Multi-pollutant, Multi-Effect Assessment of European Air Pollution Control Strategies: an Integrated Approach

(M E R L I N)

Deliverable 2

Non-technical emission abatement options

UCL

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Non-technical emission abatement options

1 Methodological aspects of the incorporation of non-technical abatement measures in the MERLIN analysis

1.1 Introduction

The objectives of this part 1 of Deliverable 2 are to:

- Set out a coherent economic framework for the project, that supports the modelling approach that has been adopted, and allows technical and non-technical measures to be compared on a consistent basis.
- Provide a theoretical analysis of social cost minimisation problem, and determine the role for non-technical measures in the solution.
- Describe a solution algorithm that incorporates changes in sector activity levels into a technical cost minimisation model.

The key conclusions of the analysis are:

The distinction between technical and non-technical measures is rather more subtle and complex than might initially be supposed. While MERLIN is set up on the basis of a distinction between technical measures (i.e. those that affect sectoral emission coefficients) and non-technical measures (i.e. those that affect activity levels), this does not recognise that technical measures would generally be expected to affect both emissions coefficients and activity levels. From an economic perspective it is more useful to distinguish between measures that affect the supply of final consumption goods and services (the “supply side”) and measures that affect the demand for those goods and services (the “demand side”). Consequently, it seems natural to characterise the distinction between technical measures and non-technical measures on this basis; defining technical measures as those that affect the supply side, and non-technical measures as those that act on the demand side.

Under this definition, non-technical measures are never used as part of the optimal mix of abatement measures. While social cost minimisation requires reductions in output levels (activity levels), these result solely from the increases in the marginal cost of production induced by the introduction of technical abatement measures. There is no justification for additional demand side measures to further reduce activity levels.

A distinction needs to be made between measures and the mechanisms (i.e. policy instruments) used to implement those measures. It is perfectly possible for a technical measure to be implemented through the use of an emissions tax or other pricing measure. Similarly a non-technical measure might be implemented through the introduction of a demand quota. Thus care should be taken in interpreting the implications of the preceding conclusion. In particular, it does not imply that there is no role for taxes and other price instruments in implementing the optimal mix of technical measures.

It is possible to estimate the optimal solution to the choice of abatement measures, allowing for changes to activity levels as well as emissions coefficients, using an iterative algorithm that is designed fit in with the approach traditionally used to analyse technical measures. Specifically, the algorithm allows the determination of the optimal mix of technical measures (for a given level of activity in each sector) to be separated from the determination of the optimal reduction in sectoral output levels.

The structure of the report is as follows. Following this introduction there are five sections. Section 1 discusses the differences between technical and non-technical abatement measures, and identifies the pathways by which each type of measure will influence emissions. It also discusses the differences between abatement measures (technical or non-technical) and the mechanisms that may be used to implement them. In section 1.2, a stylised economic model is defined. This is used to derive expressions for sector / pollutant emission functions that are consistent with the modelling approach that has been adopted in MERLIN, together with an expression for the social cost of abatement. The social cost minimisation problem is analysed in section 3, and the necessary conditions for a social cost minimum are derived. Section 4 outlines an iterative algorithm that will yield the optimal solution while allowing the determination of the optimal mix of technical measures to be separated from the determination of the optimal reduction in output levels. The final section summarises the main conclusions of the report.

1.2 Abatement measures

This section discusses, from an economic perspective, the differences between technical and non-technical abatement measures, and the differences between abatement measures (technical or non-technical) and the mechanisms (i.e. policy instruments) that may be used to implement them.

1.2.1 An economic interpretation of the distinction between technical and non-technical measures

From an economics perspective the most useful distinction between measures is between those that affect the supply of final consumption goods and services (the supply side) and those that affect the demand for those goods and services (the demand side). Consequently, it seems natural to characterise the distinction between technical measures and non-technical measures on this basis. Specifically, technical measures are those that affect the supply side, while non-technical measures are those that act on the demand side.

An example of a technical measure in these terms would be a change in the production technology (e.g. the installation of emissions filters) that changed the relationship between activity and emissions. A non-technical measure could be a demand quota or sales tax on the consumption of a final commodity (e.g. domestic heating services).

Technical measures result in an upward shift in the supply curve because they would be expected to increase the marginal cost of production. In contrast, the introduction of non-technical measures (consumption measures) would act on the demand curve - typically such measures would shift the demand curve downwards. As can be seen in Figure 1, in each case the introduction of the measures leads to a reduction in the equilibrium quantity of the commodity produced and consumed (i.e. a reduction in the activity level). Starting from the initial equilibrium A, the introduction of a technical measure leads to a shift to a new equilibrium B with a reduced quantity consumed (quantity declines from X^0 to X^T). Alternatively the introduction of a non-technical measure would move the equilibrium to C. Again quantity will be reduced, in this case from X^0 to X^N.

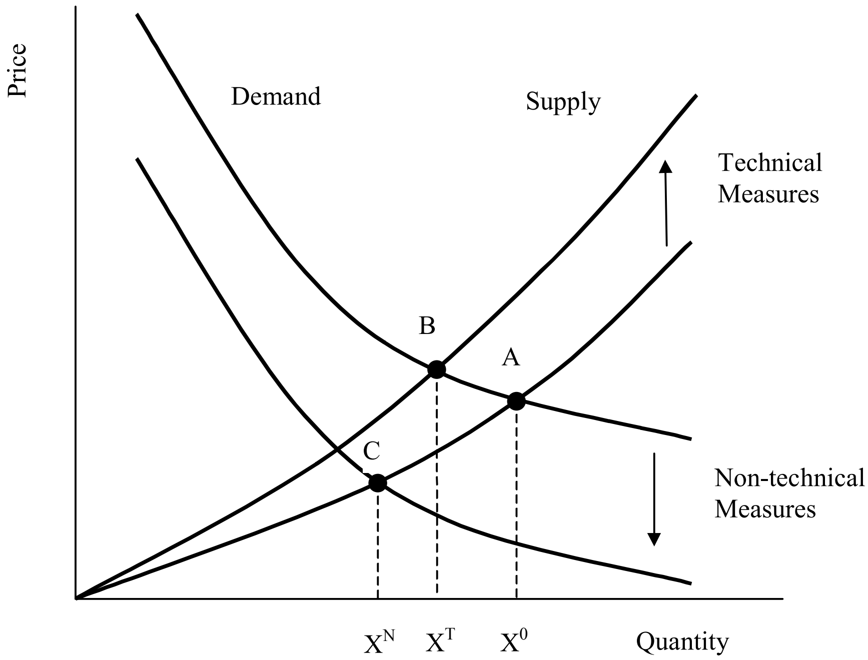

Figure 1: Impacts of technical and non-technical measures on activity level

Therefore it is incorrect to assume that technical measures do not affect activity levels. In fact there are two pathways by which technical measures affect emissions (see Figure 2). The first is through their impact on emissions intensity. The impact may be direct (i.e. on the sector's own emissions), or it may be indirect (i.e. on other sector emissions). For example, the latter would be the case for technical measures that improve energy efficiency. The second is through their impact on activity levels (i.e. output levels), arising from the resultant rise in the marginal cost of production. In contrast, non-technical measures only impact on activity levels.

An important feature of the way in which we have characterised abatement measures in this framework is that non-technical measures only apply to goods and services that enter into the final utility function of individuals. Thus, heating services or personal mobility are final consumption commodities, whereas electricity, heating apparatus, motor fuel and motor vehicles are inputs to the production of the respective final consumption commodities. This implies that some measures that are commonly thought of as non-technical measures are classified as technical measures in our analysis. For example, a shift between electric and gas central heating, or a shift between petrol and diesel vehicles would both be classified as technical measures.

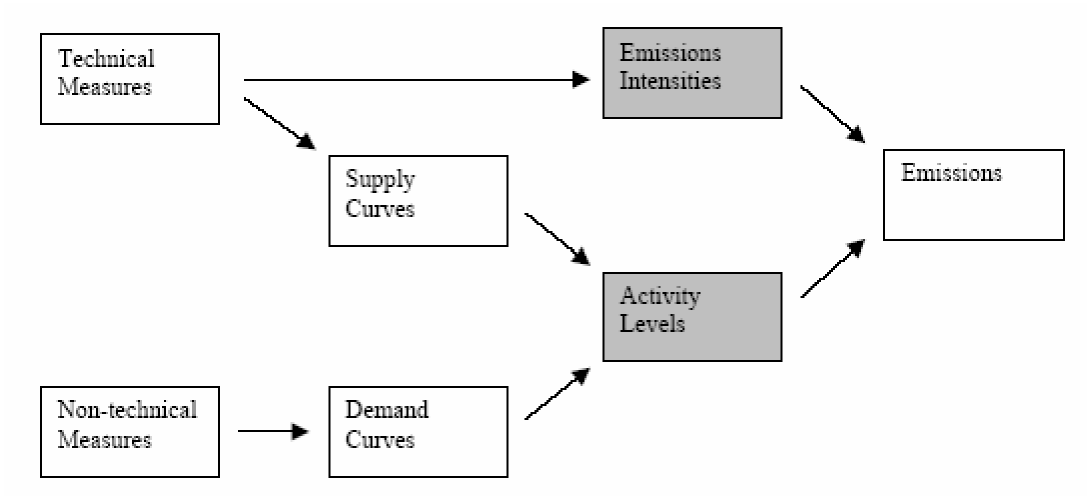

Figure 2: Impact pathways for measures

1.2.2 Measures versus implementation mechanisms

It is important to make a distinction between measures and the mechanisms used to induce the introduction of those measures (i.e. policy instruments). A technical measure (or combination of technical measures) may be implemented via the use of a tax or other economic instrument. For example, much of the impact of the US Acid Rain Program on production processes and technologies (installation of FGD equipment, changes to lower sulphur input fuels, etc) was achieved through the use of an emissions trading programme. These changes (which are clearly technical measures) resulted from the incentive effect of emissions trading, but could also have been achieved through direct command-and-control instructions to employ FGD abatement technologies, or a requirement to switch to low-sulphur coal.

Figure 3a) shows the effect of a technical measure that restricts the relative values of two input variables. The curve is an output isoquant, and the unrestricted choice of inputs would lead to the point A, where the isoquant is tangent to the line showing the relative prices of the two inputs. Under the technical measure, firms are required to operate at point B. However it is clear that this point could alternatively have been achieved by changing the relative prices of inputs by imposing a tax on input 1, or subsidy on input 2.

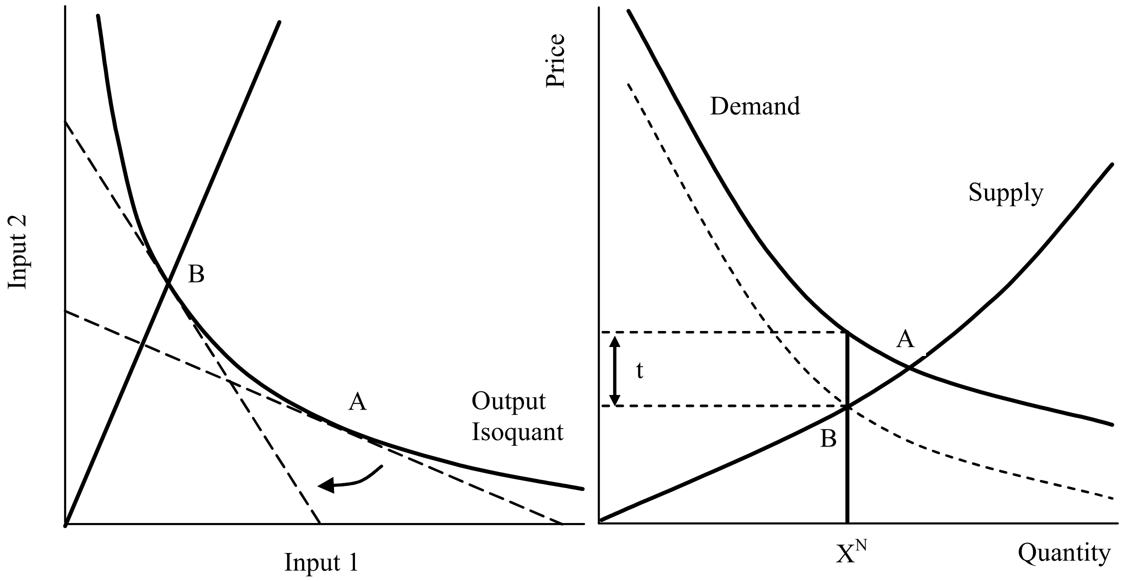

Figure 3: Implementation of abatement measures

a) Technical measure **b) Non-technical measure**

Similarly, non-technical measures may be implemented directly by the imposition of quotas or quantity restrictions, or indirectly by the use of consumption taxes. While the use of quotas in this way may be relatively unusual, it is not unheard of. An example of a quota used to reduce consumption was post-war rationing of motor fuel and other commodities.

This is shown in Figure 3b), where point A represents the pre-regulation equilibrium, and point B represents the equilibrium after the introduction of the non-technical measure. It is clear that this point can be achieved either by introducing a quantity quota X^N, or by setting a consumption tax equal to t, which has the effect of shifting the demand curve downwards.

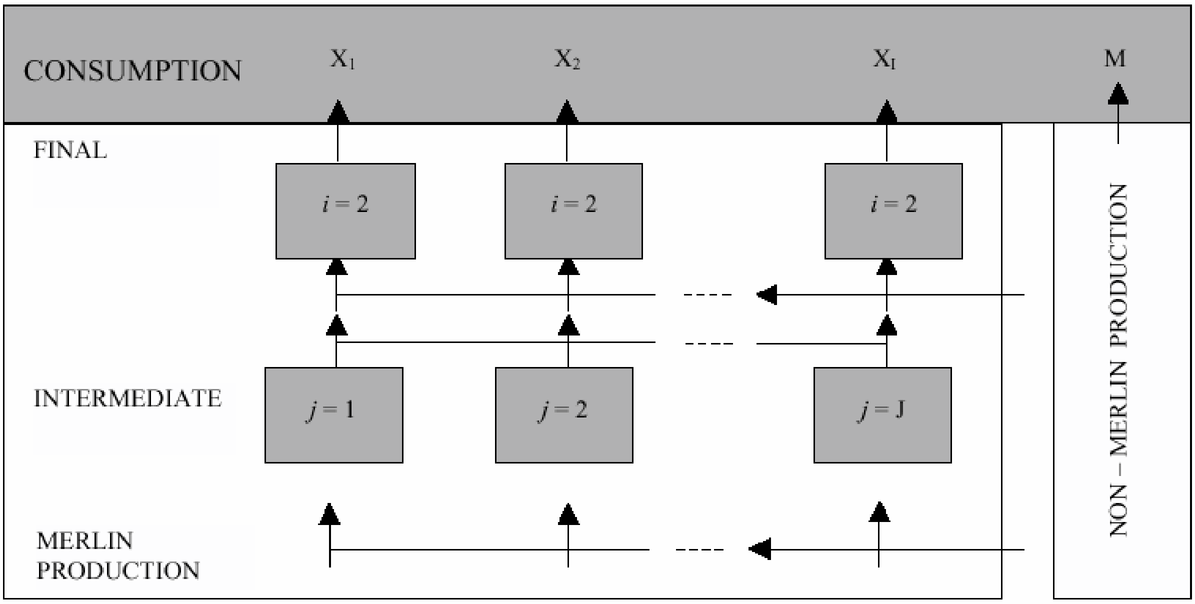

Figure 4: Merlin economic model

1.3 Economic model

In this section, a stylised economic model is defined. This is used to derive expressions for sector cost functions and emission functions that are consistent with the modelling approach that has been adopted in MERLIN, together with an expression for the social cost of abatement.

Figure 4 provides a schematic representation of the economic model that underpins the MERLIN cost minimisation exercise. In this stylised, partial equilibrium model, the economy is divided into three sectors: a consumption sector; a MERLIN production sector; and a non-MERLIN production sector.

1.3.1 MERLIN production sector

1.3.1.1 Production structure and technologies

There are two types of production activity in the MERLIN production sector – the production of final commodities $i \in I$, and the production of intermediate commodities $j \in J$. While firms carry out all intermediate production activities, final production activities may be undertaken by households (e.g. the production of private transportation, or domestic heating, etc.). All output from final production activities is consumed, while the output from intermediate activities is used only as an input to final production.[1]

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[1] It is assumed that sales of intermediate MERLIN commodities to the non-MERLIN sector account for only a small proportion of total production, and hence revenues and profits. Consequently, in order to simplify the analysis, it is assumed that sales to the non-MERLIN sector are equal to zero.

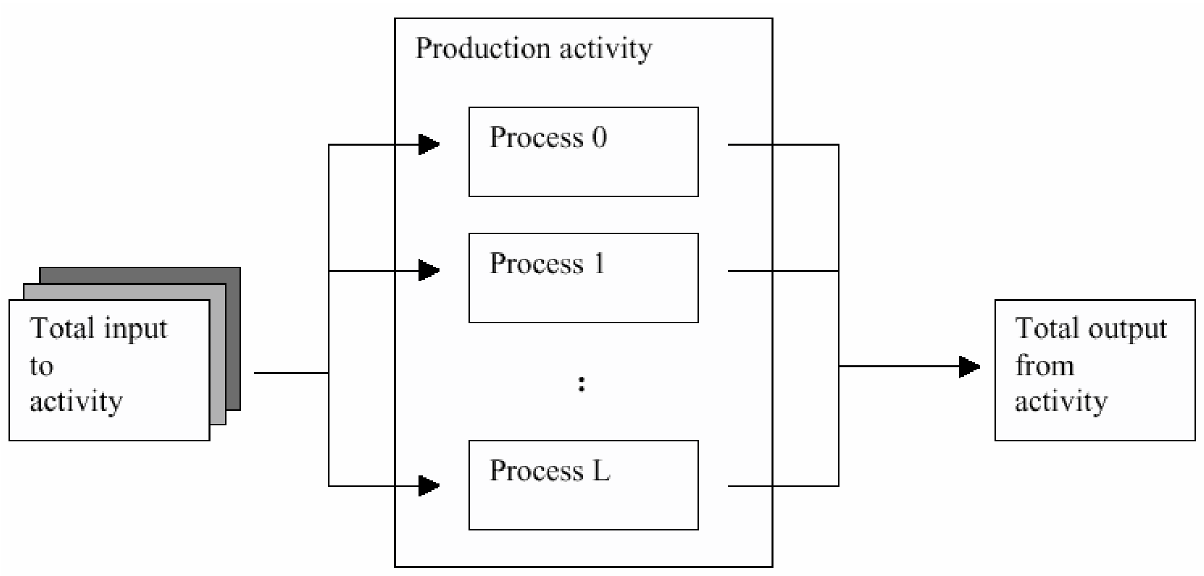

Figure 5: Production activity and processes

All production activities are assumed to have the same basic structure (see Figure 5). Each commodity (intermediate or final) can be produced by a number of different processes – indexed by $l \in \{0\} \cup L$,[2] with each process being characterised by Leontief technology (i.e. inputs are used in constant proportions). Total output (i.e. the activity level) is equal to the sum of the process outputs. Similarly, the total amount of each input used is equal to the sum of the process inputs. Thus, for final production activities:

$$X_i = \sum_l X_i^l$$

$$X_i^l = \mathrm{Min}\left[\frac{Y_{i1}^l}{\alpha_{i1}^l}, \ \cdots \ , \frac{Y_{iJ}^l}{\alpha_{iJ}^l}, \frac{W_{i1}^l}{\beta_{i1}^l}, \ \cdots \ , \frac{W_{iK}^l}{\beta_{iK}^l} \right]$$

where Y_{ij}^l and W_{ik}^l are, respectively, the quantities of intermediate commodity j and non-MERLIN commodity k used by process l in the production of commodity i, and α_{ij}^l and β_{ik}^l are exogenous parameters.[3] Assuming that production costs are minimised within each process, it follows that

$$Y_{ij}^l = \alpha_{ij}^l X_i^l$$

$$W_{ik}^l = \beta_{ik}^l X_i^l$$

Similarly, for intermediate production activities:

$$Y_j = \sum_l Y_j^l$$

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[2] By definition, the index $l = 0$ is taken to represent the baseline process that is used before the introduction of the new environmental targets. This could be a mix of different processes.

[3] In order to simplify notation, it is assumed that all production activities have the same number of possible processes (L). However, the number of processes can be made activity specific by setting the values of α_{ij}^l and β_{ik}^l equal to infinity for some values of l. This ensures that they will never be used.

$$Y_j^l \quad = \quad \text{Min}\left[\frac{W_{j1}^l}{\beta_{j1}^l}, \;\cdots\; , \frac{W_{jK}^l}{\beta_{jK}^l}\right]$$

$$W_{jk}^l \quad = \quad \beta_{jk}^l \, Y_j^l$$

The shares of the total output of final commodity $i \in \mathrm{I}$ attributable to each production process $l \in \mathrm{L}$ are denoted by the vector $\sigma_i = (\sigma_i^1, \sigma_i^2 \ldots , \sigma_i^{\mathrm{L}})$, where $\sigma_i^l = X_i^l / X_i$. Since the shares must sum to one, the share of total output attributable to the baseline process $l = 0$ is equal to $1 - \sum_{l \in L} \sigma_i^l$

Similarly, the shares of total output of intermediate commodity $j \in \mathrm{J}$ attributable to process $l \in \mathrm{L}$ are denoted by the vector $\omega_j = (\omega_j^1, \omega_j^2 \ldots , \omega_j^{\mathrm{L}})$, where $\omega_j^l = Y_j^l / Y_j$, and the share attributable to the baseline process $l = 0$ is equal to $1 - \sum_{l \in L} \omega_j^l$

If each production process $l \in \mathrm{L}$ represents a different combination of technical abatement measures, then the vectors σ_i and ω_j can be interpreted as representing the mix of technical abatement measures introduced for sectors i and j respectively. For example, if $\sigma_i = 0$ then no technical measures have been introduced for the sector, while if $\sigma_i^1 = \sigma_i^2 = 0.5$ then half of the sector's output is produced using the combination of technical measures included in process 1, and half using the combination included in process 2.

Given the assumption that all intermediate output is used in the production of final MERLIN commodities, and assuming that there is no excess production of intermediate commodities, then it follows that:

$$Y_j \quad = \quad \sum_{i \in \mathrm{I}} \left(\alpha_{ij}^0 \; + \sum_{l \in \mathrm{L}} \sigma_i^l (\alpha_{ij}^l \; - \; \alpha_{ij}^0) \right) X_i \qquad \text{for all } j \in \mathrm{J}$$

$$\equiv \quad \sum_{i \in \mathrm{I}} \alpha_{ij}(\sigma_i) \;\; X_i$$

Note that

$$\frac{\partial \alpha_{ij}}{\partial \sigma_i^l} \; = \; \alpha_{ij}^l \; - \; \alpha_{ij}^0 \qquad \text{(which is constant)}$$

1.3.1.2 Emissions of pollutants

Production of both intermediate and final commodities may result in the emission to the atmosphere of a number of pollutants – indexed by $m \in \mathrm{M}$. The emissions of pollutant m by final production activity i is denoted by:

$$Z_{im} \quad = \quad \rho_{im}(\sigma_i) \, X_i$$

where

$$\rho_{im}(\sigma_i) = \left[\rho_{im}^0 \; + \sum_{l \in \mathrm{L}} \sigma_i^l \left(\rho_{im}^l \; - \; \rho_{im}^0 \right) \right] \quad \text{and} \quad p_{im}^l = \left(\sum_{j \in J} \alpha_{ij}^l \gamma_{jm} + \sum_{k \in K} \beta_{ik}^l \eta_{km} \right)$$

The parameters γ_{jm} and η_{km} denote respectively the <u>specific emissions content</u> of intermediate commodity j and non-MERLIN commodity k (i.e. the emissions of pollutant m generated when one unit of that commodity is used in production), which are assumed to be constant. Similarly, the emissions of pollutant m by intermediate production activity j is denoted by

$$Z_{jm} \quad = \quad \rho_{jm}(\omega_j) \, Y_j$$

$$= \quad \rho_{jm}(\omega_j) \left[\sum_{i \in I} \alpha_{ij}(\sigma_i) \; X_i \right]$$

where

$$\rho_{jm}(\omega_j) = \left[\rho^0_{jm} + \sum_{l \in L} \omega^l_j \left(\rho^l_{jm} - \rho^0_{jm} \right) \right] \qquad \text{and} \qquad \rho^l_{jm} = \left(\sum_{k \in K} \beta^l_{jk} \eta_{jm} \right)$$

Thus, for each type of production activity, emissions of pollutant *m* are directly proportional to output, with the emissions intensity being equal to the weighted average of the (post-abatement) emissions intensities of each process, with the weights equal to the respective shares of total production. However, since the output of each intermediate process is determined by the outputs of the final production sectors, emissions can be expressed as a function of the outputs of the final consumption commodities. It is assumed that for each pollutant *m*, $\rho^l_{im} < \rho^0_{im}$ for some $l \in L$, and $\rho^l_{jm} < \rho^0_{jm}$ for some $l \in L$ (i.e. at least one of the alternative processes has a lower emissions intensity than the baseline process).

Note that:

$$\frac{\partial Z_{im}}{\partial \sigma^l_i} = (\rho^l_{im} - \rho^0_{im}) X_i$$

$$\frac{\partial^2 Z_{im}}{\partial \sigma^l_i \partial \sigma^{l'}_{i'}} = 0$$

$$\frac{\partial Z_{jm}}{\partial \omega^l_j} = (\rho^l_{jm} - \rho^0_{jm}) \sum_i \alpha_{ij}(\sigma_i) X_i$$

$$\frac{\partial Z_{jm}}{\partial \sigma^l_i} = (\alpha^l_{ij} - \alpha^0_{ij}) \rho_{jm}(\omega_j) X_i$$

$$\frac{\partial^2 Z_{jm}}{\partial \sigma^l_i \partial \omega^{l'}_j} = \frac{\partial^2 Z_{jm}}{\partial \omega^{l'}_j \partial \sigma^l_i} = (\alpha^l_{ij} - \alpha^0_{ij})(\rho^l_{jm} - \rho^0_{jm}) X_i$$

$$\frac{\partial^2 Z_{jm}}{\partial \sigma^l_i \partial \sigma^{l'}_{i'}} = \frac{\partial^2 Z_{jm}}{\partial \omega^l_j \partial \omega^{l'}_{j'}} = 0$$

Thus, changes in the abatement measures used in final production activities not only affect the emissions from these activities. By changing the pattern of factor demands they also affect the emissions from intermediate production activities, and the impact of changes in the abatement measures used in these sectors.

1.3.1.3 Costs and profits

Denoting the prices of final commodity *i*, intermediate commodity *j*, and non-MERLIN commodity *k* by p_i, p_j and q_k respectively, the aggregate profit across all MERLIN production sectors is given by:

$$\Pi(\sigma, \omega, X) = \sum_{i \in I} p_i X_i - C(\sigma, \omega, X)$$

where

$$C(\sigma, \omega, X) = \sum_{i \in I} c^i(\sigma_i, \omega) X_i$$

$$c^i(\sigma_\iota, \omega) \quad = \quad \left(c_i^0 \ + \ \sum_{l \in L^i} \sigma_i^l \, (c_i^l - \ c_i^0) \right) \ + \ \left(\sum_j \alpha_{ij}\,(\sigma_i) \left(c_j^0 \ + \ \sum_{l \in L^i} \omega_j^l \, (c_j^l - \ c_j^0) \right) \right)$$

$$c_i^l \quad = \quad \sum_{k \in K} \beta_{ik}^l \, q_k$$

$$c_j^l \quad = \quad \sum_{k \in K} \beta_{jk}^l \, q_k$$

That is, the aggregate profit earned by the firms in the MERLIN production sector is equal to the revenue received from sales of final commodities, less the cost of non-MERLIN commodities used in the production processes.

Note that:

$$\frac{\partial C}{\partial \sigma_i^l} \quad = \quad \left((c_i^l - \ c_i^0) \ + \ \left(\sum_j (\alpha_{ij}^l - \ \alpha_{ij}^0) \left(c_j^0 \ + \ \sum_{l \in L^i} \omega_j^l \, (c_j^l - \ c_j^0) \right) \right) \right) X_i$$

$$\frac{\partial C}{\partial \omega_j^l} \quad = \quad \alpha_{ij}\,(\sigma_i)\,(c_j^l - \ c_j^0)\, X_i$$

$$\frac{\partial^2 C}{\partial \sigma_i^l \partial \sigma_{i'}^{l'}} \quad = \quad \frac{\partial^2 C}{\partial \omega_j^l \partial \omega_{j'}^{l'}} \quad = \quad 0$$

$$\frac{\partial^2 C}{\partial \sigma_i^l \partial \omega_j^{l'}} \quad = \quad \frac{\partial^2 C}{\partial \omega_j^{l'} \partial \sigma_i^l} \quad = \quad (\alpha_{ij}^l - \ \alpha_{ij}^0)\,(c_j^l - \ c_j^0)\, X_i$$

Thus for a given level of final output, a change in the mix of processes used in the production of a final commodity affects the total cost of production in two ways. In addition to the impact on the marginal cost of production of that commodity, the resultant change in factor demands affects the total cost of production for all intermediate commodities that are used in its production.

1.3.2 Consumption sector

There is a single representative consumer with a separable, quasi-linear utility function

$$\sum_{i \in I} U^i(X_i) \ + \ M$$

where X_i is the quantity of final MERLIN commodity $i \in I$ that is consumed, and M is the total expenditure on non-MERLIN commodities. The consumer has three sources of income: the profits of the MERLIN production sector (Π); a lump sum transfer payment from the government, representing the return of any commodity taxes that are imposed (T)[4]; and other fixed income (L). The consumer's budget constraint is therefore

$$\sum_{i \in I} (p_i \ + \ t_i)\, X_i \ + \ M \ \le \ \Pi + T + L$$

[4] Given the assumption of a quasi-linear utility function, the imposition of a revenue-neutral programme of commodity taxes has the effect of transferring consumption from MERLIN to non-MERLIN commodities, as all of the returned revenue is spent on the latter.

where p_i is the price of commodity $i \in$I, and t_i is the tax imposed on commodity $i \in$I. Since the budget constraint will always be binding, the consumer's welfare can be expressed in terms of the variables *t*, *T*, σ, *a*, *X*, *Y* and L:

$$W(t, T, \sigma, \omega, X, L) = \sum_{i \in I} \left(\int_0^{X_i} \left(P^i(\zeta) - t_i \right) d\zeta - p_i X_i \right) + \Pi(\sigma, \omega, \underline{X} + T + L$$

$$= \sum_{i \in I} \left(\int_0^{X_i} \left(P^i(\zeta) - t_i \right) d\zeta \right) - C(\sigma, \omega, X) + T + L$$

where $P^i(X_i) = \dfrac{d\,U^i}{d\,X_i}$ is the inverse demand function for final commodity $i \in$I.

1.4 Analysis

In this section the social cost minimisation problem is analysed, and the necessary conditions for a social cost minimum are derived. These conditions are then used to determine the optimal values of the consumption taxes on final commodities.

The problem for the social planner is to find values for the variables *t*, *T*, σ, ω, and *X* which maximise welfare W(*t*, *T*, σ, ω, *X*) subject to:

(a) achieving the desired air quality / deposition targets at all receptor points, i.e.

$$\sum_{i \in I} a_{ni}^m z_i^m + \sum_{j \in J} a_{nj}^m z_j^m \le b_n^m \qquad \text{for all } m \in M,\ n \in N$$

where b_n^m is the air quality / deposition target for pollutants $m \in$M at receptor point $n \in$N, and a_{ni}^m and a_{nj}^m are source-receptor coefficients.[5]

(b) satisfying the fiscal constraint, i.e.

$$T \le t \cdot X$$

This optimisation problem must be solved in two stages. In the first stage, locally optimal values of $\sigma^*(t,T)$, $\omega^*(t,T)$ and $X^*(t,T)$ are determined for arbitrary (fixed) tax parameters *t* and *T*. In the second stage the optimal values of the tax parameters are determined. Although not necessary, it is instructive to split the first stage into two parts: (a) the identification of the optimal mix of technical measures σ^*, ω^* for an arbitrary vector of final outputs *X*, and (b) the determination the optimal levels of final outputs.

1.4.1 Stage 1a

In this stage, locally optimal values of $\sigma^*(X)$ and $\omega^*(X)$ are determined for an arbitrary (fixed) vector of final outputs *X*. The technical cost minimisation problem is:

$$C(X; B) = \underset{\sigma,\ \omega}{\text{Minimize}}\ C(\sigma, \omega, X)$$

σ, ω subject to

[5] For simplicity, a linear source-receptor relationship has been assumed. However, this is not necessary, and the results of the analysis remain would not be changed if the relationship between emissions and ambient air quality is non-linear.

$$\sum_{i \in I} a_{ni}^{m} z_{i}^{m} \quad + \quad \sum_{j \in J} a_{nj}^{m} z_{j}^{m} \quad \leq \quad b_n^m \qquad \text{for all } m \in M,\ n \in N$$

$$\sum_{l \in L} \sigma_i^l \quad \leq \quad 1 \qquad \text{for all } i \in I$$

$$\sum_{l \in L} \omega_j^l \quad \leq \quad 1 \qquad \text{for all } j \in J$$

where

$$z_i^m \quad = \quad Z^{im}(\sigma_i, X_i)$$

$$z_j^m \quad = \quad Z^{jm}(\omega_j, \sigma, X)$$

C(X; B) is the conditional aggregate production cost function. That is the minimum total cost of producing the vector of final outputs X, conditional on satisfying the air quality / deposition targets B = [b_n^m].

The Lagrangian for this problem is

$$L \quad = \quad - \quad C(\sigma, \omega, X) \quad + \quad \sum_{m} \sum_{n} \lambda_{mn} \left[b_n^m \ - \ \sum_{i} a_{ni}^m z_i^m \ - \ \sum_{i} a_{nj}^m z_j^m \right]$$

$$+ \quad \sum_{i \in I} \mu_i \left[1 - \sum_{l \in L} \sigma_i^l \right] \quad + \quad \sum_{i \in I} \nu_i \left[1 - \sum_{l \in L} \omega_j^l \right]$$

The necessary Kuhn-Tucker first order conditions for the solution are:

$$\frac{\partial L}{\partial \sigma_i^l} \quad = \quad - \quad \frac{\partial C}{\partial \sigma_i^l} - \sum_{m \in M} \sum_{n \in N} \lambda_{mn} \left[\sum_{i \in I} a_{ni}^m \frac{\partial Z^{im}}{\partial \sigma_i^l} \ - \ \sum_{j \in J} a_{nj}^m \frac{\partial Z^{jm}}{\partial \sigma_i^l} \right] - \mu_i \quad \leq 0$$

$$\sigma_I \quad \geq \quad 0$$

$$\sigma_i^l \frac{\partial L}{\partial \sigma_i^l} \quad = \quad 0$$

$$\frac{\partial L}{\partial \omega_j^l} = \quad - \frac{\partial C}{\partial \omega_j^l} - \sum_{m \in M} \sum_{n \in N} \lambda_{mn} \ a_{nj}^m \ \frac{\partial Z^{jm}}{\partial \omega_j^l} - \nu_j \qquad \leq 0$$

$$\omega_j^l \quad \geq \quad 0$$

$$\omega_j^l \frac{\partial L}{\partial \omega_j^l} \quad = \quad 0$$

$$\frac{\partial L}{\partial \lambda_{mn}} \quad = \quad b_n^m \ - \ \sum_{i} a_{ni}^m z_i^m \ - \ \sum_{i} a_{nj}^m z_j^m \qquad \geq 0$$

$$\lambda_{mn} \quad \geq \quad 0$$

$$\lambda_{mn} \frac{\partial L}{\partial \lambda_{mn}} \quad = \quad 0$$

$$\frac{\partial L}{\partial \mu_i} \quad = \quad 1 - \sum_{l \in L} \sigma_i^l \quad \geq 0$$

$$\mu_i \quad \geq \quad 0$$

$$\mu_i \frac{\partial L}{\partial \mu_i} = 0$$

$$\frac{\partial L}{\partial \nu_j} = 1 - \sum_{l \in L} \omega_j^l \geq 0$$

$$\nu_j \geq 0$$

$$\nu_j \frac{\partial L}{\partial \nu_j} = 0$$

Assuming that the total cost function is convex in (σ, ω) and that the emissions function for all intermediate activities are convex in (ω_j, σ), then these conditions are also sufficient for a solution.[6]

Furthermore, differentiating the Lagrangian with respect to each final output X_i yields the following expression for the marginal cost of increasing production of final commodity i:

$$C_i(X; B) \equiv \frac{\partial C(X;B)}{\partial X_i} = c_i(\sigma_i^*, \omega^*) + \sum_m \sum_n \lambda_{mn}^* \left[a_{ni}^m \, \rho_{im}(\sigma_i^*) + \sum_i a_{nj}^m \, \rho_{im}(\sigma_i^*) \right]$$

In the absence of any environmental regulation, $C_i(X; \infty) = c_i(0,0) = c_i^0$ (i.e. the baseline marginal cost of production for that commodity). In this case, the marginal cost of producing each commodity is independent of the output levels of all other commodities. However, if any of the environmental constraints are binding, then this is no longer the case, and the marginal cost of increasing production of a particular commodity depends on the outputs of all of the others. Since $c_i(\sigma_i, \omega) \geq c_i(0, 0)$, and assuming that the source-receptor coefficients are all positive, then $C_i(X; B) > C_i(X; \infty)$ for any matrix of environmental targets B for which at least one constraint is binding in the solution (i.e. $\lambda_{mn}^* > 0$ for some m, n)

1.4.2 Stage 1b

In this stage, locally optimal values of $X^*(t,T)$ are determined for arbitrary (fixed) tax parameters t and T. The conditional welfare maximisation problem is:

$$W(t, T; B) = \text{Maximize} \sum_{i \in I} \left(\int_0^{X_i} \left(P^i(\zeta) - t_i \right) d\zeta \right) - C(X; B) + T + L$$

The necessary Kuhn-Tucker first order conditions for a solution of this unconstrained maximisation problem are:

$$X_i \geq 0$$

$$P^i(X_i) - t_i - C_i(X; B) \leq 0$$

$$X_i [P^i(X_i) - t_i - C_i(X; B)] \quad \text{for all } i \in I$$

Assuming that the choke price $P^i(0)$ is greater than the maximum value of the marginal cost at $X_i = 0$, then the condition is guaranteed to hold with equality. Thus, conditional welfare maximisation (for

[6] It should be noted that the convexity of these functions is not guaranteed under the model outlined in section 3, it will depend on the values of the various parameters. This does not present any problems for this analysis, as only the necessary conditions are required.

given tax parameters t and T) requires that the price of each final commodity i is set equal to the marginal cost of producing an incremental unit (with the outputs of all other final commodities set at their optimal levels), plus the value of any commodity tax that is imposed on that commodity. (see Figure 6)

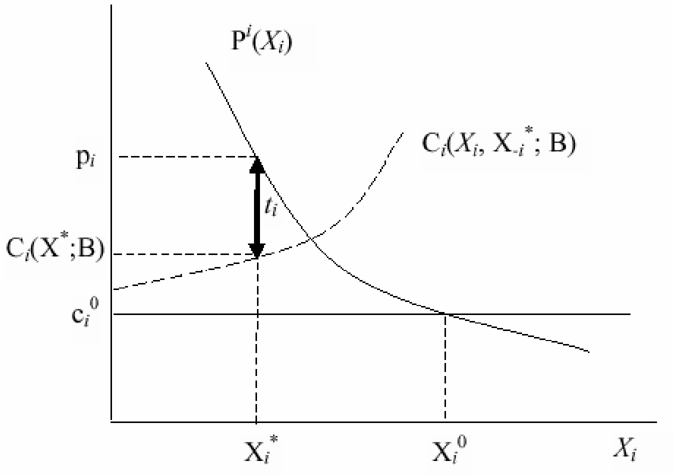


Figure 6: Optimal output for commodity *i*

As was noted above, with the quasi-linear utility function, the values of the final outputs are independent of the value of the lump sum transfer T. Therefore, denoting the solution by X(t; B), it follows that:

$$\frac{\partial \mathrm{W(t,T;B)}}{\partial t_i} = -X^i(t;B) \quad \text{and}$$

$$\frac{\partial \mathrm{W(t,T;B)}}{\partial \mathrm{T}} = 1$$

Substituting the solution into the first order conditions gives

$$P^i(X^i(t;B)) - C_i(X(t;B);B) \equiv t_i \quad \text{for all } i$$

Partially differentiating these identities yields a system of equations that can be represented by the matrix equation

$$\mathrm{I} = \Delta X \cdot \Delta^2(U\text{-}C)$$

where

$$\mathrm{I} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & \\ \vdots & & & \\ 0 & & & 1 \end{bmatrix}$$

$$\Delta X = \begin{bmatrix} X_1^1 & X_1^2 & \cdots & X_1^1 \\ X_2^1 & X_2^2 & & \\ \vdots & & & \\ X_1^1 & & & X_1^1 \end{bmatrix}$$

$$\Delta^2(\text{U-C}) \quad = \quad \begin{bmatrix} U_{11}-C_{11} & -C_{21} & \cdots & -C_{I1} \\ -C_{12} & U_{22}-C_{22} & & \\ \vdots & & & \\ -C_{1I} & & & U_{II}-C_{II} \end{bmatrix}$$

$$X_j^i = \frac{\partial X^i}{\partial t_j}$$

$$U_{ii} \quad = \quad \frac{\partial^2 U}{\partial X_i^2} \quad = \quad \frac{d P^i}{d X_i}$$

Thus Δ^2(U-C) is the inverse of matrix ΔX. Since $U_{ii} < 0$ and $C_{ii} \geq 0$, it is clear that

$\Delta^2(U - C) \neq 0$

1.4.3 Stage 2

In this stage the optimal values of the commodity taxes and the lump sum transfer are determined. The welfare maximisation problem is:

W(B) = Maximize W(t, T; B)
t, T subject to

$T \leq t \cdot X(t)$

The Lagrangian for this problem is

$$L \quad = \quad W(t, T, B) \quad + \lambda \left(\sum_{i \in I} t_i X^i(t_i; B) - T \right)$$

and the necessary first order conditions for the solution are:

$$\frac{\partial L}{\partial t_i} = \frac{\partial W}{\partial t_i} + \lambda \left(X^i(t_i; Z) + \sum_{h \in I} t_h \frac{\partial X^h}{\partial t_i} \right) = 0 \qquad \text{for all } i \in I$$

$$\frac{\partial L}{\partial T} = \frac{\partial W}{\partial T} - \lambda = 0$$

$$\frac{\partial L}{\partial \lambda} = \sum_{i \in I} t_i X^i(t_i; \mathbf{Z}) - T \geq 0$$

$$\lambda \geq 0$$

$$\frac{\partial L}{\partial \lambda} = 0$$

However, from *stage 1b* we know that

$$\frac{\partial W}{\partial t_i} = -X^i(t_i; B) \quad \text{and that} \quad \frac{\partial W}{\partial T} = 1$$

Consequently, it follows from the last two conditions that $\lambda^* = 1$, and that

$$\sum_{i \in I} t_i^* X^i(t_i^*; B) = T^*$$

Hence, the first set of conditions implies that

$$\sum_{h \in I} t_i^* \frac{\partial X^h(t_i^*;B)}{\partial t_i} \quad = \quad 0 \qquad \text{for all } i$$

Writing these conditions in matrix form $t^* \Delta X = 0$ and post multiplying both sides by the matrix Δ^2(U-C) gives:

$$t^* \Delta X \, \Delta^2(U\text{-}C) = 0 \, \Delta^2(U\text{-}C) \quad \Rightarrow \quad t^* I = 0 \, \Delta^2(U\text{-}C)$$
$$\Rightarrow \quad t^* = 0$$

Thus, welfare maximisation requires that all commodity taxes are set equal to zero. It follows directly from the above that the lump sum transfer is also equal to zero.

Note that if there had been a requirement to raise a specified amount of revenue (G) to fund government expenditure, and it is not possible to impose a lump sum tax (i.e. $T \geq 0$), then the optimal commodity tax condition would become

$$-\sum_{h \in I} t_i^* \frac{\partial X^h(t_i^*;B)}{\partial t_i} = \frac{\lambda^* - 1}{\lambda^*} \qquad \text{for all } i$$

with $\lambda^* > 1$, which is the usual Ramsey condition for optimal commodity taxes.

1.5 Solution Algorithm

In this section an algorithm is described that allows the determination of the optimal mix of technical measures to be separated from the determination of the optimal reduction in sectoral activity levels.

The proposed solution algorithm – which is defined in Figure 7– is based on the two-step process used in the previous section to analyse stage 1 of the social optimisation problem.

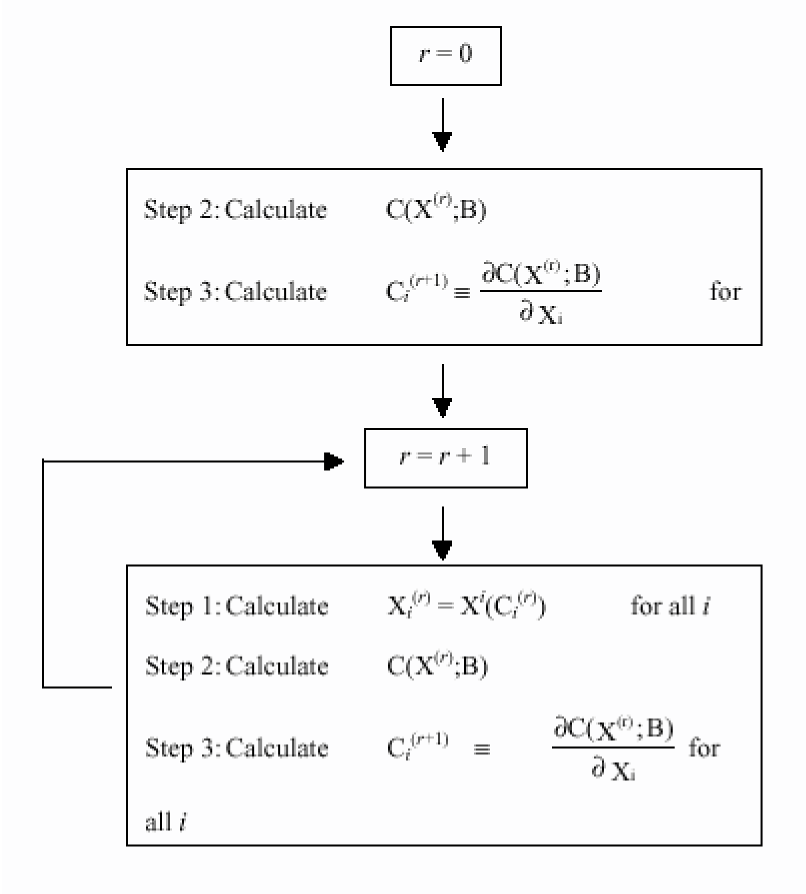


Figure 7: Iterative solution algorithm

For all iterations apart from the first (r = 0), there are three calculation steps. First, output levels are determined for each final sector, using the demand functions and the current values for the marginal costs of production. Second, the technical cost minimisation problem is solved for these output levels. Third, sensitivity analyses are performed to derive new estimates for the marginal costs of production for each sector. In the first iteration, the baseline output levels are used, and hence only the second and third calculation steps are performed.

The algorithm generates an oscillating sequence of ordered pairs $S_i = \{(X_i^{(r)}, C_i^{(r+1)})\}$ for each sector i; with $X_i^{(1)} < X_i^{(0)}$, $X_i^{(2)} > X_i^{(1)}$, $X_i^{(3)} < X_i^{(2)}$, … , and $C_i^{(2)} < C_i^{(1)}$, $C_i^{(3)} > C_i^{(2)}$, … (see Figure 8).

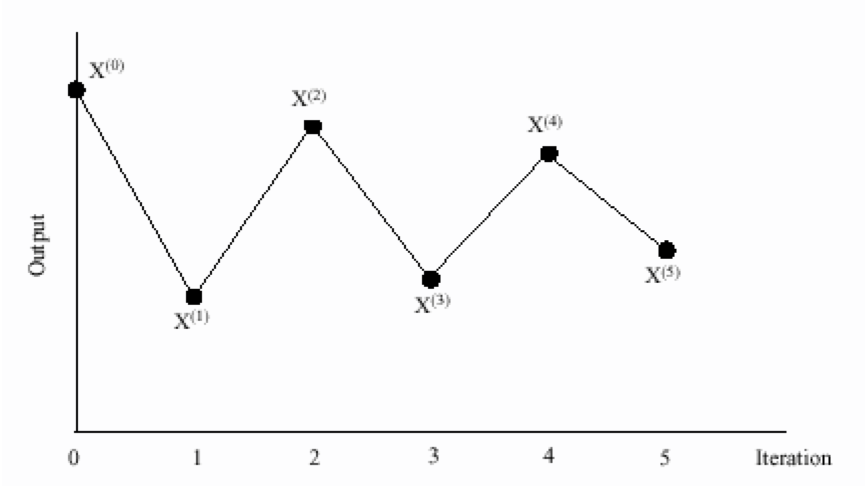


Figure 8: Output sequence

However, under the following assumptions regarding the properties of the demand curves for each final sector, and the conditional production cost function C(X; B), it can be shown that each sequence converges to a unique point $S_i^{\#} = \{(X_i^{\#}, C_i^{\#})\}$.[7]

$$\frac{\partial X^i}{\partial p_i} < 0 \quad \text{for all } i \qquad \text{and} \qquad \frac{\partial X^i}{\partial p_k} = 0 \quad \text{for all } k \neq i$$

$$C_i(X;\, B) \equiv \frac{\partial C(X;B)}{\partial X_i} > \frac{\partial C(X;\infty)}{\partial X_i} \equiv C_i(X;\,\infty) = c_i^0 \quad \text{for all } i \text{ and all } B < B^0$$ [8]

$$\frac{\partial^2 C}{\partial X_i \partial X_k} \geq 0 \qquad \text{for all } i, k \qquad \text{with strict inequality for at least one } k$$

$D^2h^i(X)$ is positive semidefinite for all $X^{(1)} \leq X \leq X^{(0)}$, where $h^i(X) \equiv X^i(C_i(X^1(C_1(X)), X^2(C_2(X)), \ldots, X^I(C_I(X))))$

The first assumption says that the demand curve for each final commodity is strictly downward sloping, and that there are no cross-price effects. The second assumption requires that the marginal cost of production for each sector is always higher than the baseline value for any set of environmental constraints that is binding (i.e. at least one shadow price is strictly positive). Both of these assumptions are satisfied by the economic model set out in section 2. The third assumption implies that if the outputs of all sectors increase (decrease), then the marginal cost of production for every sector will strictly increase (decrease). Unfortunately, this assumption is not guaranteed to be satisfied under the economic model outlined in 1.2– it is possible that the marginal cost may remain unchanged. However, the assumption is more likely to be satisfied, the greater the number of final sectors (I), and / or the greater the number of alternative processes (L), and / or the greater the number of pollutants (M). The implications of relaxing this assumption (i.e. allowing the marginal cost to remain constant over a range of outputs) are discussed below. The final assumption implies that the function relating alternate values of X_i in the algorithm (i.e. $X_i^{(r)}$ and $X_i^{(r+2)}$) is convex for all possible values of commodity outputs that may occur during the course of the algorithm. If one assumes that

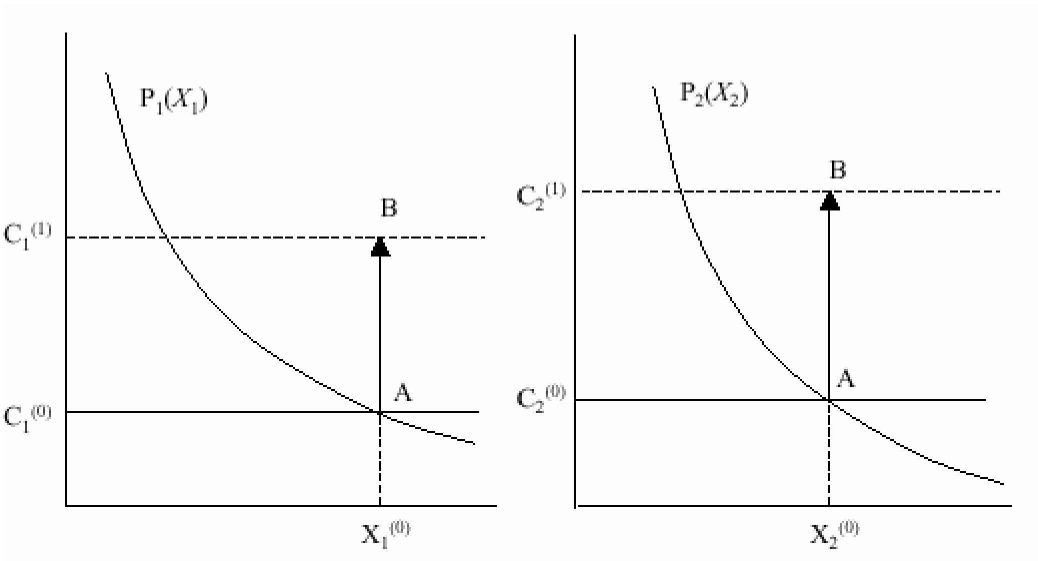
7 See appendix for proof of convergence.

8 The matrix inequality **A** < **B** means that at least one of the elements of the matrix **A** is strictly less than the corresponding element in matrix **B**, and no elements are strictly greater.

the cost function is convex, then this will be the case for any iso-elastic demand function (i.e. $X(p) = p^{-\gamma}$).

Figure 9 provides an illustration of the process for the first two iterations (i.e. $r = 0$ and $r = 1$) when there are two final production sectors. It should be noted that at the end of each iteration (i.e. points B and D), the environmental objectives are satisfied, but the market is not in equilibrium. In contrast, at points A and C, the market is in equilibrium, but the environmental constraints are either not satisfied (point A), or over achieved (point C). Only at ($X^{\#}$, $C^{\#}$) are all the markets in equilibrium and the environmental constraints just satisfied.

***r* = 0** **Sector 1** **Sector 2**



***r* = 1** **Sector 1** **Sector 2**

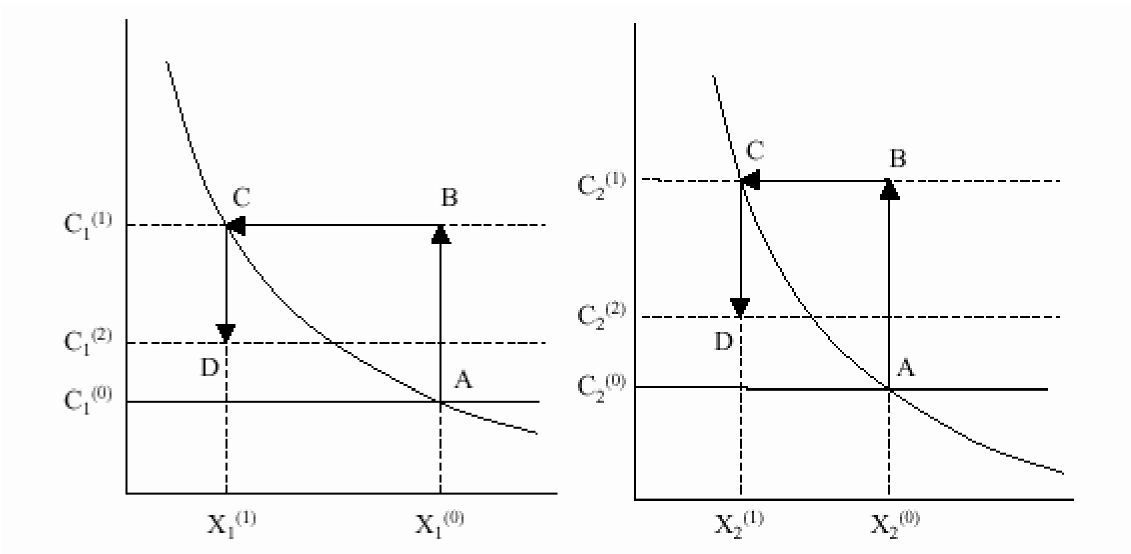


Figure 9: Iterative solution algorithm for two final sectors

Under the above assumptions, $X^{(0)} > X^{(2)} > X^{(4)} > \ldots$ etc, and $X^{(1)} < X^{(3)} < X^{(5)} < \ldots$ etc. it follows directly that $W(X^{(r)};B) < W(X^{(r+2)};B)$ for all r. However, the relative magnitudes of the conditional cost for successive iterations depends on the functional forms of the demand and cost curves, and it is possible to have $W(X^{(r)};B) > W(X^{(r+1)};B)$. Thus the sequence of welfare costs is not necessarily monotonically decreasing.

From the definition of the algorithm, it follows that $X_i^{\#} = X^i(C_i^{\#})$, which implies that $C_i^{\#} = P_i(X_i^{\#})$ for all *i*. But this is the necessary and sufficient condition for the social cost minimum (see section 3, stage 1b). Hence $X^{\#} = X^*$, and $W(X^{\#};B) = W(X^*;B)$. Thus, the algorithm will eventually yield the solution to the social optimisation problem. However, it may require a relatively large number of iterations before this is achieved.[9] Given the amount of work involved in calculating the marginal costs for each final sector at each iteration, it is unlikely to be feasible to follow the algorithm through to find the true solution. In practice it will be necessary to truncate the algorithm.

> There are several possible ways in which the algorithm could be truncated. The simplest way is to stop after a pre-determined number of iterations. For example, the algorithm could be stopped after the third iteration ($r = 2$). However, because the welfare cost values are not necessarily monotonically decreasing, $W(X^{(r)}; B)$ will have to be calculated for the last two iterations and compared. The iteration with the higher value can then be used as the solution. While this will yield a lower social cost than $W(X^{(0)}; B)$, it may not be a close approximation of $W(X^*; B)$.

An alternative approach, based on the concept of contraction paths, is illustrated in Figure 10. The sequence generated by the algorithm can be split into two sub-sequences:

$S_i^1 \quad = \quad \{(X_i^{(0)}, C_i^{(1)}), (X_i^{(2)}, C_i^{(3)}), (X_i^{(4)}, C_i^{(5)}), \ldots\}$

$S_i^2 \quad = \quad \{(X_i^{(1)}, C_i^{(2)}), (X_i^{(3)}, C_i^{(4)}), (X_i^{(5)}, C_i^{(6)}), \ldots\}$

Under the above assumptions, S_i^1 is monotonically decreasing, and S_i^2 is monotonically increasing, with both converging to (X_i^*, C_i^*). For each sub-sequence, the contraction path is defined to be the concatenation of lines joining successive elements. By definition, the two contraction paths "meet" at (X_i^*, C_i^*).

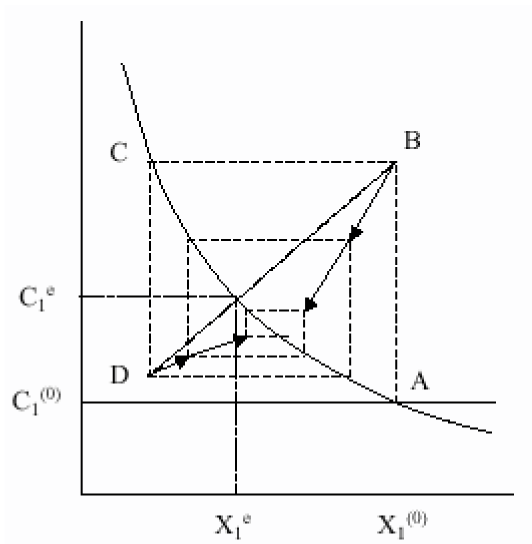


Figure 10: Contraction paths for sector 1

Of course, the actual contraction paths are only fully known after the algorithm is completed. However, they can be approximated by drawing a line between the first element of each subsequence

[9] It is assumed that the solution is attained when $| X_i^{(r+1)} - X_i^{(r)} | / X_i^{(r)} < \delta$, where δ is the pre-defined tolerance level.

(i.e. between points B and D in Figure 10).[10] The intersection of this line with the inverse demand curve provides an estimate (X_i^e, C_i^e) of the true solution. The estimated equilibrium output values X^e can then be used in a final run of the technical cost minimisation model.

Thus, under this approach, the estimation of the social cost minimum involves the following five steps:

- Step1: Solve the technical cost minimisation model for the baseline output levels $X^{(0)}$. Run sensitivity analyses for small changes in sector output levels (e.g. ± 5% say) to estimate marginal conditional production costs $C_i(X^{(0)};B)$.[11]
- Step 2: Calculate revised output levels $X^{(1)}$ using derived demand curves for each sector.[12]
- Step 3: Solve the technical cost minimisation model for the baseline output levels $X^{(1)}$. Run sensitivity analyses for small changes in sector output levels (e.g. ± 5% say) to estimate marginal conditional production costs $C_i(X^{(1)};B)$.
- Step 4: Construct linear approximations of contraction paths, and estimate equilibrium output levels X^e for each sector. Calculate reduction in consumer welfare versus baseline output levels
- Step 5: Solve the technical cost minimisation model for the estimated equilibrium output levels X^e to give increase in production costs

It should be noted that while the assumption of a strictly increasing marginal cost of production (assumption 3 above) was necessary to ensure the convergence of the algorithm, it is not necessary when this truncation approach is adopted. It is required for convergence because a constant marginal cost of production (over a range of outputs) can cause the algorithm to "cycle" between two values. However, with the linear interpolation used in the truncated algorithm, this problem does not arise. Indeed, if $C_i(X^{(1)};B) = C_i(X^{(0)};B)$, then the constructed line will be an exact representation of the contraction paths, and hence $X_i^e = X_i^{(1)} = X_i^*$.

The five-step approach outlined above still requires that the marginal cost values for each sector be calculated twice, and that the technical cost minimisation problem be solved three times. If this involves a prohibitive amount of work, step 3 could be omitted, and ($X_i^{(1)}$, $C_i^{(2)}$) replaced by ($X_i^{(1)}$, $C_i^{(0)}$) in step 4. This will have the effect of increasing the estimated output values X^e. Depending the shape of the actual contraction paths, this may improve the estimate (as would be the case in Figure 10) or make it worse. However, since the constructed line will now always be upward sloping, this simplification will preclude the exact estimation of the equilibrium output level when $C_i(X^{(1)};B) = C_i(X^{(0)};B)$.

1.6 Conclusions

There are a number of conclusions that can be drawn from the discussion and the analysis set out in sections 1.1 – 1.4.

First, the distinction between technical and non-technical measures is rather more subtle and complex than might initially be supposed. While MERLIN is set up on the basis of a distinction between technical measures (i.e. those that affect sectoral emission coefficients) and non-technical measures (i.e. those that affect activity levels), this does not recognise that technical measures would generally be expected to affect both emissions coefficients and activity levels. From an economic perspective it

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[10] The line can be drawn between any two elements of the respective sub-sequences. For example, a line could be drawn between the third element of each sub-sequence. Of course, the greater the number of iterations that have been performed before the line is constructed, the better the approximation.

[11] This requires the output level of each final sector to be varied in turn, with the outputs of the other sectors held constant.

[12] Demand curves, which are assumed to be iso-elastic, can be derived from empirical estimates of price elasticities combined with information on total expenditure and output levels.

is more useful to distinguish between measures that affect the supply of final consumption goods and services (the "supply side") and measures that affect the demand for those goods and services (the "demand side"). It seems natural to characterise the distinction between technical measures and non-technical measures on this basis; defining technical measures as those that affect the supply side, and non-technical measures as those that act on the demand side.

Second, under this definition, non-technical measures are never used as part of the optimal mix of abatement measures. While social cost minimisation requires reductions in output levels (activity levels), these result solely from the increases in the marginal cost of production induced by the introduction of technical abatement measures. There is no justification for additional demand side measures to further reduce activity levels.

Third, a distinction needs to be made between abatement measures and the mechanisms (i.e. policy instruments) used to implement those measures. It is perfectly possible for a technical measure to be implemented through the use of an emissions tax or other pricing measure. Similarly a non-technical measure might be implemented through the introduction of a demand quota. Thus care should be taken in interpreting the implications of the preceding conclusion. In particular, it does not imply that there is no role for taxes and other price instruments in implementing the optimal mix of technical measures.

Finally, it is possible to estimate the optimal solution to the choice of abatement measures, allowing for changes to activity levels as well as emissions coefficients, using an iterative algorithm that is designed fit in with the approach traditionally used to analyse technical measures. Specifically, the algorithm allows the determination of the optimal mix of technical measures (for a given level of activity in each sector) to be separated from the determination of the optimal reduction in sectoral output levels.

1.7 Appendix: Proof that the solution algorithm converges

Assumptions

A1: $\frac{\partial X^i}{\partial p_i} < 0$ for all $i \in I$ and $\frac{\partial X^i}{\partial p_k} = 0$ for all $i, k \in I$, $k \neq i$

A2: $\frac{\partial C(X;B)}{\partial X_i} > \frac{\partial C(X;\infty)}{\partial X_i} \equiv c_i^0$ for all $i \in I$ and all $B < B^0$ [13]

A3: $\frac{\partial^2 C}{\partial X_i \partial X_k} \geq 0$ for all $i, k \in I$

with strict inequality for at least one k

A4: $D^2 h^i(X)$ is positive semidefinite for all $X^{(1)} \leq X \leq X^{(0)}$, where

$h^i(X) \equiv X^i(C_i(X^1(C_1(X)), X^2(C_2(X)), \ldots, X^I(C_I(X))))$

Definitions

D1: $C_i^{(r+1)} = \frac{\partial C(X^{(r)};B)}{\partial X_i}$ with $C_i^{(0)} = \frac{\partial C(X^0;\infty)}{\partial X_i} = c_i^0$

D2: $X_i^{(r)} = X^i(C_i^{(r)})$ with $X_i^{(0)} = X_i^0$

[13] The matrix inequality **A** < **B** means that at least one of the elements of the matrix **A** is strictly less than the corresponding element in matrix **B**, and no elements are strictly greater.

Proof

Assumption A2 and definition D1 imply that for any deposition matrix $B < B^0$

$C_i^{(1)} = \dfrac{\partial C(X^{(0)};B)}{\partial X_i} > \dfrac{\partial C(X^{(0)};\infty)}{\partial X_i} = C_i^{(0)}$ for all $i \in I$

This, together with assumption A1 and definition D2 implies that

$X_i^{(1)} < X_i^{(0)} = X_i^0$ for all $i \in I$

Which, by assumptions A2 and A3 implies that

$\dfrac{\partial C(X^0;\infty)}{\partial X_i} < \dfrac{\partial C(X^{(1)};B)}{\partial X_i} < \dfrac{\partial C(X^{(0)};B)}{\partial X_i}$ for all $i \in I$

From this starting point, the following sequence of implications ensue:

$\Rightarrow$ $C_i^{(0)} < C_i^{(2)} < C_i^{(1)}$ for all $i \in I$ (by definition D1) … (1.a)

$\Rightarrow$ $X_i^{(0)} > X_i^{(2)} > X_i^{(1)}$ for all $i \in I$ (by assumption A1) … (1.b)

$\Rightarrow$ $\dfrac{\partial C(X^{(1)};B)}{\partial X_i} < \dfrac{\partial C(X^{(2)};B)}{\partial X_i} < \dfrac{\partial C(X^{(0)};B)}{\partial X_i}$ for all $i \in I$ (by assumption A3)

$\Rightarrow$ $C_i^{(2)} < C_i^{(3)} < C_i^{(1)}$ for all $i \in I$ (by definition D1) … (2.a)

$\Rightarrow$ $X_i^{(2)} > X_i^{(3)} > X_i^{(1)}$ for all $i \in I$ (by assumption A1) … (2.b)

$\Rightarrow$ $\dfrac{\partial C(X^{(1)};B)}{\partial X_i} < \dfrac{\partial C(X^{(3)};B)}{\partial X_i} < \dfrac{\partial C(X^{(2)};B)}{\partial X_i}$ for all $i \in I$ by assumption A3)

$\Rightarrow$ $C_i^{(2)} < C_i^{(4)} < C_i^{(3)}$ for all $i \in I$ (by definition D1) … (3.a)

$\Rightarrow$ $X_i^{(2)} > X_i^{(4)} > X_i^{(3)}$ for all $i \in I$ (by assumption A1) … (3.b)

$\Rightarrow$ $\dfrac{\partial C(X^{(3)};B)}{\partial X_i} < \dfrac{\partial C(X^{(4)};B)}{\partial X_i} < \dfrac{\partial C(X^{(2)};B)}{\partial X_i}$ for all $i \in I$ (by assumption A3)

$\Rightarrow$ $C_i^{(4)} < C_i^{(5)} < C_i^{(3)}$ for all $i \in I$ (by definition D1) … (4.a)

$\Rightarrow$ $X_i^{(4)} > X_i^{(5)} > X_i^{(3)}$ for all $i \in I$ (by assumption A1) … (4.b)

… and so on.

Taken together, inequalities (1.a), (2.a), (3.a), (4.a), … imply that:

$C_i^{(0)} < C_i^{(2)} < C_i^{(4)} < \ldots < C_i^{(2r)} < \ldots < C_i^{(2r+1)} < \ldots < C_i^{(5)} < C_i^{(3)} < C_i^{(1)}$

While inequalities (1.b), (2.b), (3.b), (4.b), … imply that:

$X_i^{(0)} > X_i^{(2)} > X_i^{(4)} > \ldots > X_i^{(2r)} > \ldots > X_i^{(2r+1)} > \ldots > X_i^{(5)} > X_i^{(3)} > X_i^{(1}$

Thus for all $i \in I$, the marginal cost sequence $\left\{C_i^{(r)}\right\}_{r=0}^{r=\infty}$ and the output sequence $\left\{X_i^{(r)}\right\}_{r=0}^{r=\infty}$ each comprise two monotonic subsequences – one increasing, the other decreasing.

Consider the output sequence for sector $i \in I$, and denote the two subsequences by $\bar{S}_i = \left\{X_i^{(2r)}\right\}_{r=0}^{r=\infty}$ and $S_i = \left\{X_i^{(2r+1)}\right\}_{r=0}^{r=\infty}$, where $\bar{S}_i$ is monotonically decreasing, and S_i is monotonically increasing. Since the entire sequence is bounded (above by $X_i^{(0)}$, and below by $X_i^{(1)}$) each subsequence converges.[14] Denote the respective limits by X_i and X_i^+. By construction, it must be the case that $X_i \geq X_i^+$.

In order to prove that the entire sequence converges to a single limit (rather than oscillate) it is necessary to show that $X_i = X_i^+$ for all $i \in I$. For the sake of clarity, this will be proved for the two sector case (i.e. I = 2), with reference to Figure A1. However, it is straightforward to generalise the proof to higher dimensions (i.e. for all finite values of I > 2).

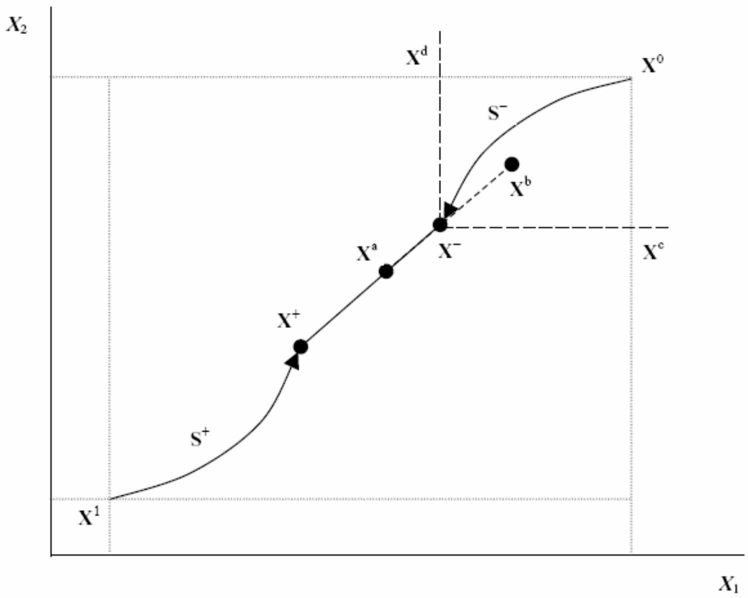

Figure 11: Sector case

The proof is by contradiction. Assume that $X_i^- > X_i^+$ for some $i \in I$.[15]

By definition, $h^i(X^+) = X_i^+$ and $h^i(X^-) = X_i^-$.

By assumption A4, the Hessian matrix D^2h^i is positive semidefinite. Consequently $h^i(X)$ is convex, which implies that:

$$
\begin{aligned}
h^i(\theta X^+ + (1-\theta) X^-) \quad &\leq \quad \theta\, h^i(X^+) + (1-\theta)\, h^i(X^-) \qquad \text{for any } \theta \in [0,1] \\
&= \quad \theta X^+ + (1-\theta) X^-
\end{aligned}
$$

Thus, $h^i(X^a) \leq X_i^a$ for all $i \in I$, for any point X^a on the (straight) line joining the points X^+ and X^-.

By inequality (1b), $X^{(2)} << X^{(0)}$. Therefore $h^i(X^0) < X_i^0$ for all $i \in I$.

The cross partial derivative of the transition function $h^i(X)$:

$$
\frac{\partial h^i}{\partial X_k} = \frac{dX^i(\cdot)}{dp_i}\left[\frac{\partial^2 C(\cdot)}{\partial X_i^2}\frac{dX^i(\cdot)}{dp_i}\frac{\partial^2 C(X)}{\partial X_i \partial X_k} + \frac{\partial^2 C(\cdot)}{\partial X_i \partial X_k}\frac{dX^k(\cdot)}{dp_k}\frac{\partial^2 C(X)}{\partial X_k^2}\right]
$$

$i, k = 1, 2$ ($i \neq k$), is strictly positive under assumptions A1 and A3.

---

[14] This is standard property of any bounded monotone sequence. See for example, Theorem 29.2 in Simon, C. & Blume, L. , *Mathematics for Economists*, Norton & Co., New York, 1994

[15] In Figure A1, both $X_1^- > X_1^+$ and $X_2^- > X_2^+$. However, this does not need to be the case, and it is possible to have equality for one of the sectors.

Consequently, $h^1(X^c) < X_1^c$ and $h^2(X^d) < X_2^d$, where $X^c = (X_1^0, X_2^-)$ and $X^d = (X_1^-, X_2^0)$.

Every point $X \in [X^-, X^0]$ can be written either as a convex combination of the corner points X^-, X^0 and X^c, or as a convex combination of the points X^-, X^0 and X^d. That is:

$$X = \omega_1 X^- + \omega_2 X^0 + \omega_3 X^c + \omega_4 X^d \quad \text{where}$$

$$\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1 \quad \text{and}$$

$$\omega_3 + \omega_4 = 0$$

Since $h^i(X)$ is convex, it follows that for all $X \in [X^-, X^0]$ and $i \in I$:

$$\begin{aligned} h^i(X) &= h^i(\omega_1 X^- + \omega_2 X^0 + \omega_3 X^c + \omega_4 X^d) \\ &\le \omega_1 h^i(X^-) + \omega_2 h^i(X^0) + \omega_3 h^i(X^c) + \omega_4 h^i(X^d) \end{aligned}$$

If $\omega_3 = 0$ then

$$h^2(X) < \omega_1 X_2^- + \omega_2 X_2^0 + \omega_4 X_2^d = X_2$$

If $\omega_4 = 0$ then

$$h^1(X) < \omega_1 X_1^- + \omega_2 X_1^0 + \omega_3 X_1^d = X_1$$

Thus for any point $X \in [X^-, X^0]$, $h^i(X) < X_i$ for <u>some</u> $i \in I$.

Now extend the line joining X^+ and X^- to the point X^b, where $X^b \in [X^-, X^0]$. Since $h^i(X)$ is convex, it follows that:

$$\begin{aligned} h^i(\theta X^a + (1-\theta) X^b) &\le \theta h^i(X^a) + (1-\theta) h^i(X^b) && \text{for all } \theta \in [0,1] \\ &< \theta X_i^a + (1-\theta) X_i^b && \text{for } \underline{\text{some}}\ i \in I \end{aligned}$$

But by construction there exists a value of $\theta \in (0,1)$ such that $X^- = \theta X^a + (1-\theta) X^b$. Thus $h^i(X^-) < X_i^-$ for some $i \in I$. But this means that X_i^- is not the limit-point of the sequence S^-_i. Consequently, the assumption cannot be true, and it must be the case that $X_i^- = X_i^+$ for all $i \in I$.

Thus the output sequence converges to a unique limit point $X^\#$. By definition D2, it follows directly that the marginal cost sequence also converges to a unique limit point $C^\#$, where $C_i^\# = P^i(C_i^\#)$ for all $i \in I$.

Q.E.D.

2 Non-technical emission abatement options – practical implementation

2.1 Introduction

This paper describes a number of key "non-technical" measures for reducing air pollution emissions from the transport sector. The focus is on measures, which can be meaningfully simulated in the MERLIN framework. This means that the measures discussed are primarily those that would have a general influence on the use made of broad categories of transport, such as motor fuel tax increases, parking charges, congestion charging, and public transport subsidy. There are, in addition, many other locally-specific measures, which might be employed to reduce air pollution emissions from transport – such as measures to improve vehicle flow at particular locations. These, however, depend for their effect on the detail of local circumstances, and cannot be simulated using the broad-brush techniques employed in MERLIN.

A common feature of the measures discussed is that they exert influence on individual travel behaviour through their impact on prices. Thus, for example, an increase in petrol tax will increase the retail price of petrol, and hence the cost of travel compared to other goods and services that individuals can buy. This effect on the relative price of petrol may lead to a number of behavioural responses by individuals:

- a reduction in amount of travel compared with other goods and services (as consumers decide, at the margin, to shift spending to other commodities)
- an improvement in fuel efficiency (as the higher price of fuel induces consumers buying new cars to choose more fuel-efficient models),
- modal shifts within the transport sector, if the higher petrol tax has a differential effect on the prices of private motoring and public transport (for example, if the fuel cost component in the price of public transport is lower than in the case of private motoring, or if the tax increase applies only to private motorists' petrol purchases).

These effects are potentially wide-ranging, with a complex chain of adjustments being made in individual behaviour, that are likely to include changes in the consumption of different commodities (a shift away from transport to other commodities), locational choices (effects on commuting behaviour, choice of residence, sitting of workplaces and retail facilities, etc), and employment decisions (changes in labour supply, etc). Not all of these effects will be large, but, in principle, all could be experienced to a greater or lesser degree as a result of a change in the rate of tax on the single commodity, petrol. There is further complexity in the time profile of the effects. Some responses will happen relatively quickly, others (such as those working through the purchase of more fuel-efficient vehicles, or arising through individual locational choices) may take some considerable time to materialise.

Much of this detail cannot practically be simulated within the MERLIN framework, and can only be handled within detailed simulation models of the transport sector. Indeed, much work still needs to be done before some of the longer-term behavioural adjustments can be quantified with any great precision. The aim in this paper is to identify reasonable broad approximations that can be employed within the MERLIN framework, and assessed alongside a wide range of other possible measures affecting air pollution emissions.

2.2 Fiscal instruments in the transport sector

2.2.1 The level and structure of road taxes in Europe

Table 1 provides a brief summary of the overall structure of taxes on road transport in western Europe. The principal taxes are those levied on vehicle purchase and initial registration, annual charges on vehicle use, and taxes on motor fuels; in addition, various European countries operate an assortment of miscellaneous taxes and tax provisions likely to influence individual road transport decisions. The main revenue-raiser among these various taxes is the fuel excise. In 1990, motor fuel taxes accounted for 5% of total tax revenues in the UK, and 4% in France and Germany. Other taxes contribute much smaller revenues.

Table 1: The principal taxes on motor vehicles and motor fuels in Europe

Sales taxes on new motor vehicles.	New motor vehicles may be subject to additional taxes, over and above the general sales tax. In the UK, for example, motor cars are subject both to VAT at the standard rate of 17.5 per cent, and also to a special car tax at 5 per cent on five sixths of the list price of a new car. Sales taxes on new cars may reduce the level of car ownership, but may also reduce the rate at which the existing vehicle stock is replaced. This effect may have environmental benefits, if older vehicles are replaced by less-polluting new vehicles.
Recurrent annual charges.	Annual fees for the registration or use of motor vehicles are common. In the case of motor cars, these may be an annual lump-sum tax (e.g. the annual British Vehicle Excise Duty), or may be related to certain characteristics of the motor vehicle, such as engine capacity or weight. In most countries the taxes levied on commercial vehicle sales, ownership and use are higher and more complex than the taxes on private cars, reflecting amongst other things the greater variety in size and use amongst commercial vehicles. In the UK, for example, the Vehicle Excise Duty on commercial freight vehicles is substantially higher than that for cars, and is related to the number of axles and vehicle weight. Possibilities exist for the differentiation of the tax on new cars and the annual charges for registration according to the "environmental" attributes of different vehicles (eg engine size or fuel type).
Motor fuel taxes	The majority of countries in Europe levy specific excise duties upon motor fuels, in the form of a fixed amount per litre of fuel rather than a percentage of the price. In addition, the Value Added Tax is generally applied at the standard VAT rate over and above the excise duty. The combined effect of the motor fuel excises plus VAT is that motor fuels are taxed substantially more heavily than other goods, and, in general, considerably more heavily than other uses of energy. Diesel fuel is frequently taxed at a different (usually lower) rate than petrol. Within the EU, the average tax to price ratio is 0.71 for petrol and 0.56 for diesel. Most countries in western Europe (and all EC countries) have employed also introduced a tax differential between leaded and unleaded petrol, to encourage car users to switch from leaded petrol to the less environmentally-damaging unleaded fuel.
Special fuel taxes.	Besides VAT and excise taxes, motor fuels are also subject to a number of special taxes in different countries, including environmental damage taxes (the carbon taxes introduced by the Nordic countries, and the SO2 tax in Sweden), fuel storage taxes to fund emergency stocks, and taxes to fund public works on related infrastructure and R & D (eg in France).
Road-use charges and tolls.	In Europe tolls are mainly used to charge for primary roads and motorways; some 30% of motorways in Europe are tolled, of which the majority (90%) are in France, Italy and Spain. Explicit congestion charges have been rare. City centre access tolls were introduced in Bergen in 1986 (Larsen, 1988) and in Oslo in 1990 (Solheim, 1990). Much more recently, a £5 daily congestion charge has been introduced for vehicles entering the central London area. Several cities in Europe are currently exploring the possibility of introducing electronic charging systems which potentially allow charges to be related to the location, distance and time of road use.

2.2.2 Using transport taxes to reflect external costs

Taxation can play an important role in regulating the various external costs (including environmental costs) associated with road transport. Motor vehicles and on motor fuels have long been the subject of a number of different taxes in all European countries, levied for revenue reasons. Now, environmental considerations are increasingly entering into policy decisions about the level of these existing taxes. In addition, policy-makers are exploring the scope for restructuring the existing taxes on vehicles and fuels, so as to provide appropriate environmental incentives and disincentives. Many countries have, for example, introduced lower rates of tax on unleaded petrol, and some have restructured annual vehicle taxes to favour less-polluting vehicles. In addition, a number of countries have employed new fiscal instruments to address specific environmental aspects of road transport. These innovations have included the use of parking charges to discourage peak-time urban traffic, road pricing measures to discourage congestion (as in the London Congestion Charge introduced in 2003), and the introduction of scrapping subsidies to accelerate the retirement of highly-polluting older vehicles.

Formulating appropriate policies towards the taxation of road transport is, however, far from straightforward, due to the varied range of social costs (externalities) associated with road use, and the complex interactions between road transport, other modes of transport, and issues of spatial development. Road transport taxes would thus have to reflect the combined (and, perhaps, interacting) effect of different externalities, and at the same time induce environmentally appropriate choices by individuals. This complexity is amplified by the existence of significant "second best" aspects in the use of existing fiscal instruments, in at least three respects. First, the efficient pricing of road transport will depend on the pricing of substitutes, especially public transport. Second, taxes on vehicles and fuels are able to reflect the various externalities only approximately, and the optimal policy mix would generally require the use of a package of a number of instruments in combination, even where policy sought to address only one of the relevant externalities. Third, the existence of revenue-raising taxes elsewhere in the fiscal system (eg labour income taxes) will interact with the effect of road transport taxes. As Bovenberg and de Mooij (1994) and others have shown (see Goulder, 1995), the existence of other revenue-raising taxes will generally increase the deadweight losses associated with externality-correcting taxes, so that the optimal level of environmental taxes will be different, and often substantially lower, than in an economy without pre-existing fiscal distortions.

The social costs of road transport are of four main types:

- **environmental costs** - these include both global and local air pollution of various forms, including the contribution of vehicles to emissions of carbon dioxide and other greenhouse gases, nitrogen oxides which contribute to acid rain, and particulates (soot, etc) which can cause health problems. In addition to air pollution, road transport also generates noise pollution, and aesthetic "pollution" in terms of transport-related effects on the rural landscape and the urban environment. (See Button 1990, 1993).
- **accident costs** - the costs of injury and accident fatalities caused to pedestrians and other road users; the damage to physical property; the costs of treating accident victims in publicly-funded health services. (See Jones-Lee, 1990).
- **congestion costs** - the costs in terms of extra journey time which road users impose on each other when roads become congested. (See Newbery 1990).
- **consumption of the road infrastructure** - in the form of "marginal road damage costs": the physical wear and tear caused by vehicles using the roads (See Newbery 1988).

It is desirable that these social costs should be reflected in the costs of road use faced by individual road users, and, in principle, the taxation of road transport might be used to address each of these major forms of social cost involved in vehicle use. In practice, policy-makers have often been unclear about which - if any - of the various social costs is reflected in the high level of taxation on motor vehicles and vehicle fuels - a confusion which perhaps reflects the origins of these taxes as, primarily, revenue raisers, and the more recent development of an environmental rationale for their continued existence.

Over the past decade there has been a substantial volume of research aiming to quantify the external costs of road transport. Table 2 shows estimates from Maddison et al. (1996) of the marginal external costs of road transport in the UK. Total marginal external costs were estimated in the range £ 45.9 – 52.9 billion, 26.1 – 33.1 billion, with some 40 per cent of the total attributable to air pollution costs (including global warming costs), and a similar proportion arising as a result of traffic congestion.

Table 2: UK Road Transport Marginal external cost, 1993 (and 2003 equivalent, per km)

	Total marginal external cost, bn pounds, 1993	Marginal external cost per litre of motor fuel consumed, Euro cents per litre, 2003
Global warming	0.1	
Air pollution	19.7	
Noise	2.6 – 3.1	
Congestion costs	19.1	
Road damage	1.5	
Accidents	2.9 – 9.4	
Total	45.9 – 52.9	
Total, excluding global warming and air pollution	26.1 – 33.1	

Source: 1993 figures: Maddison, et al, 1996, p 141. 2003 Euro per litre equivalents, author's updating.

Maddison et al (1996) report work by Rothengatter and Mauch (1994), who use "benefits transfer" methods to estimate the total external costs of road transport in 1991 in the 15 EU countries plus Norway and Switzerland. In most countries the estimate of total external cost lies in the range 3-5 per cent of GDP, with higher percentages in Belgium (5.4% of GDP), Greece (5.6%) and Portugal (9.8%).

Table 3: Total external costs of road transport in European countries (Rothengatter and Mauch estimates)

Country	Cars (bn euros)	Total (bn euros)	Total (percentage of GDP)
Belgium	6.5	8.7	5.4
Denmark	2.1	3.4	3.2
Finland	2.2	3.3	3.3
France	22.8	40.8	4.2
Germany	45.8	61.9	4.5
Greece	1.7	3.2	5.6
Ireland	1.0	1.5	4.2
Italy	19.7	34.8	3.8
Netherlands	5.3	7.9	3.3
Norway	1.6	2.3	2.7
Portugal	4.2	5.4	9.8
Spain	11.8	20.7	4.9
Sweden	3.8	5.6	3.0
Switzerland	3.8	5.7	3.1
UK	26.6	38.5	4.7
Total, above countries	164.2	250.6	4.2

Source: Rothengatter and Mauch (1994), reported in Maddison et al (1996), page 220.

Although the first-best policy might be for road users to be charged the full marginal social cost of marginal vehicle use, it is not possible to restructure existing taxes on vehicles or fuels so as to reproduce exactly the first-best structure of incentives. This is principally because these various environmental costs differ in how closely they are related to the characteristics of vehicles or fuels. Some, such as the global warming potential of vehicle use, are closely (and broadly linearly) related to fuel consumption. Others, including the costs of particulate emissions, and noise, are related to the location, and in some cases the time of day, of vehicle use. Fuel taxes would be a poor proxy for these components of the environmental costs.

As a result, taxation of vehicles or motor fuels can only provide an approximate reflection of the marginal social costs incurred as a result of individual transport decisions. The available tax bases are only loosely linked to the various social and environmental costs which policy might aim to control. In such a "second best" context, it will generally be appropriate to make use of a wide range of instruments, to produce the closest possible approximation of the tax incentives to the structure of the various social costs. However, theoretical analysis indicates that it will rarely be possible to provide a clear answer to the question of the appropriate relationship between the contribution of the various components. Second best policy design is often complex, and can be counter-intuitive, so that the available data and models are rarely likely to be capable of identifying the optimal policy mix with any certainty.

A further important second-best dimension of road transport tax policy arises because of the revenue needs of government. While the taxation of transport may be used to reflect the various uncharged social costs incurred as a result of individual transport decisions, transport taxes are also required to play other roles within the fiscal system, not least that of a major source of revenue. Governments levy indirect taxes for the purposes of revenue-raising as well as in order to correct externalities. In broad terms, revenue-raising taxes should be levied over and above any level of taxes imposed for purposes of correcting externalities (Sandmo, 1976). Where significant revenues are raised from externality-correcting taxes, it will of course be possible to set lower rates of purely revenue-raising taxes. It has been suggested that this substitution of externality-correcting taxes in place of distortionary taxation may provide a "double dividend", in the sense that the use of environmental taxation might yield both environmental benefits and a lower welfare cost of raising public revenues.

2.2.3 Linkage between road taxes and air pollution.

Road transport is responsible for a substantial proportion of emissions of a number of important local, regional and global atmospheric pollutants. In the UK (Table 4), road transport accounts for about 90 per cent of all emissions of carbon monoxide, half of all emissions of nitrogen oxides, and more than a third of all emissions of black smoke, and of volatile organic compounds. One fifth of UK emissions of carbon dioxide, the principal greenhouse gas, originate from road transport sources.

In considering the possible contribution that can be made by taxation to the regulation of air pollution, a key issue is that of the linkage between the available tax instruments and the level of emissions from different sources. Only if the taxes closely proxy underlying environmental costs will the incentive provided by taxation lead to efficient changes in polluting vehicle use. If on, the other hand, the linkage between tax base and environmental costs is weak, taxes may lead to inefficient patterns of polluter response to the fiscal incentive.

The contribution of road transport to air pollution varies between different types of vehicle. In particular, diesel engines emit considerably higher amounts of nitrogen oxides, black smoke and particulates than petrol engines, whilst having lower emissions of carbon dioxide and carbon monoxide. Emissions are also affected by the extent to which vehicles are fitted with pollution abatement equipment. Three-way catalytic converters, which have become a standard requirement on new cars sold in the European Union since 1993 result in substantial reductions in emissions of carbon monoxide, nitrogen oxides and hydrocarbons from petrol engines, whilst, on the other hand leading to somewhat higher fuel use for equivalent power, and hence higher carbon dioxide emissions.

Table 4: Emissions of pollutants in the United Kingdom in 1991: the percentage of the total attributable to road transport

	All road transport	Cars	Diesel powered vehicles
Carbon dioxide	90	81	2
Sulphur dioxide	2	1	1
Black smoke	42	6	39
Nitrogen oxides	52	29	21
Fine particulate matter	27	10	n/a
Carbon dioxide	19	12	6
Volatile organic compounds	37	22	6

Source: Quality of Urban Air Review Group (1993), Diesel Vehicle Emissions and Urban Air Quality, Second Report of the Quality of Urban Air Review Group, University of Birmingham, Institute of Public and Environmental Health, pages 50 and 53.

If heavier taxation of road transport reduced the level of traffic, it would be liable to reduce emissions of these various pollutants. This would be true if the effect of taxation were to reduced the total number of journeys taken; it would also generally hold if heavier taxes on private motoring were to induce individual substitution away from private motoring towards public transport, assuming that public transport is less environmentally-damaging. Figures presented by Hughes (1990) suggest that the energy used per passenger mile in a mid-sized petrol-driven car with an average 1.5 occupants is some four times the energy used per passenger mile in a train with 60 per cent occupancy, and more than twice the energy required per passenger mile in a bus with a 25 per cent occupancy rate.

Nevertheless, despite the probability that higher taxes would reduce emissions, the various taxes on motor vehicles and motor fuels are not directly proportional to the amounts of atmospheric pollution damage caused, and are, at best, only a partly-efficient signal for individual decision-making. For example, there is only weak correlation between and the amount of motor fuel used and the costs of additional atmospheric pollution. The externality costs of vehicle use generally depend on where and when journeys are made, and this is not captured in the taxation of fuel consumption. Thus, for example, the level and composition of various pollutants in vehicle exhausts differs depending on traffic conditions; in congested situations, significantly more of certain pollutants such as carbon monoxide will be emitted per litre of fuel used than in normal driving conditions.

2.3 Non-technical measures in MERLIN

2.3.1 The distinction between technical and non-technical measures

The underlying structure of the MERLIN model is one in which sectors are defined, in more or less detail (in some cases sub-sectors and, within sub-sectors, particular technology types are defined separately). The emissions consequences of the sector's activity are (for a wide range of pollutants), basically modelled as the product of the sector's activity level and an emissions coefficient, showing the emissions per unit of activity.

"Technical measures" within MERLIN can be represented either as changes in the emissions coefficient for a particular sector (or sub-sector or technology type), or as a shift in the pattern of activity within a sector or sub-sector between different technology types.

In representing the impact of technical measures on emissions, activity levels are held constant at the sector level (though activity may shift between technology types). This is a simplification, because in general it would be expected that implementing technical measures will have effects on costs, and hence prices, and hence may affect the sector's level of activity.

"Non-technical measures" in the MERLIN context would then comprise those measures which have their primary impact on the level of sectoral activity and a lesser impact on the coefficient relating activity to emissions. Again, it is unlikely that any of these measures would have an effect solely confined to activity levels. Effects on the coefficient relating activity to emissions might arise through a number of routes (eg a fall in activity might lead to closure of the most-polluting plants, reducing average emissions per unit of output, etc).

Symmetrically with the treatment of non-technical measures, the analysis could be simplified by assuming that the effects of non-technical measures are confined to activity levels, and that their effect on the activity : emissions coefficient can be neglected.

2.3.2 "Measures" in MERLIN, and policy instruments

The distinction between technical and non-technical measures in MERLIN is essentially a distinction between different forms of adjustment (response) to policy measures, rather than the distinction between different types of policy instrument.

In particular, the distinction between technical and non-technical measures does not coincide with the distinction between regulatory and market-based instruments in environmental policy. For example, much of the response by energy-sector firms to the acid rain emissions trading programme in the USA takes the form of changes in production processes and technologies (installation of FGD equipment, changes to lower sulphur input fuels, etc). These changes result from the incentive effect of emissions trading, but could also result from direct command-and-control instructions to employ FGD abatement technologies, or to switch to low-sulphur coal. In the MERLIN framework, these responses would count as technical measures, regardless of the policy instrument used to induce the changes in production processes and technologies.

2.3.3 Methodology for comparing technical and non-technical measures.

In principle, as noted above, both technical and non-technical measures would have effects on both the emissions coefficient per unit activity and on the level of sectoral activity. For technical measures the primary effect is that on the emissions coefficient per unit activity, and for non-technical measures it is the effect on the activity level. In principle, however, both effects will arise with both sets of measure, and a complete comparison of both types of measure will require both effects to be quantified.

The work by Roger Salmons in this part of the project has indicated what would be necessary if the effect of technical measures on activity levels was to be quantified. Essentially this would arise through a process of adjustments in relative prices, and consequent re-equilibration of markets. Roger Salmons' paper presents an algorithm for approximating the final outcome of this market adjustment, without requiring repeated iterations of the model. Nevertheless, implementing the algorithm would add considerable complexity to simulations using the model.

Alternatively, we can maintain the existing simplification that activity levels are maintained constant when the effects of technical measures are simulated. Symmetrically, we can assume that the impact of non-technical measures is confined to effects on sectoral activity. These simplifications will make simulations of both types of measure much less complex than if these simplifying assumptions are not made. For many policy interventions the approximation involved may be small, and the simplifications may be of little consequence. However, the model will not be able to evaluate the effects of all technical and non-technical measures in a comprehensive and wholly-consistent manner. Certain types of measure - those that have significant effects on both activity and emissions coefficients - cannot easily be handled within the MERLIN framework. The principal non-technical measures that can be included are those bearing quite directly on activity levels in final goods sectors.

Measures affecting activity levels in intermediate goods sectors are impractical to handle in this way, because such measures will almost certainly induce changes in production technologies in other sectors. Increasing the price of energy inputs to industry will, for example, create an incentive for energy efficiency improvements in energy-intensive industrial sectors, and this market-driven adjustment cannot be handled, except in an ad hoc way, within the MERLIN framework.

In principle the non-technical measures that can be simulated within MERLIN (while making the above simplifying restrictions) could include taxes on all kinds of consumption goods. However, most MERLIN sectors are drawn sufficiently broadly that there would be little practical policy interest in the simulation of sales taxes at the rather high level of aggregation employed. (In many industrial sectors, also, it would be difficult to separate output for final consumption and for intermediate use). The principal sector in which non-technical measures can be defined that are both practical to incorporate within the MERLIN framework and of likely policy interest is the transport sector.

Accordingly, it is proposed that the non-technical measures to be analysed should comprise measures in the transport sector that have their primary impact on the level of activity, especially on the level of transport activity by individuals, as opposed to industrial/business transport activities such as freight transport.

2.3.4 The selection of non-technical measures

Such non-technical measures could include both fiscal and non-fiscal measures. Among the fiscal measures the relevant set of measures could include:

- Higher motor fuel taxes
- Parking charges
- Road congestion pricing
- Motorway tolls
- Public transport subsidy
- Accelerated scrapping incentives
- Restructuring vehicle fuel taxes (eg the balance between diesel fuel and petrol)
- Higher taxes on motor vehicle ownership

Non-fiscal measures could include road-use restrictions (eg city-centre pedestrianisation), and quantitative parking restrictions. Both of these, however, have effects that, at the broad level of aggregation used in MERLIN, may differ little from the impact of corresponding pricing or city-centre traffic congestion and of parking spaces.

2.4 General issues of measurement

The non-technical measures to be included in MERLIN simulations of the transport sector take the form of price instruments which reduce certain types of travel.

To avoid the problem of tracing input price changes through into price effects on end-products (an issue ignored throughout MERLIN), the analysis concentrates on instruments affecting private travel (commuter and pleasure journeys), and does not cover freight travel. Changes in vehicle technologies for freight travel could be treated in MERLIN in the same way as other technical measures.

The reduction in travel induced by non-technical measures may be general, across-the-board. For example, an increase in motor fuel taxes might have an equal proportionate effect on all types of journey, with no differences between countries, between urban and rural areas, or between vehicle "vintages".

In other cases, non-technical measures may induce greater effects on certain types of journey (eg urban driving may be affected by an increase in parking charges or congestion charging), or certain vehicle types (eg an increase in the price of diesel fuel relative to petrol might induce substitution away from diesel cars towards petrol cars).

The basic approach draws "consensus" price elasticities from the existing international literature, and uses this as the basis for calculating the percentage reduction in output of particular transport activities for a specified (typically 10%) increase in the price variable.

The environmental effects of the price variable will follow from the change of activity. The costs of employing this particular instrument will be approximated by the simple partial equilibrium deadweight loss, given by the formula

$DWL = 0.5\ E\ e\ t^2$

where E is initial expenditure, e is the price elasticity of demand, and t the tax rate.

Of course, the specified price increase is only one of a range of possible prices that could be chosen. However the MERLIN optimisation approach (evolutionary algorithm) is based on the selection of strategies from a finite set of possible strategies, rather than determining the optimal value of instruments taking the form of continuous variables. It would be possible to include more than one tax rate as separate (and mutually-exclusive) instruments in the MERLIN optimisation. Since the deadweight loss of taxes (ie the cost of employing the tax instrument) is a function of the square of the tax rate rather than linear in the tax rate, optimisation across a set of strategies including a range of different possible tax rates could determine an optimal level for the tax within the set of selected strategies. It will not always be the case that if a tax rate of x% is selected, a tax rate of 2x% would be preferred.

Typically the elasticities obtained from econometric research are point estimates and can strictly-speaking only be used to calculate the effects of marginal changes in prices. This approach cannot therefore be used to simulate the effects of very large percentage price changes.

Table 5: UK Road Transport Marginal external cost, 1993 (and 2003 equivalent, per km)

	Total marginal external cost, bn pounds, 1993	Marginal external cost per vehicle km, Euro cents per km, 2003
Global warming	0.1	0.05
Air pollution	19.7	9.3
Noise	2.6 – 3.1	1.2 – 1.5
Congestion costs	19.1	9.0
Road damage	1.5	0.7
Accidents	2.9 – 9.4	1.4 – 4.4
Total	45.9 – 52.9	21.5 – 24.9
Total, excluding global warming and air pollution	26.1 – 33.1	12.2 – 15.5

Source: 1993 figures: Maddison, et al. 1996, p 141. 2003 Euro equivalents, author's updating.

According to Newbery (1995), urban journeys account for 97 per cent of congestion costs, while constituting only 41 per cent of traffic.

Table 6 Fuel efficiency of the private car stock in 20010, United Kingdom, MERLIN estimates

	Percentage of 2010 vehicle stock of petrol and diesel cars, respectively	Specific final fuel demand (GJ of fuel per thousand km)	Fuel efficiency, relative to average 2010 vehicle stock of petrol and diesel cars, respectively
Passenger cars (petrol)			
Pre Euro I	0.9	2.55	102.0
Euro I	3.1	2.68	107.1
Euro II	16.4	2.63	104.8
Euro III	34.0	2.56	102.2
Euro IV	45.6	2.44	97.2
	100.0	2.51	100.0
Passenger cars (diesel)			
Pre Euro I	1.0	2.26	115.1
Euro I	3.1	2.26	115.1
Euro II	16.4	2.13	108.5
Euro III	34.0	2.00	101.8
Euro IV	45.6	1.88	96.1
	100.0	1.96	100.0

2.5 Simulating the effects of an increase in motor fuel taxes within MERLIN

A number of the non-technical measures proposed for inclusion within the MERLIN simulation approach basically operate by increasing motoring costs. Such measures include the effects of higher motor fuel taxes (leading to higher petrol prices), congestion charges, road tolls, parking fees, etc. At the level of aggregation employed within MERLIN the simulation of each of these measures follows quite similar lines. Many of the differences between the measures that might be of interest in practice involve detailed differences that cannot be reflected within the MERLIN approach. The suggested procedure for simulating the impact of higher petrol taxes is set out in this section, and subsequent sections discuss the modifications in the simulation approach that are needed to reflect the effects of the other similar measures such as road tolls or parking fees.

The approach to simulating measures within MERLIN requires information on the quantitative consequences of the measure, and on its costs. In the case of a technical measure, such as the installation of a particular filter on polluting emissions, the quantitative effects would be on the coefficient relating emissions to output, and the costs would be the costs of installing the technology. In the case of a non-technical measure such as an increase in motor fuel taxes, the quantitative consequences will be reflected in changes in the activity level of the sector (reduced use of motor vehicles), and the cost takes the form, primarily, of a loss of consumer welfare (Deadweight Loss) as a result of the induced reduction in vehicle use.

2.5.1 Quantitative impacts on activity.

The effects of an increase in motor fuel taxes on vehicle use and other variables can be inferred from the existing evidence on the price elasticity of demand for motor fuels. There is an implicit assumption that motor fuel taxes would be wholly passed on to the consumer in higher motor fuel prices. Since petrol and other motor fuels are homogeneous and internationally-traded goods, this is probably a reasonable basis for simulating the effects of higher petrol taxes at the level of individual EU member states. Coordinated increases in petrol taxes across the EU as a whole might lead to some fall in the producer price of petrol, because changes in EU demands are probably large enough to affect the balance between world supply and demand. However, this is still likely to be small, and will be ignored.

Higher petrol prices would have three main effects:

- **reductions in vehicle ownership.** For some owners of motor vehicles, a higher petrol price would make ownership no longer worthwhile. The number of vehicles owned would fall, as a result of fewer purchases of new vehicles, and/or earlier scrapping of existing vehicles;
- **reductions in vehicle use.** The cost of each journey made would increase, and "marginal" or inessential journeys would be discouraged;
- **higher fuel efficiency of the vehicle stock.** Higher petrol prices would tend to encourage manufacturers to design more fuel-efficient motor vehicles, and to encourage purchasers of new cars to choose more fuel-efficient vehicles. Also, high petrol prices might encourage the more rapid scrapping of "gas-guzzling" older vehicles.

All of these three effects can be wrapped up in a single, summary, price elasticity of demand for motor fuels, or individual components can be analysed and estimated separately.

There is extensive empirical evidence concerning the aggregate price elasticity of demand for motor fuels, including both time series and cross section studies. In the former case, price elasticity is estimated from variation over time in the relative price of motor fuels (which is typically quite large in any data set including the OPEC oil price rises of the 1970s). In the latter case price elasticity is estimated from differences in petrol prices across countries. There are well-known limitations to either approach as a basis for assessing the effects of any future price changes. In the case of time series estimates these include issues about price expectations, about the impact of correlated changes in economic growth and activity, about the role of technological innovation in past and future responses, etc. In the case of cross-section estimates, a key issue is that differences in petrol consumption, which may be attributed to the effects of differences in petrol prices, may equally be due to differences in social, geographical and other characteristics.

There are a number of comprehensive survey reports which synthesize the results of the extensive empirical research on price elasticities. Hanly, Dargay and Goodwin (2002) confine their analysis to studies for the UK and broadly-comparable countries, but nevertheless cover 69 different studies with independent data and/or different methods. The 69 studies include 175 different estimated equations, containing 491 elasticities. Some of these elasticities were for the impact of fuel prices on traffic levels, car sales or fuel efficiency, but more than 100 were for the elasticity of fuel consumption with respect to price.

Hanly, Dargay and Goodwin (2002) conclude that the overall consensus of the studies, based on the best-defined results, is that a 10% increase in the real price of motor vehicle fuel would:

- **reduce the volume of fuel** consumed by 2.5% within one year, and over 6% in the longer run (ie 5 years+)
- **increase the efficiency of fuel use** by about 1.5% within one year, and about 4% in the longer run
- **reduce the number of vehicles owned** by less than 1% within the first year, and 2.5% in the longer run
- **reduce the volume of traffic** by 1% within the first year, and 3% in the longer run.

Broadly similar results are found in other literature surveys of the fuel price elasticity literature. In particular there seems to be considerable consensus that the short-run fuel price elasticity is around -0.2 to -0.3, and that the elasticity over a longer time period is perhaps twice the short-run elasticity.

It is proposed that the estimates from this consensus literature should form the basis for simulating the effects of an increase in fuel prices within MERLIN. Three major issues arise for this simulation:

- **choice of time scale.** The adaptation of the economy to changes in relative prices is dynamic. Much larger changes are encountered over a time period of five years than in the one or two year short-term. The approach taken in MERLIN is more consistent with simulating the long-term consequences of different policies, rather than trying to forecast the short-term adjustment dynamics, and for this purpose long-run elasticities would be more relevant than short-run elasticities.

- **integrating the effects of vehicle ownership and the effects on vehicle use.** MERLIN has both "capital stock" (ie number of vehicles) and "use" (kilometers driven, etc) data. Describing how higher fuel prices would impact on the MERLIN model will therefore require us to trace through the series of adjustments to both vehicle stock and use variables. Unfortunately, the available estimates of these disaggregated components of the adjustment are estimated with less precision, and command less consensus agreement, than the overall elasticities. In addition, many of the "stock" and "use" estimates are produced separately, while in principle both should be estimated together. While in principle MERLIN could be programmed so that both the capital stock and use effects of non-technical measures are reflected in the simulation, the initial approach being taken confines attention to the use effects. It should be noted that this means that some significant channels through which non-technical measures affect behaviour and emissions will be disregarded.
- **disaggregating these consensus estimates to provide separate estimates for the various vehicle categories within MERLIN.** A further feature of MERLIN poses additional problems, in that sectors are disaggregated into technology "vintages". It is not at all clear that an aggregate elasticity can be applied to each of these technology vintages. One reason for this is that a (say) 10% rise in petrol price has different effects on the rice of motoring services for vehicles with different levels of fuel efficiency. It is therefore not realistic to assume that someone owning a highly fuel-efficient car would change their behaviour in the same way (including reducing their fuel consumption by the same percentage) as someone owning a less fuel-efficient car. For this to be modelled it would be necessary to make some assumptions about how the aggregate elasticities for vehicles as a whole should be divided across the various MERLIN sub-sectors and technology vintages. It will, in general, not be possible to estimate fresh elasticities at the MERLIN level of disaggregation, because it is unlikely that an adequately-long disaggregated data set can be constructed at the MERLIN level of disaggregation. On the other hand, with the existing information any sub-division of the aggregate elasticity will be a matter of little more than guesswork.

The starting point is one in which the average price of premium unleaded petrol (95 RON) in EU countries is some 97 cents per litre (Table 7). The basic scenario of a petrol tax increase (the "10 per cent scenario") takes the form of a 9.7 cents per litre increase in petrol tax in each European country, an increase which on average would increase EU petrol prices by 10 per cent. The increase has the same monetary value in all countries, but the percentage increase in petrol price caused by the measure will differ across countries because initial petrol prices differ. The highest percentage increase in petrol prices from the 9.7 cents per litre measure will be about 26 per cent in Greece, the country with the lowest initial price, and the lowest percentage impact on prices will be an 11 per cent increase in the UK, the country with the highest initial petrol price (Table 8). An alternative, in which each country makes the same percentage increase in the petrol price (or in the level of tax) could of course be simulated, but this would mean that, typically, much larger increases were being simulated in countries with high existing petrol taxes than in countries with low existing taxes.

In addition to the 97 cents "10 per cent" base case, two further cases are simulated, corresponding to average increases of petrol prices of 5 per cent and 20 per cent respectively. Because of the non-linearity of costs, these need to be handled as mutually-exclusive measures in the MERLIN simulation routine, which selects a package of measures from a wider set of potential measures. Only one of the three petrol tax measures can therefore be employed in any chosen package.

The quantitative impact of the 9.7 cents price increase would then be estimated using the "consensus" elasticities discussed earlier. These are to the effect that at 10 per cent increase in motor fuel price would result in the following effects

- 3% reduction in traffic
- 4% increase in fuel efficiency
- 2.5% reduction in vehicle ownership
- 6% reduction in fuel consumption.

The 6% impact on fuel consumption arises as the combined outcome of the other changes, and reflects some rounding error.

For the 9.7 cents increase (the "10 per cent" case), the traffic, fuel efficiency and vehicle ownership effects are shown in Table 9. On average across the EU countries for which results are available, vehicle mileage would fall by 3.3 per cent, fuel efficiency would rise by 4.4 per cent, and vehicle ownership would fall by 2.8 per cent (unweighted averages in each case). For the 5 per cent case, the effects would be approximately half those shown in Table 9. For the 20 per cent case the effects would be approximately double those in Table 9.

There is, unfortunately, relatively little quantitative evidence on the impact of motor fuel taxation on the use of public transport. However, studies of the demand for bus transport generally show it to be relatively insensitive to price in the short run, with more responsiveness indicated in the longer term. The extent of substitution will vary across locations, depending on the availability of existing public transport, and the pattern of settlement, which will affect the profitability of any increase in public transport supply.

For the purposes of MERLIN simulation, it is suggested that 50 per cent of the calculated mileage reduction be assumed to take the form of a shift to public transport. In the absence of better evidence, it is suggested that each form of public transport (urban bus, interurban coach and rail) be increased by same proportion.

2.5.2 Cost impacts

The key element of the cost calculation is a deadweight loss estimate, reflecting the welfare cost of the induced change in consumer behaviour.

Assessment of the deadweight loss from petrol taxes and other policy measures affecting the cost of private motoring is in principle complicated. Estimation of the deadweight loss from petrol taxes in the US and the UK by Parry (2003) shows the importance of taking account of the full range of effects across the economic system. The deadweight loss is, for example, affected by the level of other taxes and their structure, as well as by the existence of other regulatory interventions affecting the generation of transport externalities. In principle, therefore, the calculation of the deadweight loss from any particular measure needs to reflect the full set of other fiscal and environmental policies being employed. Within MERLIN, however, the simulation approach, which repeatedly tests different permutations and combinations of measures, would be unmanageably cumbersome if the costs associated with each measure were to be allowed to vary depending on the set of other measures employed. At the very least this would require continual recalculation; at the worst it could affect (unpredictably) the convergence properties of the MERLIN optimising algorithm. For practical reasons, therefore, it is necessary to define an approximation to the costs which can be applied without reference to the other measures employed.

The suggested approach is to use a very simple estimate of the deadweight loss, based on partial equilibrium analysis of the demand for motor fuel for private transport. Implicitly we are assuming that motor fuel expenditures are the principle variable cost of private motoring. We calculate deadweight loss as the standard welfare "triangle" under the demand curve, with one significant further step.

This is to note that, up to a certain point, motor fuel taxes would be welfare-improving rather than welfare-reducing, in the sense that they effectively charge a price for costs (of public transport infrastructure damage, congestion, accidents, pollution, etc) which are otherwise uncharged in the economic system. The part of the existing petrol tax which reflects this cost is treated as an element of the initial "full" price for private transport, and the initial "fiscal" tax on private motoring is defined as the remainder of the tax, after the externality tax element (the "Pigovian" element) is deducted. Deadweight losses are thus defined with respect to the initial "full" price, and the taxation which gives rise to deadweight losses is the "fiscal" element of existing taxes, plus whatever additional taxation is imposed.

To implement this approach in practice requires a division of the existing taxes on motor fuels into "Pigovian" and "fiscal" elements. Based on the detailed estimates for the UK in Parry (2003) it is assumed that the Pigovian element in current petrol taxes (ie the element that can be justified in terms of the marginal external costs of motoring) is 27.5 cents per litre. In the absence of detailed data for other member states the UK figure is applied throughout, and the "fiscal" element in existing taxes is then calculated as the remainder, after this deduction. Symmetrically, the initial price is increased to include the Pigovian element, resulting in a "full" price, including the Pigovian element which charges for external costs. (Table 10).

The initial rates of petrol tax (defined with respect to this "full" price), and the rates of tax under the 5 per cent, 10 per cent and 20 per cent tax-increase measures are set out in Table 11. On average, the initial fiscal tax on petrol in EU member states is 44 per cent of the pre-tax "full" price, and the 5 per cent, 10 per cent and 20 per cent petrol tax measures result in average taxes of 52 per cent, 60 per cent and 75 per cent, respectively.

Based on these tax rates, existing expenditures on petrol, and an assumed elasticity of –0.6, deadweight losses are calculated for each of three measures, and reported in Table 12. Across the EU as a whole, the 10 per cent petrol-tax measure (a petrol tax increase which raises petrol prices on average by 10 per cent) has a cost, in terms of deadweight loss, of some Euro 5.5 billion. The 5 per cent and 20 per cent variants have deadweight costs of Euro 2.6 billion and Euro 12.4 billion, respectively. It will be noted that these deadweight losses are, as would be expected, non-linear in the tax rate.

Table 7: Petrol prices, and petrol taxes, in EU countries, 2000

	Petrol price (premium unleaded, 95 RON), US dollars per litre	Percentage of taxes in petrol price	Petrol tax, as percentage of pre-tax price
Austria	0.87	60.6	154
Belgium	0.96	65.9	193
Denmark	1.03	66.3	197
Finland	1.05	67.3	206
France	1.01	69.8	231
Germany	0.94	69.3	226
Greece	0.72	52.8	112
Ireland	0.82	58.9	143
Italy	1.00	64.8	184
Luxembourg	0.76	55.7	126
Netherlands	1.07	66.4	198
Portugal	0.80	49.4	98
Spain	0.76	59.2	145
Sweden	1.04	67.0	203
UK	1.21	75.5	308
Bulgaria			
Czech Republic	0.74	55.8	126
Estonia			
Hungary	0.82	60.0	150
Latvia			
Lithuania			
Poland	0.72	57.0	133
Romania			
Slovak Republic	0.73	53.9	117
Slovenia			
EU average	0.90	61.9	171
EU average (weighted)	0.97	66.7	211

Source: Column 1 International Energy Agency, Energy Prices and taxes, 4th Quarter 2002, Table 12 (for column 1) and Table 11 (for column 2). Column 3 and averages, author's calculations. Weights are MERLIN data on total fuel consumption.

Table 8: Increase in petrol prices with petrol tax increase: "10 per cent" case (9.7 cents per litre increase in all member states)

	Petrol price (premium unleaded, 95 RON), US dollars per litre	Percentage increase in petrol price from 9.7 cent per litre tax increase.	Tax increase, as percentage of initial tax
Austria	0.87	11.3	18.6
Belgium	0.96	10.2	15.4
Denmark	1.03	9.5	14.3
Finland	1.05	9.4	13.9
France	1.01	9.8	14.0
Germany	0.94	10.5	15.1
Greece	0.72	13.6	25.8
Ireland	0.82	11.9	20.2
Italy	1.00	9.8	15.2
Luxembourg	0.76	12.8	23.1
Netherlands	1.07	9.2	13.8
Portugal	0.80	12.3	24.8
Spain	0.76	13.0	21.9
Sweden	1.04	9.4	14.1
UK	1.21	8.1	10.7
Bulgaria			
Czech Republic	0.74	13.2	23.6
Estonia			
Hungary	0.82	11.9	19.8
Latvia			
Lithuania			
Poland	0.72	13.6	23.8
Romania			
Slovak Republic	0.73	13.5	25.0
Slovenia			
EU average	0.90	11.1	18.4
EU average (weighted)	0.97	10.2	15.7

Source: Column 1 International Energy Agency, Energy Prices and taxes, 4th Quarter 2002, Columns 2 and 3 and averages, author's calculations. Weights are MERLIN data on total fuel consumption.

Table 9: Effects of 9.7 cents per litre Increase in petrol prices in EU member states ("10 per cent" case)

	Percentage reduction in traffic	Percentage increase in fuel efficiency	Percentage reduction in vehicle ownership
Austria	3.4	4.5	2.8
Belgium	3.0	4.0	2.5
Denmark	2.8	3.8	2.3
Finland	2.8	3.7	2.3
France	2.9	3.9	2.4
Germany	3.1	4.1	2.6
Greece	4.0	5.4	3.4
Ireland	3.5	4.7	2.9
Italy	2.9	3.9	2.4
Luxembourg	3.8	5.1	3.2
Netherlands	2.7	3.6	2.3
Portugal	3.6	4.9	3.0
Spain	3.9	5.1	3.2
Sweden	2.8	3.7	2.3
UK	2.4	3.2	2.0
Bulgaria			
Czech Republic	3.9	5.2	3.3
Estonia			
Hungary	3.5	4.7	2.9
Latvia			
Lithuania			
Poland	4.0	5.4	3.4
Romania			
Slovak Republic	4.0	5.3	3.3
Slovenia			
EU average	3.3	4.4	2.8

Source: author's calculations.

Table 10: Decomposition of existing taxes on petrol into a Pigovian component, charging for the resource costs of fuel and vehicle use, and a pure fiscal element.

	Initial petrol tax, US dollars per litre	Initial "fiscal" tax on petrol (initial tax minus Pigovian element)	Petrol price per litre, before tax, US dollars	Full-cost price, before "fiscal" tax (ie pre-tax price plus 27.5 cents per litre Pigovian tax)
Austria	0.53	0.25	0.34	0.62
Belgium	0.64	0.36	0.38	0.65
Denmark	0.68	0.41	0.41	0.68
Finland	0.70	0.43	0.41	0.69
France	0.70	0.43	0.40	0.67
Germany	0.65	0.37	0.37	0.64
Greece	0.38	0.10	0.28	0.56
Ireland	0.49	0.21	0.32	0.60
Italy	0.65	0.37	0.39	0.67
Luxembourg	0.42	0.15	0.30	0.58
Netherlands	0.71	0.43	0.42	0.70
Portugal	0.39	0.12	0.31	0.59
Spain	0.45	0.17	0.30	0.57
Sweden	0.70	0.42	0.41	0.68
UK	0.91	0.64	0.48	0.75
Bulgaria				
Czech Republic	0.41	0.14	0.29	0.57
Estonia				
Hungary	0.49	0.22	0.32	0.60
Latvia				
Lithuania				
Poland	0.41	0.14	0.28	0.56
Romania				
Slovak Republic	0.39	0.12	0.29	0.56
Slovenia				
EU average	0.56	0.29	0.35	0.63

Source: author's calculations.

Table 11: Initial fiscal tax on petrol, and the impact on fiscal petrol taxes under three possible options.

	Initial "fiscal" tax, as percentage of "full" price	Initial fiscal tax plus tax increase, as percentage of "full" price		
		10 per cent option	5 per cent option	20 per cent option
Austria	41	56	49	72
Belgium	55	70	62	85
Denmark	60	74	67	89
Finland	62	77	69	91
France	64	78	71	92
Germany	58	73	66	88
Greece	19	36	27	53
Ireland	35	51	43	67
Italy	55	70	63	85
Luxembourg	26	43	34	60
Netherlands	62	76	69	90
Portugal	20	37	29	53
Spain	30	47	39	64
Sweden	62	76	69	90
UK	85	98	91	111
Bulgaria				
Czech Republic	25	42	33	59
Estonia				
Hungary	37	53	45	69
Latvia				
Lithuania				
Poland	24	42	33	59
Romania				
Slovak Republic	21	38	29	55
Slovenia				
EU average	44	60	52	75

Source: author's calculations.

Table 12: Estimated deadweight loss from petrol tax increase: "10 per cent" base case (9.7 cents per litre increase in all member states), and 5 per cent and 20 per cent variants. Thousands Euros per annum.

	10 per cent option	5 per cent option	20 per cent option
Austria	346699	167092	743459
Belgium	468883	227346	994530
Denmark	348320	169249	735927
Finland	485120	235896	1023554
France	2941191	1430056	6206694
Germany	6184871	3000563	13104719
Greece	183837	87445	403457
Ireland	108815	52292	234557
Italy	2840915	1378101	6020683
Luxembourg	14750	7051	32092
Netherlands	633101	307921	1335238
Portugal	119155	56779	260702
Spain	778249	372802	1687082
Sweden	675703	328479	1426387
UK	6916692	3384134	14427081
Bulgaria	66823	31072	152358
Czech Republic	106410	50815	231943
Estonia	15581	7240	35567
Hungary	98984	47598	213121
Latvia	18295	8588	41068
Lithuania	44204	20661	99933
Poland	349058	166635	761269
Romania	99533	47555	216764
Slovak Republic	70915	33781	155243
Slovenia	30590	14501	67528
EU total	23946694	11633651	50610958

Source: author's calculations.

2.6 Parking fees

Parking charges may be used to reduce the volume of urban traffic, and consequent traffic-related environmental problems.

The charges could apply to various different categories of parking, including on-street parking, off-street parking facilities (run either on a commercial basis or by the public authorities), workplace parking, customer parking, etc. It is conceivable that charges could also be levied for residential parking, but this issue is not considered here.

These various different types of parking charges raise somewhat different practical and analytical issues. For simulation in MERLIN the proposed measure is a general charge for all categories of parking in urban areas. This is naturally a rather broad-brush scenario, and will omit a lot of detail which more specialised models of transport can include.

One major policy attraction of parking charges in managing urban transport problems is that they can be differentiated in various relevant directions. Different charges can be levied

- ***according to the time of day***, so as to discourage rush-hour journeys, for example
- ***according to location***, so as to ensure optimal use of parking spaces; more inconvenient spaces would be priced lower, and more attractive spaces would be priced higher, with

the aim of ensuring some availability of all types of space. (Part of the aim of optimal parking pricing is generally seen as reducing search costs; time spent searching for a parking space is costly, and searching can add to vehicle congestion and pollution)

- ***according to duration of stay***, so as to distinguish between "workers" and "customers", for example.

A lot of the available evidence on the behavioural consequences of parking charges relates to specific scenarios (eg a particular package of charging measures, with elements of the above differentiation, or a change in the level or structure of parking charges). An element of judgement is needed to assess how the results of such studies might provide elasticities for a MERLIN simulation including a general parking charge.

In any analysis based on comparative simulation of a number of measures, it is important also to consider the relationship between the patterns of behavioural response expected from the different measures. Estimated elasticities may differ for all sorts of data and methodological reasons. However, if different elasticities are to be applied to different measures in a comparison of effects, it is important that this can be justified in terms of reasons to expect real differences in the behavioural response.

As with all of the transport demand-side measures, there are important geographical aspects to the impact of parking charges. Parking charges will have much larger effects on short urban journeys than on interurban journeys. In general, more use is made of parking charges in dense urban areas than in less densely-developed rural areas.

Much of the available evidence relates to the impact of parking charges in the US. Given the spatial pattern of development, and the major differences between US and European cities, it is difficult to be confident that elasticity evidence from the US can be applied, unmodified, to the European context.

2.6.1 Likely behavioural effects of parking charges

By increasing the cost of journeys to charged locations, parking charges would encourage

(1) some cancellation of journeys;

(2) substitution to other modes of urban transport (eg rail, bus);

(3) substitution towards journeys to uncharged locations (eg out-of-town developments).

In addition, there may be further consequences of parking charges

(4) parking charges will lead to changes in traffic-related environmental problems. If they are effective at discouraging journeys at peak hours they would reduce congestion, and consequently reduce congestion-related vehicle emissions.

(5) parking charges (like congestion charges) also have benefits to road users. In particular, by improving the availability of parking spaces, they can reduce search time, and allow drivers to park more conveniently.

(6) parking charges generate revenues, which may be of public value (in that they reduce the need for other forms of taxation).

2.6.2 How can we, in principle, incorporate these effects in MERLIN?

We might begin by assuming that the effects of parking charges will be the same (as a percentage of initial activity) for all types of private cars in MERLIN. Arguably the owners of older cars would be poorer and therefore more price-sensitive than the owners of newer cars. However, in the absence of good evidence that would allow this to be reflected in MERLIN, the same scale of response might be assumed across all vehicle categories.

Effects (1) and (2) are then relatively straightforward. Given an elasticity (ideally for "km with respect to parking charge"), effects (1) and (2) could be modelled as a reduction in the activity level for all vehicle types. Effect (2) would then require a corresponding increase in the activity level of alternative (public) transport.

Effect (3) is something that can only really modelled in a context which allows detailed spatial representation. Likewise, it is not easy to see how to represent (4) to (6) within MERLIN.

2.6.3 Elasticities from existing empirical literature

For MERLIN purposes, what is needed is evidence on the relationship between parking charges and vehicle activity. In the various empirical studies in the literature, the impact of parking prices is represented by elasticities of typically two sorts:

- the elasticity of demand for *parking space* with respect to the parking price,
- the elasticity of demand for *vehicle journeys* with respect to the parking price.

The second of these provides us with one possible starting point for assessing the impact of parking prices on vehicle activity, although some assumptions would have to be made about how a change in vehicle journeys translates into a change in vehicle activity. (eg Do parking charges have a greater impact on shorter vehicle journeys? If so, a particular percentage reduction in journeys would lead to a smaller percentage reduction in activity (km)).

Interpreting elasticities requires some consideration of the initial level of parking charges. Where this is very low, high percentage changes in parking prices would be more feasible than where charges are already high. Some studies look at the impact of charges at a given monetary level. In some respects these are easier to translate into a form useful for simulation in MERLIN.

Some indication of the range of possible variation in parking charges is given by some rough orders of magnitude for, on the one hand, existing vehicle operating costs, and , on the other, full charging for parking space. The Victoria TPI TDM Encyclopedia (at http://www.vtpi.org/ tdm/tdm26.htm, page 2) suggests that that, in the US, the stock of off-street and on-street parking spaces would have an aggregate value of some $1500 per vehicle, equivalent to about 12 cents per vehicle mile, about equal to average vehicle operating costs. Full charging for parking thus has the potential to roughly double the cost per mile of driving in the US, and hence seems likely to have considerable potential to influence behaviour.

Interpreting this in the European context, some adjustments to values would be appropriate, although these may have partly-offsetting effects. On the one hand, it is likely that the value of European parking spaces would be higher, because European cities are more densely-developed, with less available space. On the other hand, existing motoring costs per km in Europe tend to be substantially higher than in the US, mainly because fuel is taxed much more heavily.

The price elasticity of vehicle travel with respect to the price of parking is reported by Pratt (1999) to lie in the range -0.1 to -0.3, depending on a range of demographic, geographic, travel choice and trip characteristics. Other studies contain varying estimates, but -0.3 seems to be regarded as a typical or central value by the existing survey papers. For example, Pratt *et al* (2000) observe that "Empirically-derived as well as modelled parking demand elasticities for area-wide changes in parking price generally range from -0.1 to -0.6, with -0.3 being the most frequently cited value. Most such elasticities have been established on the basis of commuter (work purpose) travel, with little useful information on the sensitivity of non-work travel to the price of parking." (Pratt *et al*, 2000, p 13-4).

The implication is, then, that the price elasticities for vehicle travel with respect to fuel price and to parking price are relatively close. In the petrol tax simulation, a 10 per cent rise in petrol price was assumed to lead to a 3 per cent reduction in traffic volumes. Indeed, aside fro the possibility that parking charges might lead to behavioural responses that reduce parking, without reducing the distance of travel, is there any reason to expect a major difference between the effect on vehicle travel of increasing the overall cost of motoring by levying higher petrol taxes, and the effect of increasing the overall cost of motoring by an equivalent amount through higher general parking charges? In general the effects would seem likely to be quite close. On the one hand, it is possible that effects of parking charges on motor vehicle ownership and use could be a little larger than with the motor fuel tax, since there is no scope for reducing the impact of higher parking charges by buying a smaller, more fuel-efficient car. On the other hand, there may be some scope for reducing the amount of parking for a given vehicle mileage though better organisation of journeys, substitution to cheaper parking locations, etc, for which there is no equivalent in the case of general fuel taxes. In the absence of clear and comparable evidence justifying a difference in the vehicle travel elasticity between petrol price and parking fees, and elasticity of –0.3 might be employed for both. In other words, a 10 per cent rise results in a 3 per cent fall in traffic.

There remains of course an issue as to what the baseline for the elasticity is: 10 per cent rise in what. Here, to ensure consistency wit the petrol tax scenario, it is assumed that elasticity applies to vehicle variable operating costs, assumed to be proxied by petrol expenditure.

The effect of parking charges and the petrol tax case are, then, basically the same, with the key difference that the parking charge case is assumed to apply only to journeys in urban areas. Using MERLIN data on the proportion of journeys in urban, highway and rural locations, the fraction of urban journeys for each country can be applied, to work out the number of journeys affected by the parking charge measure. The deadweight loss, defined consistently, would then be the same fraction of the total deadweight loss.

The reduction in urban journeys will at least in part arise as a result of substitution to public transport. It is suggested that this substitution might be somewhat higher than on average in the petrol tax case. Perhaps some 75 per cent of the reduction in urban journeys might involve substitution to public transport.

2.7 Urban congestion charge

For example, estimates by Newbery of the marginal external costs of traffic congestion in the UK (Table 13), show that the marginal external cost per vehicle kilometre was some ten times higher in urban central areas at peak hours than the UK average, and was substantially less than one tenth of the UK average in rural areas. For peak hour city centre journeys the congestion cost was some 36 pence per kilometre (in 1990 prices: equivalent to 52 pence or euro 0.78 in 2003 prices). On the basis of these figures, a first-best charging scheme for vehicle congestion would thus levy a charge of euro 0.78 per kilometre in city centre areas at peak times, a roughly 20 per cent lower charge in these areas at off-peak times, lower charges still outside urban central areas, and negligible or zero charge in rural areas. On average a congestion charge of euro 0.005 per kilometre would be charged on motorway journeys.

Table 13: Marginal time costs of congestion in Great Britain, 1990

	Marginal congestion cost (pence per PCUkm)	Index of MCC (UK average = 100)
Motorway	0.26	8
Urban central peak	36.37	1070
Urban central off-peak	29.23	860
Non-central peak	15.86	466
Non-central off-peak	8.74	257
Small town peak	6.89	203
Small town off-peak	4.20	124
Other urban	0.08	2
Rural dual carriageway	0.07	2
Other trunk and principal	0.19	6
Other rural	0.05	1
Weighted average	*3.40*	*100*

Source: Newbery (1990), Table 2.

Simulating the impact of an urban congestion charge within MERLIN will, however, be difficult to differentiate from the proposed simulation of urban parking charges. Both increase to costs of urban journeys, and the interesting differences between them reflect substitutions between different parking locations, different times of day, etc. These effects require a level of detail considerably higher than in MERLIN.. If the representation of parking charges and urban congestion charge within MERLIN is identical, then there will be no way in which the optimisation algorithm could choose between the two measures.

Motorway toll

A system of generalised motorway tolls might be represented within MERLIN in much the same way as the parking charge measure. The effects on vehicle use might be similar to those of an increase in petrol price through taxation, but confined to highway mileage only. Again, the fraction of all journeys that are highway journeys might provide a scaling fraction for the change in vehicle travel and deadweight loss. Substitution is likely to be much less than in the case of measures affecting urban travel. perhaps only some 25 per cent of the reduction in private motoring journeys might be offset by increases i public transport, perhaps spread between "coach" and 'rail' categories.

2.8 Scrapping incentives

2.8.1 Description of possible measures

Some European countries, including Italy and France, have operated fiscal incentives for the scrapping of older motor vehicles. These incentives might be justified on environmental grounds, although in practice they seem to have been introduced primarily to stimulate the motor vehicle market, by accelerating vehicle replacement.

There seem to be two groups of policies in international practice, which have differing underlying objectives

2.8.1.1 Measures to regulate the scrapping process

The aim is to ensure that old vehicles are scrapped through approved channels, rather than simply dumped. Measures of this sort could be undertaken for three main reasons:

- concern about the disamenity from dumping of old vehicles
- potential economic gains from materials recovery and salvage (this would generally result in a commercial price for scrapping, but if there are external benefits from greater recycling this commercial price would be insufficient)
- to prevent dangerous vehicles continuing to operate outside the regulated system, perhaps without license, insurance, etc (eg crash write-offs, vehicle test failures, etc)

Instruments include:

- ***deposit-refund systems*** for used car hulks (as in Norway, Sweden). The purchaser pays an extra tax (deposit) on purchase, and this is then refunded when car is scrapped through approved channels. If the deposit and refund are equal there is some disincentive to car ownership (since the deposit is "loaned", interest-free, to the authorities for the lifetime of the car). In principle, without some control mechanism, imported used vehicles could qualify for the refund without having paid the initial deposit, but this is probably a relatively minor risk with motor vehicles, which are closely regulated, registered, etc.
- ***a scrapping premium***. In effect, this corresponds to the refund in a deposit-refund system, without a formal link to the initial deposit. Given the scale of taxes on motor vehicles, the differences are largely presentational.

2.8.1.2 Measures to accelerate the scrapping rate

The aim is to remove old vehicles from circulation, because of concern about greater emissions levels from older vehicles. For example, in the USA, pre-1980 cars are 18% of the vehicle stock, and account for only 8% of the miles driven, but may give rise to up to 40% of total hydrocarbon and carbon monoxide emissions, and 25% of total nitrogen oxide emissions from motor vehicles. (Alberini et al. 1995)

The environmental policy reasons for encouraging accelerated scrapping may also coincide with the interests of vehicle manufacturers in maximising the market for new vehicles.

The available policy instruments to encourage accelerated scrapping include:

- ***purchase of old vehicles*** through AVR (accelerated vehicle retirement) programmes. In the US, utilities companies have been able to use AVR as a means of complying with their overall pollution abatement requirements.
- ***higher recurrent taxes*** (eg annual taxes) on motor vehicles in general, or specifically on older vehicles in the vehicle stock
- ***costly vehicle testing and inspection programme.*** These possibly could be used to accelerate retirement, because the cost of inspection might make scrapping a preferable alternative for4 the owners of "marginal" old cars. Although vehicle testing and inspection programmes might have some effect of this sort, it is not clear whether, in practice, they have ever been designed with this as a major objective.
- ***scrapping premium***. A scrapping premium will normally have only a limited impact on scrapping decisions, except where the premium is only available for a limited period. With a permanent premium scheme, owners will receive the premium at some stage, regardless of when they choose to scrap; the only advantage of accelerated scrapping is that the premium is received sooner rather than later.

2.8.2 The costs and benefits of accelerated vehicle scrapping measures

There are three key elements in an assessment of the costs and benefits of accelerated vehicle scrapping:

- The pollution avoided through accelerated scrapping
- The economic consequences of "premature" scrapping
- Public expenditure cost

(i) The pollution impact will depend on three main elements. First there is the reduction in emissions from scrapped vehicles, which will depend on both the technical characteristics of the vehicle (can policy select the most-polluting old vehicles?), and on the pattern of use. Second, there are changes in emissions elsewhere in the vehicle stock, including the emissions of any replacement vehicles, and the pollution consequences of any chain of adjustments through the vehicle market as a whole. (It will not always be the case that the person who scraps a car is the same person who purchases its replacement. Third, we should in principle be interested in life-cycle effects, and so there will be the pollution associated with the manufacture of replacement vehicles. The first two categories of effect will be handled straightforwardly within the MERLIN simulation; it is unclear whether the pollution consequences of vehicle manufacturing can also be drawn from the existing MERLIN data.

(ii) the economic consequences of premature scrapping essentially take the form of writing off the consumer value (quasi rent) that would be obtained from continued use of the vehicle for the remainder of its economic life. If second-hand vehicles are priced efficiently, this would equal the market value of the vehicle, which in turn would equal the minimum premium that has to be paid in order to induce accelerated scrapping.

If the same premium has to be paid for all vehicles scrapped through the scheme, there will be a distribution of losses, ranging from zero (for a vehicle that was on the point of being crapped anyway) to the full value of the premium (for the marginal vehicle entering the scrapping scheme). Assuming (for simplicity) a straight line distribution of values, the average economic loss would be half the value of the premium paid. For MERLIN purposes we might assume that a premium of Euro 500 per car would result in scrapping of 50% of pre-Euro cars, 25% of Euro I cars and 10% of Euro II cars that would otherwise be in the vehicle stock in 2010, and their replacement in each case by an equivalent number of Euro IV cars. The economic cost per vehicle scrapped would be 250 Euros.

(iii) the public expenditure cost of the scheme has to be financed through taxation. Estimates of the marginal excess burden of taxation vary, but a reasonable working assumption might be 25% of the revenue raised. The 500 Euro cost of the subsidy would thus impose additional welfare losses, through the tax system, of 125 Euros. In total, therefore, items (ii) and (iii) thus amount to 375 Euros per car scrapped.

2.9 Diesel / Petrol differential

Environmental considerations might be reflected in road taxes by differentiating the taxes to encourage substitution towards less damaging fuels or vehicles. During the 1990s, all EU countries taxed **unleaded petrol** less heavily per litre than corresponding leaded petrol, with the aim of accelerating the phase-out of leaded petrol from the market. Leaded petrol has now been removed from normal sale within the EU. Similarly, the long-standing differential between excise levels on diesel fuel and petrol might equally be considered in the light of the environmental attributes of the two fuels. In fact, the relative environmental damage caused by petrol and diesel engined vehicles is complex; emissions of some pollutants, especially those affecting urban air quality, tend to be higher from diesels than from catalyst-fitted petrol cars (and in some cases than petrol cars without catalysts), whilst emissions of greenhouse gases may be rather higher. Whether diesel should be preferred to petrol on environmental grounds, or vice versa, thus depends partly on the relative weighting given to various different environmental problems.

There is little firm empirical evidence on behavioural responses to diesel fuel differentials, on which to base a simulation of this measure within MERLIN. A reduction in the motor fuel differential in favour of diesel of 5 cents per litre would increase the lifetime cost of operating a diesel car, rather than a petrol car, by some Euro 600, an effect large enough to prompt a modest amount of switching of purchaser choices away from diesel cars towards petrol cars. The MERLIN simulation could perhaps assume that this change in the differential would result in a 5 per cent reduction in the number of diesel passenger cars in Euro III and Euro IV categories, and their replacement by corresponding Euro III and Euro IV petrol cars. The environmental effects would be simulated in MERLIN in the normal way.

The economic cost of inducing this switch could be estimated in a similar way as with the scrapping incentive, by assuming a uniform distribution of consumer preferences, so that the first switch results in negligible loss in consumer welfare, while the marginal switch results in a loss in welfare equal to the full lifetime fuel cost effect of Euro 600. On average each vehicle switching would involve an associated economic cost of Euro 300.

2.10 Conclusions

Non-technical measures, taking the form of various fiscal instruments in the transport sector, could be employed as part of a package of policy measures to reduce air pollution. This paper has discussed how the effects of such measures might be incorporated within the MERLIN simulation approach, and has set out some practical recommendations for approximating their effects within a broader simulation including both technical and non-technical measures.

In the course of undertaking this work, a number of issues have been encountered which are relevant to the wider question of the feasibility of simulating on-technical measures within the MERLIN approach (and, indeed, within other models based on a bottom-up, technology-focused, air pollution model). These issues include the following:

2.10.1 Consistency and modelling approximation

The exercise has highlighted the imprecise conceptual boundary between technical and non-technical measures, and the significant approximations that are inherent even in models confined solely to technical measures. We might think of technical measures as those that act on the rate of emissions per unit of output from a given activity, and, by contrast, non-technical measures as those that affect the level of output of a given activity while holding the emissions rate constant. However, many measures – indeed, perhaps most measures – are likely to have effects that include a mix of both impacts, although the proportions may vary widely.

Thus, for example, installation of a pollution filter might seem a straightforward technical measure, affecting the emissions rate while having no implications for the level of activity. But, considered in its economic context, it is clear that this will not always be so. Where the 'filter' technology is costly (as, for example, with flue gas desulphurisation in power stations) there may be effects in the electricity market. Some part of the additional cost may be passed on to consumers through higher electricity prices, and demand consequently reduced. There may also be supply effects – some firms operations may choose to close rather than install the new equipment. These effects of non-technical measures on output levels may larger in some cases than others. But in a market economy they will rarely be zero, and neglecting them in a simulation model is an approximation and simplification of the more complex chain of consequences that would occur in reality.

Likewise, it is difficult to think of 'non-technical' measures that would have effects confined solely to the level of output. A congestion charge on motor vehicle use in urban areas, might, for example, be thought to have an effect confined to the level of activity (vehicle mileage, public transport mileage, etc). However, even in this relatively straightforward case there may be behavioural responses by individuals that take the form of non-technical measures. Fewer people might, for example, choose to buy small 'town' cars, for example, leading to a rise in the average size of vehicles, and hence a change in the average technical characteristics of the vehicle stock. This effect may be small, and perhaps sufficiently small for its neglect in a simulation exercise to be an obvious and justifiable simplification. But other non-technical measures may have a large part of their impact through behavioural responses with technology consequences. Higher fuel taxes will discourage vehicle use and hence activity in the transport sector), but they will also tend to induce both demand-side and supply-side changes in technology. Consumers may buy more fuel-efficient vehicles, and manufacturers may devote resources to developing such vehicles to meet customer demands. These responses, which take the form of technical measures induced by a non-technical instrument, may be large, especially in the medium term, and their neglect in a simulation approach based on a clear divide between technical and non-technical measures will be a more uncomfortable modelling simplification.

A systematic approach to modelling which allows for the possibility of both channels of response to both types of measure is however complex, and for many purposes impracticable. The simulation algorithm developed by Salmons (2003) as part of this project demonstrates a relatively simple, approximation-based, approach to simulating the output effects of technical measures, as the starting point for a wider approach in which both types of measure could have both types of response. However, even the rather elegant approximation suggested by Salmons would greatly increase the complexity of each model run, and this needs to be taken into account in deciding whether the gains from this approach would be worth the costs. Where the simulation model is confined to technical measures, there may well be good grounds for neglecting the behavioural responses affecting outputs. It is leas clear that this is the appropriate judgment where a comparative analysis of technical and non-technical measures is the objective.

2.10.2 Availability of data and elasticity evidence

Work on this part of the project has highlighted a number of problems about the availability of data and parameter estimates that can be used in simulating the effects of non-technical measures in the MERLIN approach.

While there is plenty of elasticity evidence on the effects of pricing measures in the transport sector, relatively little is directly useable to provide parameter values for use within the MERLIN approach, because the elasticities needed by MERLIN are *conditional on the level of aggregation* within MERLIN. Generally, a lot of the detail which MERLIN has is lost, as far as the simulation of non-technical measures is concerned, because the available broad estimate of some elasticity has to be asumed to take the same value for all sub-categories (e.g. vehicles of different vintages), simply because no evidence is available on which to base any differentiation of the parameter.

This is potentially an even more serious obstacle to extending the coverage of non-technical measures within MERLIN beyond the transport sector. For industrial sectors, there is very much less data available on which to base elasticity estimates. There are problems of how to define the scope of each sector. Sufficiently long runs of data are rarely available for time series econometric estimation. While data on costs or effects of technical measures in MERLIN requires simply a single point estimate, data to allow an estimate of behavioural responses requires a long run of observations, defined on a consistent basis, during a period when there was significant variation in prices. This is rarely available (not least because much of the information needed is commercially-sensitive), and it is very difficult to see how the simulation of non-technical measures can then be based on robust, empirically estimated behavioural parameters.

2.10.3 Interdependence of costs

A further major issue encountered in the course of this work is that the costs of many of the non-technical measures that might be simulated in MERLIN are interdependent. In principle, this is the case for <u>all</u> measures that involve public expenditures or that raise revenues, and defining costs (such as deadweight losses) for individual non-technical measures has required this issue to be overlooked. It is difficult to see any scope for a wholly-satisfactory resolution of this difficulty, that would allow permutations of non-technical measures to be combined flexibly within the MERLIN optimisation routine, in the same way as with technical measures.

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