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INTERNALISATION OF TRANSPORT NOISE EXTERNALITIES: ACTIVITY DISTURBANCE PRICING AND IMPLEMENTATION*

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Abstract

A transport noise-pricing model is developed, which distinguishes between transport sound externalities, real resource costs of transport noise externalities and monetary valuations of such costs. It differs from existing approaches (hedonic pricing and contingent valuation), which aim at monetary valuations directly. The internalisation of transport noise externalities is modelled at the micro-level and allows aggregation across a population to any desired extent. A transport noise externality is characterised for every individual as a set of maps from the space of (non-marketable) transport sound commodities into the set of feasible actions (marketable and non-marketable human activities) such that the set of feasible actions is reduced. The concept of real resource costs to an individual corresponds to the duration of disturbances of optimally chosen human activities and is measured in units of time. Monetary valuations of such costs require only positive personal incomes, irrespective of their source. One example is given of applying a dominant strategy mechanism (Mookherjee and Reichelstein) to the solution of the model, assuming the objective is to select transport service productions which maximise economic profit, appropriate noise measurement technology exists to allow the identification of transport sound sources, and 'polluter pays' legislation exists which can be enforced costlessly.

INTERNALISATION OF TRANSPORT NOISE EXTERNALITIES, DURATION OF ACTIVITY DISTURBANCES, INCENTIVE COMPATIBLE MECHANISMS, INCOMPLETE MARKETS, SINGLE NOISE EVENT METHOD

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* An earlier version of the activity disturbance noise-pricing model was presented at the Workshop - Economic Assessment of Transport Noise, 7th International Congress on Noise as a Public Health Problem, November 1998, Sydney. This paper is an up-dated version of MGSM WP 2004-1, ©Ernestine M.A. Gross

1. INTRODUCTION

Transport noise (and other community noise) has become an important problem for individuals, urban planners, governments, and transport service providers (WHO, 1993; Lambert and Vallet, 1994; Gross, 1994; Berglund and Lindvall, 1995, Report by the Senate Select Committee on Aircraft Noise in Sydney, 1995; Lambert et al, 1998; Schwela, 1998 among others). There is a problem of conflicting interests and this problem is expected to increase in the future: Demand for transport services is projected to increase but residents in many urban environments would like a reduction in noise pollution. Failure to address this problem entails misallocation of resources, either in the sense of some individuals gaining while others lose in terms of their personal welfare, or in the sense that the aggregate welfare losses due to transport noise outweigh the welfare gains from the provision of transport services. There is no 'market solution' to this problem of conflicting interests because there is no 'market' for transport sound. The institutional invention of tradeable pollution rights does not solve this problem; a non-market agent is required to determine the total amount of pollution, including an accepted methodology for measurement and costing of pollution levels. The need for economic methods to estimate the cost of transport noise for the purpose of project evaluation and the efficient 'internalisation' of these costs by means of polluter pay policies is recognised (eg OECD/ECMT, 1994). It has also been recognised by the scientific community, concerned with the physiological effects of noise, particularly long-term adverse health effects (ICBEN, 1998). To be useful for private and public sector decision makers, who employ financial methods as decision making aids, the economic cost estimates need to be expressed in monetary terms. Similarly, 'polluter pays' policies involve monetary payments.

There are two existing economic methods of estimating a monetary value (cost) of transport noise, namely hedonic pricing and contingent valuation[1]. These methods have a common underlying theoretical framework and they share a welfare criterion. They differ in the assumption made about the market structure and how much information can be inferred from market prices.

Hedonic pricing, makes a strong assumption about the structure of markets and hence the role of markets in allocating resources efficiently. It assumes asset (real estate) market prices completely span the state space of decision variables.[2] The asset prices are assumed to reveal individuals' budget constrained preferences ('revealed preference approach') and the aim of empirical studies is to impute the cost of transport noise from real estate market prices. (Walter, 1975; Pearce, 1978; Nelson, 1980; O'Byrne et al 1985; Pennington et al, 1990; Uyeno et al 1993, Levesque, 1994; Renew, 1998 among others).

The alternative economic method, known as contingent valuation, makes an equally strong assumption about the role of markets in allocating resources, however at the opposite extreme. This method essentially assumes that market prices contain 'no relevant information'. Consequently, attempts are made to estimate the 'social cost' of

[1] In special circumstances where noise insulation restores the welfare of individuals, the direct cost method would also belong to this class of models.

[2] In the specialist area of finance, the Capital Asset Pricing model makes an equivalent spanning assumption regarding financial assets (eg Jarrow, 1988)

noise by trying to elicit information about individuals' preferences directly ('stated preference approach') within the context of simulated choice situations (Soguel, 1996; Weinberger, 1992).

Hedonic pricing, developed in the specialist area of transport economics (Walter, 1975), is the most widely used and accepted economic method. Its apparent appeal is the objectivity of data (market prices). However, its applicability is restricted to those cases where the 'complete spanning' assumption sufficiently closely approximates the actual conditions. Empirical researchers do not seem to appreciate the importance of the spanning condition (Starret, 1988; see also Kanemoto, 1988). For example, the aircraft noise sharing policy, introduced in Sydney and elsewhere, is not consistent with the complete spanning condition; in the limit there is not even one house, the price of which can reflect the absence of 'noise'. Similarly, if residential location *per se* is an element in the utility function of an individual (historical value, proximity to friends or place of work) then the spanning condition is violated, too.

Contingent valuation originated in the specialist area of environment and resource economics (Davis, 1963; Mitchell and Carson, 1989; Flatley and Bennett, 1996 among others). This method is considered to be controversial and costly (Arrow et al, 1993, Lambert et al, 1998). However, if a local environmental problem is 'big', in the sense that its solution would significantly disturb all local market prices, then these prices cannot be presumed to contain any relevant information and the contingent valuation approach seems to be difficult to avoid.

The model presented in this paper assumes market prices do contain relevant information but 'not all of it'. The incompleteness of markets is reflected in the solution to the model, which requires market and non-market information. The welfare criterion in this model is the same as in the existing methods. However, in contrast to hedonic pricing and contingent valuation, which use traditional microeconomic concepts and methods to arrive at monetary values directly, the approach taken in this paper is to first characterise an efficient internalisation of transport noise externalities in a general equilibrium model, assuming 'price-taking in utility' (Lindahl equilibrium). Second, a 'transport noise-pricing' model is developed, the solution of which does not require information on the marginal rate of substitution (personalised relative price) between 'noise' and a numeraire commodity. In this model, a transport noise externality for an individual is characterised by maps from the space of non-marketable transport sound commodities into an individual's set of feasible actions (marketable and non-marketable human activities) such that the set of possible actions is reduced. In contrast to the existing methods, this model separates transport noise externalities into real resource costs (duration of disturbance of human activities, measured in units of time) and the monetary valuation. The real resource costs are independent of the institutional environment. They can be aggregated across individuals by addition. They lend themselves for comparative studies across space and time. Monetary values can be made dependent on the institutional environment (labour market prices, or administratively determined prices or both). A strictly positive money income is sufficient to achieve monetary valuation, irrespective of its source. To avoid cumbersome notation, the transport noise-pricing model does not include securities markets, while recognising that such markets would provide yet a further possibility for positive incomes other than those provided by labour markets or income transfers. The model is presented in minimalist form in section 2.

The assumption of 'price-taking in utility' is a strong one for a model such as the present, which is intended to be of practical use, because this assumption excludes strategic behaviour. The approach taken to deal with this problem is contained in section 3 of this paper. It consists of examining the properties of the transport noise-pricing model in section 2 from the perspective of implementation theory. One example of implementation is considered. On the assumption that there exists an appropriate transport noise measurement and reporting technology, and polluter pays legislation (with negligible costs) the solution of the noise-pricing model is implementable with a dominant strategy mechanism (Mookjerjee and Reichelstein, 1989).

Section 4 contains a brief discussion of possible applications of the model, including alternative assumptions about the institutional environment for the purpose of policy formation.

2. TRANSPORT NOISE-PRICING MODEL

Theoretical models of non-dictatorial resource allocation systems take as axiomatically given that each individual knows what is 'best' for him or her in terms of consumption of *commodities.* This idea is made precise by the concept of *preferences* (a preordering). A *commodity* is defined in terms of its physical properties, date of availability, location of availability. (Taking into account one notion of uncertainty, a *state dependent commodity* is defined as a *commodity*, which is made available conditional on a 'state of nature' occurring.[3]) The interpretation of a 'location' in terms of geographical dimensions and the interpretation of a 'date' in terms of calendar time depend on the practical problem at hand. Quantities of a commodity are measured in appropriate units, eg. grams, miles, $\{\text{amplitude, phase}\}$. Transport sound satisfies the definition of a commodity.

Let $I = \{1, \cdots, I\}$ denote the index set of individuals in an urban community. As an approximation, all commodities are assumed to be measurable in real numbers. Let $x_z^i \in \Re$ denote the quantity of *commodity* z; $x_z^i > 0$ if commodity z is consumed by individual i, $x_z^i < 0$ if z is supplied by i and $x_z^i = 0$ if neither consumed nor supplied. Let $x_M \in \Re^M$ denote an M-dimensional vector of marketable consumption commodities (including transport services) and let $p_M > 0$ denote a strictly positive vector of prices for these commodities. Let $x_L \in \Re_-^L$ denote an L-dimensional vector of marketable labour services with prices (wages) $p_L > 0$, and let $x_I^i \in \Re_+^{I_i}$ denote a vector of services, which are supplied by i for *i's* own consumption. Examples of such services include gardening, watching TV, going shopping, sleeping. These activities are non-marketable commodities and therefore there are no market prices. Marketable and non-marketable labour services may be referred to as 'human activities'.

Let $y_N \in \Re_+^N$ denote a vector of transport sound commodities and let $y = (y_L, y_M, y_N) \in \Re_-^L \times \Re^M \times \Re_+^N$ denote a production vector (project); input commodities are non-positive quantities and output commodities are non-negative quantities. To save on notation, *M*, *L*, *I*, and *N* denote respectively both, the set of and the (finite) number of

[3] Debreu (1959)

marketable non-labour commodities, marketable labour, non-marketable labour activities, and noise commodities. The representation of transport sound by a finite dimensional Euclidean space is an approximation with the following interpretation. To allow for different human reactions to noise levels, as measured by say $L_{(max)}$dB between 'night' and 'day' time, two 'noise commodities' are required for each day. Allowing for longer time periods or finer partitions of the time unit 'day', say hours, as well as other noise measures, say $L_{(eq,\ x\ hrs)}$, $L_{(eq,\ y\ hrs)}$ etc, the number of noise commodities, N, may be very large[4]. Noise commodities are non-marketable.

Each individual is assumed to have convex and closed preferences. Hence, preferences can be represented by smooth real valued utility functions[5], $u^i : \Re^L_- \times \Re^M_+ \times \Re^{L_i}_+ \to \Re \; \forall i \in I$. Let $u^i_{kz}(x^i)$ denote the i^{th} individual's marginal rate of substitution (trade-off) for the commodities k and z at a point $x^i = (x^i_L, x^i_m, x^i_{L_i}) \in \Re^L_- \times \Re^M_+ \times \Re^{L_i}_+$. Each individual is assumed to be non-satiated in the consumption of marketable commodities and non-marketable human actitivies. To save on notation, asset markets are ignored and individuals' endowments are assumed to consist of marketable and non-marketable human activities.

A transport service production is characterised by a production vector, $y = (y_L, y_M, y_N) \in \Re^L_- \times \Re^M \times \Re^N_+$. Transport sound occurs if $y_h > 0$ for some $h \in N$.

Assuming individuals are 'price takers in utility', a decentralised solution to the problem of transport noise is provided by a Lindahl equilibrium[6]. In this case an efficient internalisation of the pollution costs means that the polluting transport service provider pays for the cost $c = \sum_{i \in I} \sum_{h \in N} p^i_{rh} y_h$ where $p^i_{rh} = u^i_{rz}(x ; y_h) < 0$ is the i^{th} individual's personalised relative price of noise commodity h in terms of a numeraire commodity r. Each individual's transfer ('compensation') is $c^i = \sum_{h \in N} p^i_{rh} y_h$. If the polluter pays policy is not imposed, then the i^{th} individual carries a personal cost ('noise tax'?) equal to c^i and the financial (commercial) value of project y over-estimates the economic value by an amount equal to c .[7]

The assumption of 'price taking in utility' implies ethical behaviour, which is often considered to be at variance with observed behaviour and it is incompatible with the assumption of 'non-satiation'. Individuals may have an incentive to misrepresent their preferences to, say increase their transfer payments. The application of non-cooperative game theory to design a 'mechanism' to induce individuals to 'truthfully reveal' their private information will be discussed in section 3. At present, the aim is to simplify the problem by finding conditions such that the pricing of transport noise commodities does not require information on individuals' marginal rates of substitution between 'transport noise' and a numeraire commodity.

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[4]Similarly, noise events, which differ regarding their frequency components, but not in terms of noise level, would constitute different commodities.

[5] Debreu (1954)

[6] Lindahl (1967). For applications to environmental problems see Blad and Keiding (1990)

[7] An example of the confusion between economic and financial value of an airport project and its consequences is described in Gross (1994). The idea of the model presented here is contained in the same paper.

The elementary time period chosen is a 'day', denoted by t. This interpretation of a *date* seems appropriate in terms of physiological characteristics of humans. It is assumed that the market structure is sequential (eg Radner, 1972, Kreps and Wilson, 1982) and that on any 'day' each individual can sell only one type of labour service commodity in the market.[8] On each day, each individual decides how to allocate his or her real resources ('time') between selling labour services for the purpose of 'making money' to buy 'goods and services' and non-marketable human activities. The set of feasible choices of the i^{th} individual is real resource constrained; the sum of the absolute values of the quantities of marketable and non-marketable labour services supplied on any one 'day', t, is equal to 1. Let

$$\overline{X}^i = \{(x^i_{L_t}, x^i_{I_t}) \in \Re^{L_t}_- \times \Re^{I_{i,t}}_+ : \sum_{j \in L_t} / x^i_{jt} / + \sum_{j \in I_{i,t}} x^i_{jt} = 1 \ \ \forall t = 1, \cdots, T\}, \ \text{with} \ \Re^L_- = \Re^{L_1}_- \times \cdots \times \Re^{L_T}_-$$

(identical embedding for $\Re^{I_i}_+$ and all other commodity sub-spaces), denote *i's* real resource constrained choice set (ie the set of feasible actions). Furthermore, each day, t, each individual *i* faces a budget constraint in the market for goods and services, namely $p_{M_t} x^i_{M_t} + p_{L_t} x^i_{L_t} = 0 \ \forall t$. The assumption of 'non-satiation' yields equality of income earned and income spent in the market. It is noted that the budget constraint depends on the choice variable $x^i_{L_t}$.

To save space and cumbersome notation, only one 'day' (*T=1)* will be considered in the following and the subscript *t* will be dropped. This simplification is innocuous for the purpose at hand because the market structure is sequential and intertemporal choices are not the subject of analysis.[9]

Without transport sound, ie. $y_h = 0 \ \forall \ h \in N$, individual *i* decides on an allocation, which is 'best' in the sense of being most preferred by *i* ('utility maximising') and the chosen allocation is budget and real resource feasible. Let $\hat{x}^i = (\hat{x}^i_M, \hat{x}^i_L, \hat{x}^i_I)$ denote i^{th} choice with ($\hat{x}^i_L$, $\hat{x}^i_I$) $\in \overline{X}^i$ and $p_M \hat{x}^i_M + p_L \hat{x}^i_L = 0$.

Let L_i denote the marketable labour service, which *i* can make available at t and define all marginal rates of substitution for individual *i* with respect to L_i. (The marketable commodity L_i provides a personalised numeraire commodity.) Individual *i's* preference maximising choice is characterised by: (i) The equality of the marginal rates of substitution (personalised prices) of the non-marketable human activities and the personalised numeraire commodity, ie $p_{L_i,k}(\hat{x}^i_{I_i}) = p_{L_i z}(\hat{x}^i_{I_i}) \ all \ k, z \in I_i, \ k \neq z$; (ii) The equality of the marginal rates of substitution and the prices of consumption goods and services relative to the personalised numeraire commodity, i.e. $p_{L_i m} = p_{L_i} / p_m \ all \ m \in M$.

The opportunity cost (market value foregone) of non-marketable human activities can be deduced from *i's* real resource constraint on human activities.[10] It suffices to

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[8] As with asset markets, long term labour contracts could be incorporated by introducing more notation but without changing the basic structure of the model.

[9] In an applied context, time and location may affect the parameter values.

[10] Some time for sleep per period of time is essential for survival. On the face of it this would suggest that the actual hours available for individuals to allocate is less than 24 hours per day. However, if one were to

consider two non-marketable human activities, *k* and *z*. The real resource constraint is $\hat{x}^i_k + \hat{x}^i_z + /\hat{x}^i_{L_i}/ = 1$. The money income from selling an amount $\hat{x}^i_{L_i}$ of the marketable labour commodity L_i is $p_{L_i}(-\hat{x}^i_{L_i})$. The feasible choice of non-marketable human activities, $\hat{x}^i_k, \hat{x}^i_z > 0$, implies that individual *i* values these activities at least as highly as the purchase of marketable commodities, which could be achieved by using the time to 'make money', i.e. $p^i_{L_ik}\hat{x}^i_k + p^i_{L_iz}\hat{x}^i_z \geq p_{L_i}(1-/\hat{x}^i_{L_i}/) = p_{L_i}\hat{x}^i_k + p_{L_i}\hat{x}^i_z$.

Individual *i's* optimal choice is illustrated in Figure 1 for the case of one marketable consumption good, *m*, one non-marketable labour service, *s*, and the marketable labour service, L_i. The points marked $-\bar{x}^i_{L_i}$, $\bar{x}^i_s$ indicate the real resource constraint. The relative market prices, p_{L_i}/p_m, imply a trade-off relationship between *m* and *s*, ie the implied opportunity cost.

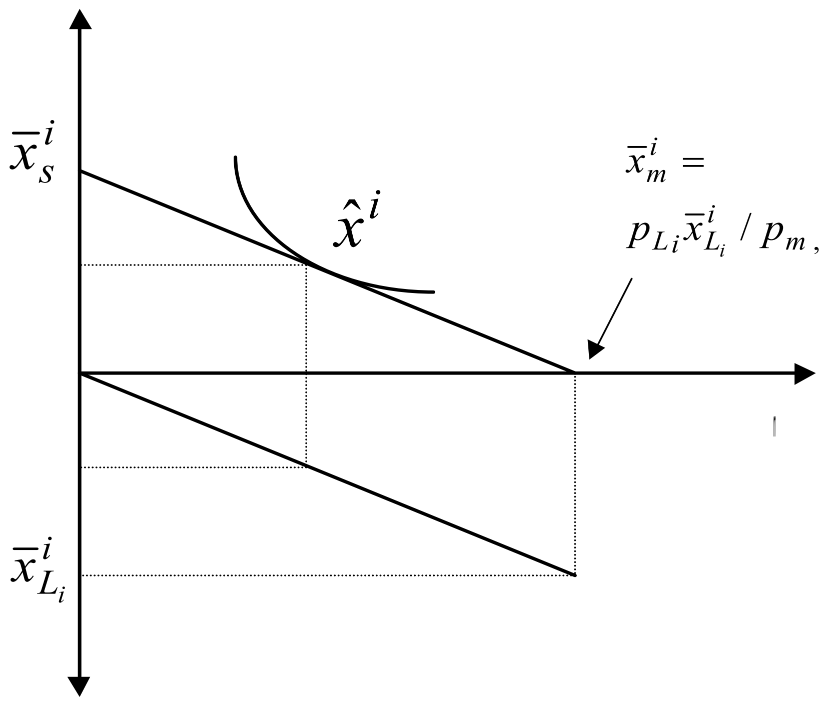

Figure 1.

The production of transport services creates a negative externality if for at least one individual in the urban environment the set of feasible acts is reduced.[11] Examples

follow this approach then the valuation of sleep disturbance due to transport noise would be excluded a priori.

[11] The above definition of a negative externality is a straightforward application of the notion of an 'externality' as found in mathematical economics. For example in Blad and Keiding (1990, pp 253-4): "The fundamental common feature of all types of externalities is that the acts of one agent affects the set of feasible acts of other agents. The result may either be that the other agents obtain a larger set of possible

of transport noise reducing the set of feasible acts for individuals are widely reported; sleep disturbances, reduced power of concentration, interference with viewing of television, listening to music, and conversations are some examples of activity disturbances, which were found to be associated with noise in psycho-acoustic studies (eg Hede and Bullen, 1982, Gross and Sim, 1997, among many other).

In the present model, negative transport noise externalities[12] are characterised for each individual, *i,* as maps from the space of transport sound commodities into the individual's set of feasible actions, $f_z^{\,i} : \Re_+^N \rightarrow \overline{X}^i$, $\forall z \in L_i \cup I_i$ all $i \in I$, such that for some $i \in I$ and some $h \in N$ the resulting set of possible choices $\widetilde{X}^i$ is 'smaller' than $\overline{X}^i$, i.e. $\widetilde{X}^i \subset \overline{X}^i$ strict.

Let $y_h > 0$ denote the quantity of transport sound commodity h associated with the production of transport service $y = (y_L, y_M, y_N) \in \Re_-^L \times \Re^M \times \Re_+^N$ and let $x_z^i(y_h)$ denote the quantity of activity z which by f_z^i is no longer a possible choice for individual i due to the transport noise event $y_h > 0$. Noting the sign convention for marketable and non-marketable human activities, $/x_z^i(y_h)/$ takes values in the closed interval $[0,1]$ for the relevant range of values of $0 \le y_h \le \bar{y}_h$ (for the purpose of economic analysis, $\bar{y}_h$ is a technologically given parameter). The transport noise externality $/x_z^i(y_h)/$ is measured in units of time and expressed as a fraction of the elementary time interval, called 'a day'.

An external effect is illustrated in Figure 2. In this example $f_z^{\,i}$ is assumed to be non-decreasing in *h* and twice differentiable over the relevant range. The transport sound event $\widetilde{y}_h$ has the effect of reducing the endowment of the real resource L_i from $\bar{x}_{L_i}^{\,i}$ to $\widetilde{x}_{L_i}^i$ with $x_{L_i}^i(y_h) = \bar{x}_{L_i}^i - \widetilde{x}_{L_i}^i$. The externality function $f_z^{\,i}$ depends on the individual and on the type of human activity.[13].

choices - in this case we speak of a positive external effect - or they experience a reduction in their possibilities of choice, a negative external effect".

[12] There are examples of transport sound creating positive externalities. A parent tries to calm a screeming toddler. The parent hears an approaching plane, points to the sky, the toddler sees the plane and stops screeming. The parent's set of feasible choices has expanded; time used to calm the toddler is now available for something else. It seems such positive externalities are quantitatively unimportant.

[13] Individual A may be more 'noise sensitive' than individual B with respect to all human activities ($x_z^A(y_h) > x_z^B(y_h)$ all z) or an individual may be may be more 'noise sensitive' with respect to activity *k* than *z* ($x_k^A(y_h) > x_z^A(y_h)$). The notion of relative 'noise sensitivity' in this definition is unrelated to preferences. The notion is rather akin to the observation that some people do not respond well to some type of food and they say they 'can't eat it even though they like the taste of it'; ie a restriction on the consumption technology. Given the definition of a *commodity*, changes in relative noise sensitivity over time can be taken into account.

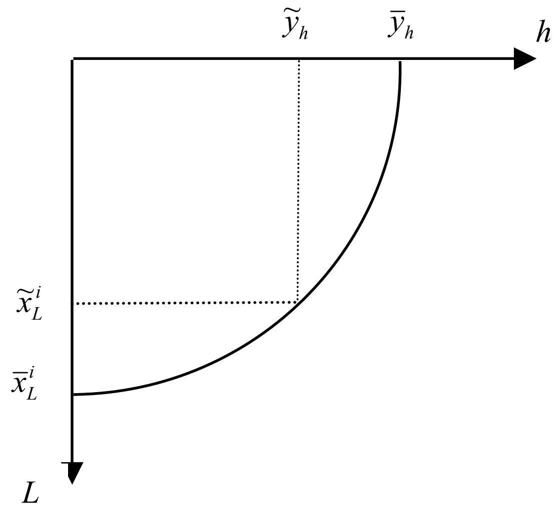

Figure 2

The transport noise externality $x_z^i(y_h)$ is costless for the individual if $/\tilde{x}_z^i/ > /\hat{x}_z^i/$ because the most preferred choice is not disturbed. Let $x_z^i(y_h\,;\hat{x}_z^i)$ denote the duration of the disturbance of activity *z*, given the optimally chosen amount of this activity, $\hat{x}_z^i$. This is a measure of the real resource cost of a transport noise externality, $f_z^i(y_h) = \tilde{x}_z^i$, to the i^{th} individual. It is defined by $x_z^i(y_h\,;\hat{x}_z^i) := \begin{cases} /\hat{x}_z^i/-/\tilde{x}_z^i/ & \text{if } /\hat{x}_z^i/>/\tilde{x}_z^i/ \\ 0 & \end{cases}$.

The total real resource cost to individual *i* of the transport sound event y_h is given by $0 \le x^i(y_h;\hat{x}^i) = \sum_{z \in L_i \cup I_i} x_z^i(y_h\,;\hat{x}_z^i) \le 1$. The total real resource cost of the transport sound event y_h to the 'community' $i = 1, \ldots, I$ is the sum of the costs to the individuals, $0 \le x(y_h\,;\hat{x}) = \sum_{i \in I} x^i(y_h\,;\hat{x}^i) \le I$.

The monetary valuation of individual *i's* real resource costs of a transport noise event, y_h, is given by $p_{L_i} x^i(y_h\,;\hat{x}^i)$, where p_{L_i} is the price of the labour service sold by *i* at *t*.

Assuming not all members of a community derive monetary income from the sale of labour services (and there are no asset markets for intertemporal wealth transfers), but the social norms of a particular community are such that income transfers (social welfare payments) are legislated, then a monetary valuation of individual's real resource costs of a transport noise event is still possible. Let $p_{S_i} > 0$ denote the transfer payment received by individual *i* during period, t (a 'day'). Keeping all else constant, individuals on income support allocate their time among non-marketable human activities. The monetary valuation of the duration of disturbances of human activities is given by $p_{S_i} x^i(y_h\,;\hat{x}^i)$.

The foregoing description of the model is minimalist in the sense that only one transport sound event has been considered. The aim of section 2 was to bring out the distinction between the notion of a transport sound externality, the real resource costs of such an externality to an individual and to the 'community', and its monetary valuations under alternative assumptions about the institutional environment by means of applying the methodology of general equilibrium theory. The primitives of this theoretical framework represent the philosophical stance that the material welfare of individuals is central to economic analysis.

It is convenient to treat the aggregation of several transport sound events for an individual and the disaggregation of transport service production in the following section. The simplifying assumption of one *date*, *t*, and one location ('community') will be maintained.

3. IMPLEMENTATION

There is a finite number of transport services producers, $j = 1, \ldots, J$. Let J also denote the index set for such producers. The internalisation of transport noise externalities requires that transport service producer j with production $y^j = (\tilde{y}^j, y_N^j)$, $\tilde{y}^j = (y_L^j, y_M^j) \in \Re_-^L \times \Re^M$ and sound events $y_N^j \in \Re_+^N$ pays $c^j = \sum_i p_{L_i} x^i(y_N^j; \hat{x}^i)$, where $x^i(y_N^j; \hat{x}^i) = \sum_h \sum_z x_z^i(y_h^j; \hat{x}_z^i)$ and individual i receives a transfer payment $c^i = p_{L_i} x^i(y_N^j; \hat{x}^i)$ from transport service provider j. In contrast to the Lindahl equilibrium, the internalisation of transport noise externalities does not require information on individuals' marginal rate of substitutions between transport sound commodities and a numeraire commodity.

Let $Y \subset \Re_-^L \times \Re^M \times \Re_+^N$ denote the total set of technologically possible transport service productions for an economy ('community')[14], with $y = \sum_j y^j$ being an element in Y. Efficient resource allocation amounts to choosing that transport service technology, $y^* \in Y$, which yields the highest economic profit, i.e. $\tilde{p}\tilde{y}^* - c^{y^*} \geq \tilde{p}\tilde{y} - c^y$ all $y \in Y$.

The first term in the definition of economic profit, $\tilde{p}\tilde{y}$, corresponds to the commercial or 'market value' of a transport service project[15]. The second term, c^y, is the total monetary value of the transport noise externalities associated with the total transport production *y*. The transport noise pricing model of section 2 specifies that $c^y = \sum_{j \in J} \sum_{i \in I} p_{L_i} x^i(y_N^j; \hat{x}^i)$ for a given $y \in Y$.

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[14] For the present purpose, it is sufficient to make only one assumption on the properties of the total production technology, namely that it is technologically possible to have no transport services, ie $0 \in Y$.

[15] In an applied context project y' may differ from project y in terms of the type of transport infrastructure (air, water, rail, road) or in terms of the utilisation of an infrastructure type (eg light aircraft versus heavy aircraft, time of the day of operation, flight paths modes, etc) or in terms of geographical locations, or in terms of construction methods (different road surfaces). Trade-off decision problems between noise externalities and construction methods or operating modes amount to comparing the economic profits of alternative projects. Similarly, 'abandonment decisions' involve comparing the economic profits of existing versus alternative transport infrastructure or alternative utilisations. For some transport noise problems (eg aircraft, infrequent trucks, motor cycles), single noise events can be used to describe differences in transport service technologies. The single noise event technology seems to be particularly suitable for applying the model described in this paper

While all variables in the solution to the model of section 2 are measurable, the empirical measurement raises familiar methodological problems in research that involves human subjects. Laboratory studies offer control over at least some conditions. However, these methods may be intrusive, inducing behaviour changes. Alternatively, field studies, which rely on asking people to report the duration of activity disturbances (and state their personal incomes), are subject to the problem of strategic behaviour. In particular, non-satiated individuals have an incentive to overstate the duration and opportunity cost of activity disturbances in order to increase their wealth[16]. On the other hand, private owners or operators of transport infrastructure, whose objective it is to maximise shareholders' monetary returns (ie commercial profits), or managers whose bonuses depend on the monetary returns have an incentive to minimise the transfer payments to noise affected residents by, say, under-reporting transport service productions. There is a conflict of interest problem and all agents have an incentive to misrepresent their private information.

The objective of internalisation of transport noise externalities, as described above, belongs to a class of planning problem ('economic engineering'), which is addressed in the theory of implementation. The aim of this theory is to design game forms (called 'mechanisms') such that the equilibria satisfy socially desirable properties but which do not require vast amounts of knowledge by the planning authority. The 'rules of the game' should be such that the social arrangements are self-policing. The designer of the mechanism should only have to make sure that all 'players' respect the 'rules of the game'. This may entail enforcement of the rules by means of monetary or non-monetary fines.

The design of a mechanism requires the selection of a suitable solution concept, given the information structure of the game form[17]. A social objective (such as the efficient resource allocation with the internalisation of transport noise externalities) is said to be implementable with respect to the chosen solution concept. Since the pioneering work by Clarke (1971), Mirrlees (1971), Groves (1973), Groves and Ledyard (1977), implementation theory has developed rapidly, both in terms of basic research (eg necessary and sufficient conditions for implementation with respect to various solution concepts[18], the efficiency[19] and dynamic properties[20] of alternative mechanisms) and in specialist areas such as voting mechanisms, incentive compatible contracts, and the allocation of public goods.[21]

Assuming an appropriate and agreed upon transport sound measurement technology exists and it is recognised in 'polluter pays' legislation and the enforcement costs are negligible then the dimensionality of the planner's decision (the choice of y^*) can be reduced from M+L+N to one (ie, $c \in \Re$). For any given total transport noise

[16] Whether people are as 'greedy' as assumed in general equilibrium models of competitive economies and in non-cooperative game theory is an unresolved empirical question.

[17] ie complete or incomplete information

[18] see Maskin (1977), Maskin (1985), Repullo (1987) on Nash equilibria. Moore and Repullo (1989) on subgame perfect implementation. Abreu and Matsushima (1992) on virtual implementation in iteratively undominated strategies, Abreu and Matsushima on exact implementation of iteratively weakly undominated strategies. Fudenberg and Tirole (1996) on Bayesian implementation.

[19] eg Mookherjee and Reichelstein (1989), Laffont and Tirole (1987)

[20] eg Cabrales (1999)

[21] see Myerson (1991), Corchón (1996)

externality cost, *c,* the decision about the commercial part of transport service production, $\tilde{y}$, can be decentralised, using market prices. The disaggregation of a total noise externality cost to the individual producers depends on the accuracy of the transport sound measurement technology in distinguishing between different transport noise sources. For the purpose of the present discussion, the technology is assumed to be sufficient. The problem reduces to finding a mechanism to induce consumers to 'truthfully reveal' their private information, given alternative transport service productions.

The solution to the model in section 2 satisfies the conditions provided by Mookherjee and Reichelstein (1989) for a class of models in which dominant-strategy implementation involves no welfare loss for the planner relative to Bayesian implementation.[22] A dominant-strategy mechanism has the property of inducing each player to announce his type ('tell the truth') independently of the announcements of the other players. Mookherjee and Reichelstein assume that each individual $i = 1, \cdots, I$ has a quasi-linear utility function, $u^i(x,k,\theta) = V^i(x^i,\theta^i) + k^i$, where θ is a 'state variable' (ie agent type) and k^i is the transfer to agent *i*. They allow x to be multi-dimensional, but require V^i to depend on x only through a one-dimensional statistic $h^i(x)$ such that $u^i(x,k,\theta) = V^i(h^i(x^i),\theta^i) + k^i$. Furthermore, they assume that agent types are independently distributed on a closed interval of agent types, $[\underline{\theta}, \overline{\theta}]$, and the distribution of the i^{th} type satisfies the monotone hazard rate condition[23], and preferences satisfy the sorting assumption[24].

The interpretation of the transport noise model in section 2 in terms of Mookherjee and Reichelstein's conditions is straightforward. Let $x = (x_M, x_L, x_I)$ be a M+L+I dimensional consumption of marketable commodities and marketable and non-marketable human activities, as defined in section 2. The state variable (agent type) is the maps (f_z^i). Assume for each individual *i*, f_z^i is continues and non-decreasing in *h,* all $h \in N$ and $z \in L \cup I_{\mathrm{i}}$. Let $k^i = c^i = \sum_h \sum_z x_z^i(y_h;\hat{x}_z^i)$, i.e. the duration of the disturbances of optimally chosen human activities due to transport noise externalities[25]. Define

$$\hat{\hat{x}}_z^i(y_h;\hat{x}_z^i) := \begin{cases} /\hat{x}_z^i/ & if \ /\tilde{x}_z^i/ \geq /\hat{x}_z^i/ \\ /\hat{x}_z^i/ - x_z^i(y_h;\hat{x}_z^i) & if \ /\tilde{x}_z^i/ < /\hat{x}_z^i/ \end{cases}$$

and $h^i(x) := \sum_z \hat{\hat{x}}_z^i(y_h;\hat{x}_z^i)$. $h^i(x)$ is a one-dimensional statistic.

For the purpose of real resource costs, all agent types are in the closed interval [0,1]. For the purpose of monetary valuation based on labour market prices, all agent types are an element in the closed interval $[\underline{p}_{L_i}, \overline{p}_{L_i}]$. The assumption of an independent distribution of agent types does not seem to be a strong one in this context.

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[22] See Fudenberg and Tirole (1996, 7.4.2)

[23] $\frac{d}{d\theta}\left(\frac{a(\theta)}{1-A(\theta}\right) \geq 0$

[24] $\partial V^i / \partial\theta^i \partial h^i \geq 0$. They also assume that $\partial^2 V_i / \partial h^i \partial\theta^i \geq 0$

[25] as defined for one sound commodity, *h,* in section 2.

The definition of the incentive compatibility constraint in dominant strategy (and Bayesian) implementation requires only that the utility derived from revealing the 'true agent type' is at least as great as the utility of the pay-off derived from revealing any other type[26]. It is assumed that when individuals are indifferent between the pay-offs obtained from the announcement of different types they will announce their 'true type'. In the above mechanism, individuals cannot improve on their pay-off by announcing any other type than their 'true type'.

4. DISCUSSION

The model provides an alternative approach to existing economic methods of assigning a value (cost) to transport noise. In contrast to hedonic pricing and contingent valuation the present model distinguishes between *transport sound externalities,* the *real resource costs of transport noise externalities* and *monetary valuations* of such costs. The internalisation of transport noise externalities is modelled at the micro-level and allows aggregation across a population to any desired extent. One example of applying a dominant strategy mechanism (Mookherjee and Reichelstein) to the solution of the model is given, assuming the objective is to select transport service productions which maximise economic profit, appropriate noise measurement technology exists to allow the identification of transport sound sources, and 'polluter pays' legislation exists which can be enforced costlessly.

The transport noise-pricing model is a one period-one location model. An extension to several periods would make the introduction of asset markets as a source of intertemporal income transfers meaningful but not interesting because the solution to the model requires only that every individual have a positive monetary income in each period, irrespective of its source. However, the possibility of long-term transport noise exposure affecting individuals' *sets of feasible choices of marketable and non-marketable human activities* cumulatively (say a deterioration of health or physical wellbeing in a more general sense) calls for care in empirical applications of the one period model.

The definition of the theoretical concept the *real resource cost to an individual* corresponds to the common language expression, 'duration of disturbances of what I wanted to do'[27]. Activity disturbance has been found to be a significant scale variable in the psycho-acoustic literature. However, the psychology-based methods do not take the duration of activity disturbances into account. The model allows disaggregation of human activities to any desired number of categories as long as the total time used for the activities is no more than 24 hours per day. This feature of the model, cumbersome as it

[26] Using the notation from the above description of Mookherjee and Reichelstein's work, as found in Feudenberg and Tirole (1996, pp 270-71), a dominant strategy mechanism is a function $y(\theta)$ such that, for each agent $i = 1, \ldots, I,$ and for each $\theta_i, \hat{\theta}_i,$ and θ_{-i}, Dominant Strategy Incentive Compatibility requires $u_i(y(\theta_i,\theta_{-i}),\theta_i) \geq u_i(y(\hat{\theta}_i,\theta_{-i}),\theta_i)$.

[27] An exploratory study, carried out in conjunction with a standard psycho-acoustic survey instrument showed that the notion of 'duration of disturbances of human activities' is meaningful to residents (Gross and Sim, 1998)

may be in terms of notation, is deliberate because empirical research in the psycho-acoustic literature indicates that the reaction of humans to noise differs across activities.

The real resource cost measure is independent of the institutional environment in an economy. This is a desirable feature. Monetary economies tend to have periods of inflation and deflation - some countries more so than others - and at times there are real estate market bubbles and the relative values of national currencies fluctuate. While these monetary phenomena do not create additional problems for the internalisation of transport noise externalities at the time when transport infrastructure projects are evaluated, they do introduce arbitrariness into the data for all other purposes. For example, comparison of data over time or space is difficult. Furthermore, monetary values based on labour market data makes the valuation of transport noise costs dependent on the income distribution, which may differ across locations within a country and between countries. Some societies may agree that some activities (eg sleep) are equally important for all its members and the duration of disturbances of these activities should have the same monetary value, irrespective of the individuals' ability to earn money in the labour markets. In such cases, administratively determined prices may be used to value the real resource cost.[28] Finally, data on the duration of the disturbance of various types of human activities may be more meaningful to legislators than monetary aggregates.

At present aircraft noise assessment methods are methodologically incompatible with methods used to allow for transport noise costs in transport infrastructure project evaluation. The former uses psycho-acoustic data while the latter uses monetary values obtained from economic methods such as hedonic pricing or direct costs. The present model provides a unified economics based framework. The real resource cost is measured in units of time, which may be expected to correlate better with acoustic data than scale variables. The present model lends itself to the application of single noise event data.

Implementation theory may also be applied to contingent valuation. However, the present noise-pricing model has advantageous features. Firstly, as outlined in section 3, the solution to the model is compatible with one-dimensional mechanisms. This is desirable because there is a greater choice of mechanisms. Furthermore, for some one-dimensional mechanisms the minimum number of players is quite small (eg 3 in the case of Abreu and Matsushima's mechanisms). Second, an empirical application of the concept of real resource costs of transport noise externalities requires data on individuals' planned activities (a 'time budget') and concurrent observations on transport noise events and the duration of disturbances of the planned activities. In contrast to contingent valuation, there are no hypothetical choice situations involved. The data may be assumed to be meaningful not only to economists but also to the general public. Furthermore, plausibility checks can be made about monetary valuations by just about anybody who has access to income data. The simplicity and transparency of the data requirements may make a method based on the present model less controversial than contingent valuation.

[28] Administered prices have been used to value positive externalities of transport. For example, 'travel time saved' is valued by means of administratively determined prices in the evaluation of road infrastructure projects in New South Wales, Australia (see the Road and Traffic Authority NSW Economic Manual, 1996) However, the theoretical justification for this method is obscure. The proposed method is a natural complement to the valuation of positive externalities, which would remove a possible bias in favour of road construction.

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