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Transport and land-use benefits under location externalities

Francisco Martínez, Claudio Araya
Department of Transport Engineering, University of Chile, PO Box 228-3, Santiago, Chile;
e-mail: fmartine@cec.uchile.cl; claaraya@cipres.cec.uchile.cl
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Abstract. Transport projects are economically assessed partly by estimating users' benefits in the transport system and by ignoring impacts on land use under the argument that these benefits are already incorporated into transport users' benefits. In this paper we discuss this argument from two main viewpoints: the level of percolation of transport benefits into land values and the presence of external economies in urban systems. We first propose and discuss measures of benefits in the transport system and in the land-use system. Then we analyse to what extent transport users' benefits percolate into land rents, showing empirical evidence that it may be limited. We then focus on the less-studied effect of three types of technological externalities: direct effects associated with traffic nuisance; location externalities, associated with economies of agglomeration of households and firms, which in some cities may be a dominant location choice factor; and land-use – transport interaction. We conclude by specifying in more detail the conditions under which the classical argument and current project appraisal methods are valid.

1 Introduction

In theory, the benefits generated in the activity system as a result of a transport project should be observed and properly measured in the transport system, as a direct consequence of the argument that travel demand is derived from individuals' demand to perform activities. This is the well-known Mohring's (1961; 1976) classical argument on the relationship between transport and land-use benefits, which is based on Alonso's (1964) urban location approach where the land market operates as a bid – auction process. Mohring (1976, page 119) studied the highway impact on land values and concluded that "changes in land values as may result from transportation improvements involve transfer of income among members of the population, not additional benefits (or losses) that must in some fashion be added to those arising directly from the improvement." As this is only a distributive effect it is irrelevant in social evaluation as long as the relative importance of all the agents' welfare is the same or, alternatively, a compensation tax system operates cancelling the losses of some with the gains of others.

Wheaton (1977) studied the same issue for the urban area, considering the residential market. His basic assumption is that competitive land bidding ensures that landlords will eventually extract savings that consumers may enjoy. He defines a measure of location benefit as the exogenous income necessary to compensate the change in transport costs (the compensating variation). As this measure depends only on the aggregated travel demand, he concludes that all the changes in the location market associated with an investment in transport can be completely ignored in the calculation of benefits if travel demand is adequately forecast. Sasaki and Kaiyama (1990) extend this result, incorporating the behaviour of firms. It is important to mention that Wheaton acknowledges that his result is valid if the transport investment generates only indirect (or pecuniary) effects on land and housing, such as those altering some other market prices (for example, transport market). According to Wheaton the existence of direct effects (which we understand as technological externalities) would invalidate this classical result. Here we shall analyse these arguments, incorporating common technological effects in the urban context, namely, traffic nuisance, location externalities, and land-use–transport interaction, concluding with the conditions needed for classical arguments to apply.

Of particular interest is to analyse current practice in transport project appraisals. The calculation of transport benefits is based on the estimate of resource savings and transport users' benefits (Williams and Lam 1991a; 1991b) and applies Mohring's and Wheaton's argument to ignore any land-value benefit. However, these methods use travel demand models that ignore land-use effects (land values and location impacts) on the transport project because they are limited to partial transport equilibrium analysis.

Our research builds upon earlier work (Jara-Díaz and Martínez, 1999) in which were derived theoretical indirect utility and willingness-to-pay functions for residential location. This framework relaxes Alonso's restrictive assumption (also made by Mohring and Wheaton) that location utility is associated only with land space, trip costs, and a composite good. Indeed, we assume that residents obtain utility from the set of *activities performed*, considering the available time constraint (hence the value of time). This microeconomic approach justifies the role of location externalities in resident and firm location, which is associated with the existence of agglomeration economies; it also clearly justifies the role of access (accessibility and attractiveness) in locators' behaviour. As access measures coincide with trip benefit, associated with trips made by locators (Martínez, 1995), the connection between transport and land rent becomes explicit and consistent.

This theoretical framework has been applied successfully in the Santiago City land-use model, MUSSA, which is used here to make empirical calculations of transport users' benefits and economic assessments of impacts on the urban land market.

In the following section we present measures of transport users' benefits, B^{TU}, used in some advanced transport project appraisal methods. In section 3, land-use benefits, B^{LU}, are derived on the basis of urban economic theory, and their variations from changes in accessibility are defined. The link between B^{TU} and B^{LU} is established by means of accessibility measures, which allow us to analyse the theoretical relationship between B^{TU} and B^{LU} in section 4. The application of this analysis with use of the land-use model MUSSA provides the empirical evidence presented in section 5, followed by a summary of main practical conclusions in the final section.

2 Transport users' benefits

The benefits derived from transport projects to users, either through infrastructure investment or operational policies, are obtained from consumers' surplus measures, S^{C}, which are derived directly from trip-utility functions or from trip-demand models. Let us consider, as an example, the well-known and widely applied doubly constrained spatial interaction model for trip distribution to represent travel demand, T_{ij}, between zones:

$$T_{ij} = a_i O_i b_j D_j \exp(-\beta c_{ij}) , \qquad (1)$$

subject to

$$\sum_j T_{ij} = 0_i ,$$

$$\sum_i T_{ij} = D_j ,$$

which distributes trips O_i exogenously generated at each zone, i, to all destinations, j, subject to complying with the also exogenously given total number of trips D_j at each destination. The fulfilment of these constraints is assured by parameters a_i and b_j, known as balancing factors. These constraints introduce a context where the land-use system is exogenous to the transport system, which we call the short-run context. The response of travel demand to the transport cost measure c_{ij} is captured by the users' sensitivity parameter β.

Williams (1976) proposed a measure of the Marshallian consumers' surplus associated with this model, which estimates the aggregated transport users' benefit (B^{TU}) variation arising from a change in transport costs. As the travel demand model assumes land use to be exogenous and fixed, these are short-run benefits ($B^{\mathrm{TU(SR)}}$) useful for comparing two situations: with and without a project, denoted by superscript (1) and (0), respectively. The difference $\Delta B^{\mathrm{TU(SR)}}$ is given by:

$$\Delta B^{\mathrm{TU(SR)}} = \frac{1}{\beta}\left[\sum_i O_i \ln\left(\frac{a_i^{(0)}}{a_i^{(1)}}\right) + \sum_j D_j \ln\left(\frac{b_j^{(0)}}{b_j^{(1)}}\right)\right]. \tag{2}$$

According to Williams and Senior (1978), each term in equation (2) represents transport users' benefits or land rents, depending on whether the traveller is assumed to be a job seeker (with fixed residence) or home seeker (with fixed job). This interpretation is asymmetrical and subject to the assumption that the traveller is seeking either a job or a place of residence. It has been argued that the first term (with factors a_i) is associated with accessibility from the trip origin, or the benefit of making trips, and the second term (with factors b_j) is associated with attractiveness at the trip destination, or the benefit of receiving trips (Martínez, 1995). Additionally, it has been argued that the transformation of these benefits into land rents is symmetrical but can be identified only in the land-use system (Martínez, 1995).

The condition that land use be fixed was recently relaxed by the authors (Martínez and Araya, 2000) obtaining an expression for the long-run benefits, $B^{\mathrm{TU(LR)}}$, in which O_i and D_j change between the two situations of being with and without a project, as before. The difference $\Delta B^{\mathrm{TU(LR)}}$, is given by:

$$\Delta B^{\mathrm{TU(LR)}} = \frac{1}{\beta}\left[\sum_i \frac{(O_i^{(0)} + O_i^{(1)})}{2} \ln\left(\frac{a_i^{(0)}}{a_i^{(1)}}\right) + \sum_j \frac{(D_j^{(0)} + D_j^{(1)})}{2} \ln\left(\frac{b_j^{(0)}}{b_j^{(1)}}\right) + (T^{(0)} - T^{(1)})\right], \tag{3}$$

where the first two terms can be interpreted as representing a pseudo-rule-of-a-half of a transport benefits at each end of the trip, and the last term $\beta^{-1}(T^{(0)} - T^{(1)})$ represents the benefit associated with total trip generation. The difference with the original rule-of-a-half is that this pseudo-rule does not assume a linear approximation of the trip-demand function.

From earlier work (Martínez, 1995), accessibility Q^{acc} and attractiveness Q^{att} may be defined as follows

$$Q_i^{\mathrm{acc}} = \frac{-1}{\beta}\ln(a_i), \qquad Q_j^{\mathrm{att}} = \frac{-1}{\beta}\ln(b_j), \tag{4}$$

which represent the expected benefits per trip generated and attracted, respectively, considering the distribution of trip destination, mode, and route choices. Note that as a_i and b_j are relative terms, that is, they can be identified only up to an unknown multiplicative constant, then Q_i^{acc} and Q_j^{att} are also relative measures.

Additionally, in other work (Martínez and Araya, 2000) we have extended the analysis deriving trip-associated measures of access and have proposed the following disaggregated accessibility expression, which is the expected household transport benefit, $\bar{Q}_{i(n)}$, strictly associated with the trip pattern, K_n, of a given household, n, for a given location, i:

$$\bar{Q}_{i(n)} = \sum_{k \in K_n} \frac{1}{\beta_{(n,R_k)}} T_{ij_k} \ln[a_{i(n,R_k)} b_{j_k(n,R_k)}] , \tag{5}$$

where k is the index for individual trips, R_k is the trip purpose, and j_k is the zone trip destination index.

In line with other work (Jara-Díaz and Martínez, 1999), these expressions can be used as accessibility attributes in households' willingness to pay for residential location. Therefore, they directly integrate the behavioural function of location models associated with Alonso's bid-rent framework. This approach guarantees that the interaction between transport and land use is performed, through accessibility, in a consistent microeconomic procedure. Note that these access measures do represent transport users' benefits, thus their explicit role in location choices provide the consistent linkage between transport benefits, location choices, and impacts on land rents, as we discuss below.

3 Benefit from land use

It is now necessary to derive and analyse appropriate measures of benefits associated with impacts in the land-use system generated by investment or policy changes in transport. For this purpose, an economic model to describe the urban system performance is required. The classical microeconomic paradigm proposes that the consumer maximises his or her utility subject to income and time constraints. From this utility-maximising problem Alonso (1964) derived functions for an individual's willingness to pay for land that enabled Alonso to introduce the classic bid-rent model, which assumes that land lots are acquired by the highest bidder.

3.1 The basic model

Let us first consider a basic model of consumer behaviour in location choices. Rosen (1974), who assumed that consumers maximise their utility, which depends on residential location, provides a detailed derivation of Alonso's willingness-to-pay functions. Utility is obtained by the consumption of a composite good, x, and the location choice is described by a vector of attributes, z. Assuming an exogenous income constraint, the optimal behaviour of consumer h is given by the solution of

$$\underset{x,j}{\text{maximise}}\ \mathrm{U}_h(x, z_j) , \tag{6}$$

subject to

$$Px + r(z_j) = I_h ,$$

where P is the price of the composite good and $r(z_j)$ is the hedonic price or rent of land located in zone j which is assumed to be dependent on location attributes, z_j; I_h is the fixed income of individual h. Optimising, we obtain the conditional demand function for the composite good, x^*, which is then replaced in the direct utility function to obtain the indirect utility function conditional in the choice of location j:

$$\mathrm{U}_h\{x^*[P, I_h - r(z_j)], z_j\} \equiv \mathrm{V}[P, I_h - r(z_j), z_j] . \tag{7}$$

Fixing the utility level at U_h^* and inverting in $r(z_j)$, we obtain the willingness-to-pay function:

$$W_{hj} = I_h - V^{-1}(P, z_j, U_h^*), \tag{8}$$

which represents the maximum value that consumer h is willing to pay for a location with characteristics z_j, in order to obtain a level of utility U_h^* and subject to the exogenous values P and I_h. This function represents the inverse of the Hicksian compensated demand for land with characteristic z_j.

This basic model allows us to derive measures of consumer surplus associated with a change in land attributes. For that purpose, it is worth noting the the expression $V^{-1}(P, z_j, U_h^*)$ is the minimum expenditure, e, in all goods other than land required to reach the level of utility U_h^*; therefore W_{hj} represents the maximum that the consumer is willing to pay for that location. We postulate the following theorem:

Theorem: *The location benefit or consumer surplus (S_{hj}^{c}), measured by the compensating variation, v_h, obtained by a consumer h at location j, is well defined (in a microeconomic sense) by the difference between the willingness to pay (or real location value for the consumer) and what he or she actually pays for that location (r_j):*

$$S_{hj}^{c} = W_{hj}(U_h^*) - r_j, \tag{9}$$

with U_h^* a reference utility level.

Proof: By definition, the compensating variation v is the income change necessary to compensate for a price change to maintain utility; it is measured by the difference in the expenditure function calculated after the price change. Consider two cases: the consumer changes his or her location and, second, the set of location attributes and price change, without relocation. Assume the change is from (z_i, r_i) to (z_j, r_j). The income compensation or compensating variation for these changes is given by the expenditure differential to obtain the reference utility level U_h^*. Then

$$v_h = e_h(z_i; P, U_h^*) + r_i - e_h(z_j; P, U_h^*) - r_j,$$

or, introducing equation (8), we obtain:

$$v_h = W_h(z_j; I_h, P, U_h^*) - r_j - \{W_h(z_i; I_h, P, U_h^*) - r_i\} \equiv \Delta S_h^{C}.$$

Therefore, a well-defined measure of the consumer surplus is

$$S_{hj}^{C} = W_h(z_j; I_h, P, U_h^*) - r_j,$$

which proves the theorem.

On the supply side, a change in the land prices (or rents) is capitalised by landowners and represents the variation of the producer surplus (ΔS^{P}). Then, assuming that location j is occupied by household h before and after the change in one or more attributes, the total variation in land-use benefits (B_{hj}^{LU}) is given by:

$$\Delta B_{hj}^{LU} = \Delta S_{hj}^{C} + \Delta S_j^{P} = \Delta W_{hj} - \Delta r_j + \Delta r_j = \Delta W_{hj}, \tag{10}$$

which turns out to be identical to the variation of the locator's change of the willingness to pay for that location. If we consider relocations, total benefits are calculated by adding consumers' surplus at the location before (0) and after (1) the project, plus the producers' surplus:

$$\Delta B^{LU} = \sum_{h \in H}[W_h^{(1)} - r_l - (W_h^{(0)} - r_k)] + \sum_{s \in \Omega} \Delta r_s = \sum_{h \in H}(W_h^{(1)} - W_h^{(0)}), \tag{11}$$

where H is the set of locators and Ω the set of location options in the city. Note that this calculation of ΔB^{LU} requires identifying the location of each consumer before and after the project; that is, all relocation caused by the project should be estimated.

Second, remember that in equations (10) and (11) willingness to pay should be calculated with the utility level held constant which makes the variation in land-use benefits different from the variation of the expected location prices in the city.

With regard to transport impacts, it is also worth noting that variations in willingness to pay and rents are generated by an original variation of location attributes (contained in vector z) which include accessibility and attractiveness. This implies that a change in any attribute z_k will induce an impact on land-use benefits according to two conditions: the sensitivity of the household to that attribute, which produces changes in willingness-to-pay values (the behavioural response), and the effect of this change in the land-use market equilibrium.

3.2 A marginal deterministic analysis

In order to focus on the role accessibility plays in land-use benefits, let us consider the microeconomic residential location model of Jara-Díaz and Martínez (1999). They analysed the consumer utility regarding residential location constrained by time and income, and the available distribution of land use in the city that defines location attributes. From this framework the individual willingness to pay for alternative locations was derived as an explicit function of the consumer's perception of transport benefits, interpreted by the authors as a measure of accessibility (according to Martínez, 1995). The proposed willingness-to-pay function is:

$$W_i = C + I + \alpha t^{\text{tot}} + \omega \sum_d \sum_l f_d \delta_{dil} Q_{dil}^{\text{acc}} , \tag{12}$$

where i denotes the residential location, I the household income, and t^{tot} the total available time; Q_{dil}^{acc} is the net trip benefit (benefit minus cost) or relative accessibility generated by performing activity d in zone l while located in zone i; f_d is the activity frequency; δ_{dil} is a dummy variable that takes the value 1 if the dth activity is carried out in zone l and 0 if not (it represents a trip destination choice model); α and ω are parameters; and C is an individual specific constant. Relative accessibility is expressed as the difference between the benefit obtained by performing an activity at some destination minus the transport cost involved in reaching that destination from the residential location:

$$Q_{dil}^{\text{acc}} = U_d(z_l) - G_{dil}(t_{il}, c_{il}) , \tag{13}$$

where $U_d(z_l)$ is the monetary utility obtained from carrying out activity d in zone l, which depends on the set of attributes z_l at the destination zone; G_{dil} (t_{il}, c_{dil}) is the transport-generalised cost to travel from i to l, including fare (c_{il}) and travel time (t_{il}). Notice that accessibility combines land-use attributes, expressed by z, and transport costs, which explicitly states that trip benefits integrate a consumer's behaviour in location [equation (12)] and transport choices in a consistent way.

A variety of effects of transport projects in location behaviour can be identified from equations (12) and (13). If the transport cost decreases in one origin–destination pair, the origin and destination zones both become more attractive locations, and willingness-to-pay functions change for all potential bidders owing to the last term in equation (12). This modifies location attributes (z_l) and willingness to pay and represents the *access* effects on land use, through transport and time costs, which are what Wheaton calls indirect or pecuniary externalities. Direct or technological effects, such as pollution, traffic noise, and accidents, may also affect location choices, which may be referred to as nuisance externalities. In this case transport variables other than access should be represented in z in order to affect willingness-to-pay functions directly.

A third and highly relevant effect is generated by location attributes endogenous to the location process. Indeed, W depends on environmental attributes z_l [equation (13), first term], including land-use attributes (for example, location of activities in zone l), which makes the location choice dependent on the land-use pattern, that is, dependent on the location choice of all other locators. Therefore, further location and accessibility changes are expected to follow after any location change, which is also a type of technological externality, called a location externality, which is directly associated with agglomeration economies in urban economics, although here we refer not only to the location of firms but also to that of residences.

The impact of transport changes on B^{LU} [equation (11)] may be analysed by differentiating the willingness-to-pay function [equations (12) and (13)] with respect to a given trip benefit:

$$\frac{\partial W_{hi}}{\partial Q_{mij}^{\mathrm{acc}}} = \sum_{dl} f_d \delta_{dil} \left[\frac{\partial U_{hd}(z_l)}{\partial z_l} \frac{\partial z_l}{\partial z_j} \frac{\partial z_j}{\partial Q_{mij}^{\mathrm{acc}}} - \frac{\partial G_{dil}}{\partial Q_{mij}^{\mathrm{acc}}} \right] . \tag{14}$$

These terms describe the transference of transport benefits (Q^{acc}) into location willingness to pay and hence into the land-use market. The first term represents all technological externalities. It is composed of the dependence of the utility of each activity on the local environment where the activity is performed ($\partial U_{hd}/\partial z_l$), the interdependence of local environments or the internal dependence of land-use pattern ($\partial z_l/\partial z_j$), and the dependence of the local environment on the accessibility to activity m in zone j ($\partial z_j/\partial Q_{mij}^{\mathrm{acc}}$). The second term represents the access effect, which includes all interactions between G and Q^{acc} at the level of trip generation, destination choice, transport mode choice, and road congestion.

Observe that equations (12)–(14) may be extended to include not only outward trips from zone i, associated with accessibility, but also inward trips in order to include attractiveness effects; such extension to the above analysis would provide analogous effects related to attractiveness.

3.3 Towards an operational approach: the stochastic model

Several models of urban location are based on stochastic versions of Alonso's bid–rent economic theory (Hayashi and Doi, 1989; Miyamoto and Kitazume, 1989), including the bid–choice theory (Martínez, 1992) applied in the Santiago land-use model MUSSA (Martínez and Donoso, 1996). The bid–choice theory assumes that bids o_{hi} for a location, defined as willingness to pay minus a speculation factor w, are stochastic variables, which make these models operational and more realistic. Assume bids are given by:

$$o_{hi} = W_{hi} - w_{hi} + \varepsilon_{hi} , \tag{15}$$

with W_{hi} the systematic term and ε_{hi} a random term to be distributed, in this example model, identical and independent Gumbel. The rent for a given location i is directly obtained by the expected value, E, of the maximum bid, so that:

$$r_i = E\left[\underset{h \in H}{\mathrm{maximise}}(W_{hi} - w_{hi} + \varepsilon_{hi}) \right] = \frac{1}{\mu} \ln \sum_{h \in H} \exp[\mu(W_{hi} - w_{hi})] + \frac{\gamma}{\mu}, \tag{16}$$

with μ the scale parameter of the Gumbel distribution and γ the Euler's constant (approximately 0.577); H is the set of individual bidders at a given time. Additionally, according to the rule of the highest bidder the probability that an individual h will locate his or her residence in a given place i, $p(h/i)$, is

$$p(h/i) = \frac{\exp \mu(W_{hi} - w_{hi})}{\sum_{h' \in H} \exp \mu(W_{h'i} - w_{h'i})} = \exp \mu(W_{hi} - w_{hi} - r_i + \gamma) . \tag{17}$$

According to the bid–choice theory, and under Walras's type of equilibrium (no excess of demand), the best-bidder clearing rule is equivalent to the choice rule where each locator maximises her or his consumer surplus (Martínez, 1992). Thus, for any forecasting year, the expected consumer's surplus value obtained by a locator type h facing an exogenous rent r is:

$$E(S_h^{\mathrm{C}}) = \frac{1}{\mu}\ln\sum_{i\in\Omega}\exp[\mu(W_{hi} - r_i)], \tag{18}$$

with Ω the set of available locations. This equation is a direct result of the assumed Gumbel distribution and the assumption that consumers behave as price-takers. Additionally, the expected surplus for the landlord of an elementary lot is equal to the expected rent given by equation (16).

Assume consumers are categorised, with N_h consumers in category h, and assume supply is grouped into zones, with N_i locations in zone i. The expected total change in B^{LU}, obtained by adding benefits of all consumers and producers between situation $s = 0$ and $s = 1$, is:

$$E(\Delta B^{\mathrm{LU}}) = \left\{\sum_{h\in H_s} N_{hs} E[S_{hs}^{\mathrm{C}}(U^*)] + \sum_{i\in\Omega_s} N_{is} r_{is}\right\}_{s=0}^{s=1}. \tag{19}$$

Observe that ΔB^{LU} depends on the exogenous variation of population (H_s) and the variation of supply options (Ω_s), which is endogenously defined in the MUSSA model, both affecting the land market equilibrium defined by W, w, and r (Martínez and Donoso, 1995). Also observe that the consumer surplus should be calculated for a fixed utility level.

Analogous to the deterministic case, the variation of location benefits should be analysed noting that the location willingness to pay is a function of the access attributes (accessibility and/or attractiveness, depending on the activity being located). The expected marginal variation on B^{LU} with respect to a generic attribute z_{hi} of the willingness-to-pay function is:

$$\begin{aligned} \mathrm{d}E(B^{\mathrm{LU}}) &= \sum_{h\in H_s}\sum_{i\in\Omega_s}\frac{\partial E(B^{\mathrm{LU}})}{\partial z_{hi}}\mathrm{d}z_{hi} \\ &= \sum_{h\in H_s}\sum_{i\in\Omega_s} N_{i,s}\left\{\frac{\partial W_{his}}{\partial z_{hi}}p_s(h/i) + \frac{\partial r_i}{\partial z_{hi}}[1 - p_s(h/i)]\right\}\mathrm{d}z_{hi}, \end{aligned} \tag{20}$$

with

$$\frac{\partial r_i}{\partial z_{hi}} = p(h/i)\left(\frac{\partial W_{hi}}{\partial z_{hi}} - \frac{\partial w_{hi}}{\partial z_{hi}}\right). \tag{21}$$

These equations assume that the Walras equilibrium condition holds in the urban market; if this is not the case, the bid–choice equivalence does not hold and these equations are slightly more complex because some terms do not cancel out.

It can be observed that the effect on B^{LU} associated with rent variations depends upon the highest bidder probability, $p(h/i)$. Consider the extreme case where it is equal to one, which can happen only if $o_{hi} = r_i - \gamma$ [see equation (17)], to see that the rent effect vanishes (assuming speculation constant) yielding the variation on the expected B^{LU} value equal to the expected variation in willingness to pay, which is the result obtained for the deterministic case [equation (11)]. In all other cases, there is a combination of willingness-to-pay and rent effects. This shows that, in line with the deterministic case, the variation of rents does not correctly represent land-use benefits.

4 Transport and land-use relationship

In the analysis of the relationship between location benefits (B^{LU}) and transport benefits (B^{TU}), the values of the derivatives $\partial W_{hi}/\partial Q_{hi}^{\mathrm{acc}}$ and $\partial W_{hi}/\partial Q_{hi}^{\mathrm{att}}$ are decisive in defining the degree of similarity between these measures. For example, consider W as a linear function of access, that is:

$$\frac{\partial W_{hi}}{\partial Q_{hi}^{\mathrm{acc}}} = \xi_h, \quad \frac{\partial W_{hi}}{\partial Q_{hi}^{\mathrm{att}}} = \chi_h, \qquad \forall i, \tag{22}$$

then (assuming the bidder's speculation is independent of access), expression (21) reduces to

$$\mathrm{d}E(B^{\mathrm{LU}}) = \frac{1}{\mu}\sum_{i\in\Omega_i} N_i \sum_{h\in H}\{p(h/i)+p(h/i)[1-p(h/i)]\}(\xi_h \mathrm{d}Q_{hi}^{\mathrm{acc}} + \chi_h \mathrm{d}Q_{hi}^{\mathrm{att}}) + \Lambda\,, \tag{23}$$

where Λ represents technological externalities, inducing direct and endogenous location effects.

If we remember that the total variation in accessibility and attractiveness directly represents the total transport benefit (B^{TU}), then we can see that equation (23) establishes a direct relationship between B^{LU} and B^{TU}. It shows that the set of values for ξ, χ, and Λ defines whether B^{TU} could overestimate or underestimate B^{LU}. It is enlightening to note that complete equivalence between B^{TU} and B^{LU} occurs only if $\xi = 1$, $\chi = 1$, and $\Lambda = 0$. We conclude, then, that these parameters define the degree to which travellers retain benefits and the degree of percolation of these benefits into land rents. A second conclusion is that the temptation to take changes in land rents as a good estimate of transport project benefits is generally incorrect.

Let us consider the relationship between B^{TU} and B^{LU}, concentrating only on the better known effect of access, that is, let us ignore Λ for the moment. The degree of the access effect depends on parameters ξ and χ of the willingness-to-pay function, which define locators' trade-off between access (to activities other than residence) and other location amenities. Hence they are associated with household utility functions and are expected to be specific to socioeconomic and cultural characteristics. Indeed, one can think of two cities of different cultures: one with a transport-minded population, where household and firms locate themselves so as to minimise transport costs, and a second one where locations are mainly decided with regard to social ties (family or cultural background). In the first city one would expect that B^{TU} will be fully transferred into land values and is similar to (the access effect of) B^{LU}. Conversely, in the city where people are less sensitive to transport costs, transport benefits will produce a low impact in the land-use system, particularly on land rents; hence transport user benefits will be considerably greater than the land-use benefits. The obvious conclusion is that total benefits derived from a transport project should be assessed in the transport system; as B^{LU} would underestimate benefits in this case. In contrast, in a highly sensitive city B^{LU} is expected to be a close estimate of B^{TU}, although B^{TU} is still the correct estimate of total benefits on the assumption of no technological effects.

Consider now technological effects only. As for nuisance externalities of transport (pollution, noise, etc), the analysis is similar to the access effect because the relevant transport variables explicitly appear in location willingness-to-pay functions, but the conclusion is different. Indeed, in this case nuisance disbenefits can be properly determined only in the land-use system as it affects located activities (nonusers) and not travellers, hence it should be measured as part of B^{LU}. With regard to location externalities, they are not observable in the transport system and may be better analysed in a quasi-dynamic framework: direct transport impacts cause the relocation of activities, which induces further relocation as a result of location dependency. In addition, relocation generates changes in trip patterns, which in turn feeds back into more location changes, describing a cyclical interaction that settles only if the global land-use – transport system attains equilibrium. Theoretically, at the global equilibrium, all transport and land-use variables achieve a static equilibrium and every technological effect vanishes in the next iteration between transport and land use. However, at a disequilibrium stage, the technological effect may induce important relocation impacts with relevant benefits in addition to those included in B^{TU} in a partial equilibrium transport demand model.

It is clear that available travel demand models do not forecast global equilibrium, but the partial equilibrium conditional on the location of activities. Hence, under current modelling practice, technological externalities are neglected and total transport benefits are biased in at least two ways. First, it is reasonable to expect the bias to be an underestimation of total benefits because relocation will be an attempt to maximise a locator's utility under an improvement in access conditions (ceteris paribus), which should lead to an equilibrium with total benefits equal to or greater than those before the access change. Second, all relocations are neglected in the travel demand model, therefore B^{TU} measures are biased, but it is not possible to anticipate the sign of this bias.

Additionally, if we combine access and technological relocation effects, it is worth noting that the higher the sensitivity to access, the more direct effects are expected, as more relocation adjustments should occur. Hence, the closer B^{LU} is to the measure B^{TU} on access effects the larger the expected bias due to technological effects. Therefore, allowing for technological effects to be taken into account, the more sensitive to transport is the city population, the poorer the estimation of total benefit made by B^{TU} obtained from partial transport equilibrium.

This leads us to the following three conclusions.

(1) The total benefits generated by a transport project will be correctly estimated by transport users' benefits (B^{TU}) *only* if the travel demand model properly forecasts the combined land-use – transport system equilibrium, that is, that the travel demand model incorporates all technological and access effects.

However, this is far from current practice.

(2) The total benefits calculated by B^{TU} obtained from partial transport equilibrium are expected to be biased in two ways: they neglect relevant technological effects as transport nuisance and location externalities, and ignore land-use - transport feedback (for example, congestion and environmental effects). The more sensitive the city population is to access, the larger the bias; the sign of the bias cannot be anticipated. This imposes a difficult condition on the correct calculation of B^{TU}, namely, that it should be done by using a travel demand model able to anticipate all land-use externalities; on applied grounds it requires the use of a land-use – transport integrated model based on a consistent microeconomic equilibrium framework.

(3) Benefits measured in the urban land market (B^{LU}) would normally underestimate total benefits because they ignore benefits retained by transport users; the less sensitive to access is the population, the larger the bias.

This last argument invalidates the use of land-value capture as land-rent changes to assess the benefits of a transport project.

In figure 1 we summarise graphically our conclusions on the general relationship between benefits measured by using partial equilibrium models of transport and land use and the total benefits obtained by general equilibrium. Note, however, the figure

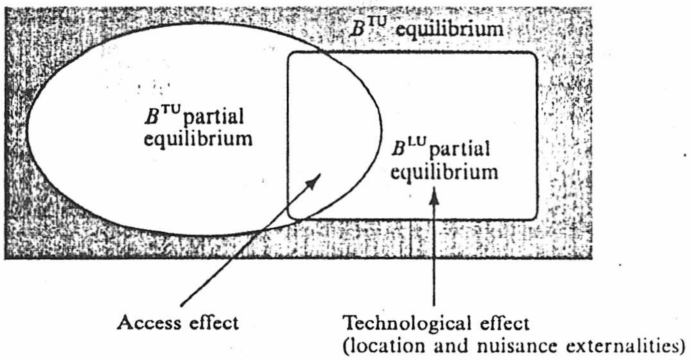

Figure 1. The composition of transport project benefits. Note: B^{TU} and B^{LU}, are transport users' and land-use benefits, respectively.

may be misleading as total benefits might be bigger or smaller than those calculated for the partial equilibrium. The figure does not display explicitly land-use–transport feedback effects.

5 Empirical analysis

In this section we present some calculations made to assess the difference between B^{TU} and B^{LU}. The purpose of this experiment is to replicate the usual calculation of B^{TU} made by partial transport equilibrium models and to compare it with B^{LU} associated with access and location effects.

Calculations of benefits were carried out by using the land-use–transport interaction model of the city of Santiago (4.5 million inhabitants), called MUSSA–ESTRAUS (Martínez, 1996; Martínez and Donoso, 1995), which is consistent with the basic theoretical and empirical approach discussed above. Population is disaggrегrated into 65 household categories (regarding income, car ownership, and household size), and 5 firm types to describe economic activity. The urban area is divided into 264 homogeneous zones, and residential supply is segmented into 10 types (to differentiate land lot size and to differentiate houses from flats). The land-use model, MUSSA, can be used to determine the market equilibrium for household and firm locations in the urban area for a given pattern of accessibility. The transport market equilibrium is modelled by ESTRAUS for the 264 origin and destination zones and 11 transport modes, including public and private transport, operating in a network subject to congestion. Although MUSSA–ESTRAUS feedback is a normal procedure, this was not performed in this test so as to approximate results to current practice. Access variables are calculated from ESTRAUS outputs by using equation (4).

We considered two hypothetical examples, depicted in table 1. In the first case we compared the long-run (time-series) values of ΔB^{LU} [equation (19)] and ΔB^{TU} [from equation (3)] taking two years (1991 and 1997) for a given transport system, where the main change is the population growth (from 4.7 million to 5.2 million inhabitants). Because the total population changes, total trips also change between these two years and ΔB^{TU} should be calculated by the long-run formula [equation (3)]. Here, the

Table 1. Comparison of land-use and transport benefits (US$ million).

CASE	ΔB^{TU}	ΔB^{LU}
Comparison of 1991 and 1997	−787	891
Comparison of a fixed population (year 2005) with and without an investment plan	1.957	419

calculation of transport benefits is performed by using the set of balancing factors associated with the corresponding trip demand model of each year, with exogenous calculations of total trip origins and destinations. In the second case listed in table 1, population is fixed, representing the year 2005, where measures of benefits for situations with and without an investment plan are compared; the plan includes road and public transport infrastructure investments. In this case benefits were again calculated by using equation (19) for ΔB^{LU} but the short-run formula was used [equation (2)] for ΔB^{TU}, which is appropriate when total trips remain fixed and their distribution across destinations changes as a result of the investment plan. Transport benefits are obtained by using balancing factors of the corresponding demand model with and without the plan.

The negative value of B^{TU} for the time series 1991–97 reflects the impact of the population increase and the consequent increase in congestion, without mediating any capacity adjustment. The land-use measure, on the other hand, reveals the development driven by the population increase and economic growth, generating higher rents and higher household income. Hence, the ΔB^{LU} index is confounded by the capitalisation of the city economic growth into urban development, in the form of land rents, despite the reduction in access resulting from higher congestion. This example clearly shows that B^{LU} is a misleading indicator of B^{TU} despite similarities in some circumstances.

In order to isolate the impacts of transport projects from changes in population, a fair comparison between B^{LU} and B^{TU} is obtained for the year 2005 with and without investments, with population held constant. Notice that B^{LU} incorporates access and technological externalities. Table 1 shows that benefits measured in the transport system (B^{TU}) are 4.6 times those in the activity system (B^{LU}). This lower B^{LU} is consistent with the low sensitivity of locators to access observed in the estimated parameters of Q^{acc} and Q^{att} in the MUSSA willingness-to-pay functions. This is important empirical evidence that transport users retain most of the transport benefits in Santiago, with only a fraction percolating into land rents.

6 Conclusions

Current methods for the evaluation of urban transport projects rely on calculated benefits to users (B^{TU}) based on the absence of equilibrium in the land-use–transport system. The first contribution of this work is to extend the theoretical measures of transport benefits to cope with inelastic demand, to be able to calculate valid measures in the case of significant changes in total trips, called the long-term case. Second, measures for land-use benefits (B^{LU}) have been specified, differentiated by consumers' and producers' benefits and have been analysed for a stochastic location model.

Previous studies (Mohring, 1961; 1976; Sasaki and Kaiyama, 1990; Wheaton, 1977) have demonstrated that total benefits generated by projects in the transport system are correctly measured by users' benefit. The assumption that allows them to reach this conclusion is implicit in their analysis; namely, that locators' behaviour is well described by the maximisation of accessibility and attractiveness; a second assumption, explicitly stated by Wheaton, is the absence of 'direct' or technological externalities, including transport nuisance, location externalities, and land-use–transport feedback. In the urban context, this assumption is highly restrictive because externalities are widely recognised as a variety of agglomeration economies. In this work we have generalised the locators' utility function to allow explicit consideration of these effects.

We have reaffirmed that, indeed, total benefit can be correctly measured by transport users' benefits *if* global transport and land-use equilibrium is achieved and well described by the travel demand function (or that all technological externalities can be neglected). This extends Mohring's and Wheaton's previous results for the case with technological externalities, retaining the assumptions that general land-use–transport equilibrium is attained and everything else remains the same. Additionally, we have concluded that the assumption that locators behave as access maximisers (or even more restrictively as transport cost minimisers), which implies full capitalisation of transport users' benefits into land rents, is not supported by the evidence. This extremely simple assumption is unlikely to occur in reality and it depends on the relevance of other location attributes affecting consumers' location choices, that is, it depends upon the level of population sensitivity to access. Hence, under global equilibrium, we expect that a significant part of transport users' benefits are retained by transport users and the rest percolate into land rents.

A widespread practice is the use of partial transport equilibrium models for transport project assessments, which, by ignoring technological externalities, implies that the resultant measures of B^{TU} underestimate total benefits. A less common practice, but one still mentioned in planning studies, is to assess transport project benefits by measuring the expected change in land rents, which is expected to underestimate total benefits, especially if sensitivity to access is not the dominant factor for activity location. Moreover, indexes of B^{LU} can be severely confounded by the impact of population and economic growth on rents and relocation. In some cases, the underestimation of benefits is considered a minor problem, assuming that higher benefits will only improve the possibilities of the project to be developed, but this should be assumed with caution as it is not clear to what extent this underestimation would favour some type of projects systematically. For example, it may bias results persistently towards some specific transport modes or population categories.

The main recommendation arising from these conclusions is that practice in transport project appraisals should move towards land-use – transport integrated models to assure global equilibrium conditions, which incorporates all access and technological location externalities.

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