuals naturally become an endogenous variable in the joint modeling of the master transport-land use, as opposed to the more usual practice of exogenous trip generation rates system.

3. DISCUSSION AND COMMENTS

In this work, a theoretical framework has been developed to study the trip generation at an individual level within an urban context. At a theoretical level, the approach states that the trip generation has the following characteristics :

- depends on the time assignation decision to all the activities ;
- it is a transportation cost function ;
- is determined by socioeconomic characteristics of the individual and by its valuation of quality, of the time devoted to the activities and the travel time ; and
- varies according to the disposition and possibility to chain activities.

These remarks void some of the assumptions used in the traditional models of trip generation. For example : the generation independence for different trip purposes is not compatible with chaining modelling; the independence respect to transportation costs is contrary to the restriction definition of the time and money behavior character. On the other hand, the approach described in this work can only be applied to individuals due to the need of counting on socioeconomic and trip behavior variables typical to each person : available time and income, time devoted and travel time for each activity, attribute valuation, and propensity to chain activities.

The developments of section 2.4 show that there exists a microeconomic link between the trip generation and the transportation way-land use system that can be useful to go forward in developing better analysis models of the urban development.

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Figure 1
Number of trips as a function of the frequency and its bounds