MEASURING ECO-EFFICIENCY OF PRODUCTION:
A FRONTIER APPROACH

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Abstract

Eco-efficiency of production is an important concept both from the viewpoint of society and business community; but as yet, there is no unambiguous way to its measurement. The purpose of this paper is to present a general measurement framework based on production theory and the activity analysis approach. Although we exploit the existing methods and techniques, our approach diverges essentially from the usual treatments of the environmental performance of firms in the productive efficiency analysis. The main difference between our approach and the earlier studies is that we build on the definition of eco-efficiency as the ratio of economic value added to the environmental damage index. Related to this orientation, we also approach eco-efficiency from a more aggregate perspective. Our general framework is illustrated by an empirical application to the evaluation of eco-efficiency of road transportation in Finland.

Key Words: *Eco-efficiency, Environmental Pressures, Aggregation, Benefit of the Doubt Weighting, Distance Function, Activity Analysis, Data Envelopment Analysis, Road transportation*

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1. INTRODUCTION

Eco-efficiency of production refers to the capability to produce goods and services by polluting the environment and using natural resources and energy as little as possible. During the past decade, the concept of eco-efficiency has received much public attention and risen to an essential role in the business community. The first reason for this is that nowadays firms[1] have to pay increasingly more attention to the environmental pressures of their activities due to more rigorous environmental legislation. Secondly, and even more importantly, firms' environmental actions have an effect on their public image and even on their financial performance (see, e.g. Konar and Cohen, 1997). At present, the improving of eco-efficiency is seen as an important competition strategy and firms can enhance their profitability with it (see, e.g. Porter and van der Linde, 2000).

The concept of eco-efficiency is related to the more encompassing notion of sustainability. Yet, ecologists have correctly argued that improvement of eco-efficiency does not guarantee sustainability. One of pioneers in the field of industrial ecology, John Ehrenfeld defines sustainability as "*the possibility that human and other life forms will flourish on the Earth forever*" (see, Ehrenfeld, 1997 and 2004). He sees eco-efficiency merely as a symptomatic solution where technology is solving technology's problems. According to Ehrenfeld and many other ecologists, achieving sustainability requires fundamental restructuring of the society such that people's wellbeing is not derived from material consumption but from immaterial values.

The key point to observe in the ecologists' critique is that even if the *relative* level of environmental pressure is low in relation to the economic output, the *absolute* environmental pressure can still exceed the carrying capacity of the ecosystem. This, however, does not mean that the concept of eco-efficiency is useless. Measurement of eco-efficiency is critically important at least for two reasons: 1) Improvement of eco-efficiency is often the most cost-effective way of reducing environmental pressures. Even if efficiency improvements as such do not always suffice for achieving a sustainable level of environmental pressure, it makes economic sense to exploit these options as much as possible. 2) Policies to improve eco-efficiency tend to be easier to justify than policies that restrict the level of economic activity. The latter type of drastic measures will remain politically difficult to implement unless the policy-makers are presented convincing evidence that shows the inadequacy of the symptomatic eco-efficiency solutions. Thus, measurement of eco-efficiency is of critical importance even if efficiency improvements as such are not enough.

A practical argument in favor of eco-efficiency is that it does have a clear and intuitive definition as the ratio of economic value added to the environmental pressure, which is in sharp contrast to the rather vaguely defined concept of sustainability. Yet, there currently is no unambiguous way of actually measuring eco-efficiency. In fact, a considerable number of measures or indicators for environmental efficiency or eco-efficiency have been suggested (see, e.g. Tyteca, 1996, for survey). Most of these measures are only simple indicators, such as "economic output per unit of waste" ratios, which consider eco-efficiency from a very limited perspective. In addition, some authors propose to

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[1] By "firm" we refer to production units in general, without discriminating between private enterprises and other types of production organizations such as public sector firms and non-for-profit firms.

use a set of simple indicators, but this does not improve the matters. Firstly, this multiple-indicators approach ignores the fact that the same outputs can be produced by using various combinations of energy, raw materials and wastes, in other words, substitution possibilities exist between different inputs, natural resources and environmental bads. Focusing on each indicator separately, we tend to identify firms that specialize in one environmental theme as good performers, and overlook firms that put a well-balanced effort in all themes but do not present superior performance in any of them. Secondly, the eco-efficiency measures are requisite information for making decisions. In the end, the different dimensions of the problem must be summarized in one way or another in order to arrive at a decision. While the politicians should take the responsibility of the normative decisions regarding which of the alternative efficient outcomes should be implemented, it is the job of scientists to identify the efficient set of alternatives. Presenting the decision-makers multiple conflicting indicators is not up to that job; it only shifts the incommensurability problem from researchers to the decision-makers.

Due to these problems with simple indicators, there is clearly a need for a more comprehensive approach for the measurement of eco-efficiency. In this paper we propose to address the problem in a general multi-dimensional framework, drawing insights from the production theory in microeconomics. To aggregate incommensurable environmental pressures, we utilize the notion of *distance function* by Shephard (1953, 1970). The distance function has been used as a generalized representation of production technology, as a measure of the technical efficiency of a firm, as well as a basis for the measurement of total factor productivity (see, e.g. Färe and Primont, 1995). The Shephard distance function is a reciprocal of the Farrell (1957) technical efficiency measures, which is widely used in the productive efficiency analysis today. The notion of distance function is also closely related to the so-called *benefit of the doubt* weighting principle, applied, for instance, by Cherchye (1999) in the context of evaluating macro-economic policy performance of the OECD countries, and by Cherchye and Kuosmanen (2004) in the context of assessing sustainable development of countries. In the present context, the benefit of the doubt weighting does not assume any *a priori* chosen weights for environmental pressures, but applies the most favorable weights that maximize the eco-efficiency ratio of the evaluated activity. Interestingly, the distance function perspective and the weighting perspective are equivalent (i.e., dual) approaches. In this paper, both approaches will be explored in detail.

To operationalize the distance function approach, we need to estimate the feasible techno-economic possibilities for emission reductions empirically. For this purpose, we follow the literature of productive efficiency analysis and employ the so-called activity analysis (or Data Envelopment Analysis, DEA) method (Koopmans, 1951; Farrell, 1957; Charnes et al., 1978). This approach considers substitution possibilities between inputs and outputs by estimating efficient production frontiers from the cross-sectional or panel data of a number of comparable production units (such as firms).

While our approach is based on the insights from the productive efficiency analysis, it differs in some important respects from the usual treatments of firm-level environmental performance analysis in that literature (see, e.g. Färe et al. 1989; Färe et al., 1996; Boyd and McClelland 1999). Firstly, we build on the most standard definition of eco-efficiency: the ratio of economic value added to the environmental deterioration. This definition gives an equal emphasis on both economic and environmental criteria. By contrast, the efficiency analysis literature typically treats the environment merely as one additional criterion (or constraint) in the technically oriented efficiency assessment. Secondly, we focus explicitly on the tradeoffs between the creation of economic value added and its undesirable side-effects to the environment, without direct recourse to physical inputs and outputs. Those physical inputs and outputs that influence the economic value added appear implicitly in the numerator of our eco-efficiency ratio and those inputs or outputs that create environmental effects appear in the denominator. Those inputs and outputs that influence neither economic value added nor environmental pressures are not of direct interest in our framework and are thus omitted; these include the primary production factors labor and capital. By contrast, the physical inputs and outputs are the key building blocks of the efficiency analysis literature. For example, the question of whether it is appropriate to model pollutants as undesirable outputs or as traditional inputs is currently subject to a lively debate in this literature (see e.g. Hailu and Veeman, 2001; Färe and Grosskopf, 2003; Hailu 2003).

In summary, our approach is to apply the sophisticated quantitative techniques of production economics to the eco-efficiency measurement problem as it is presented in the ecological literature, whereas the environmental performance literature directly incorporates physical emissions as inputs or outputs of the standard production model. We believe both approaches are useful; we are not criticizing the approach of environmental performance analysis, but try to offer a complementary, more ecologically oriented view.

The remainder of this paper unfolds as follows. In the next section, we present our conceptual framework and discuss the incommensurability problem of environmental pressures. Section 3 presents our methodology for constructing a general eco-efficiency measure, which aggregates various environmental pressures into a single index. In Section 4, we show how this eco-efficiency measure can be calculated in the framework of activity analysis. Then Section 5 applies these ideas to the measurement of eco-efficiency of the road transportation in Finland. Lastly, Section 6 presents some concluding remarks.

2. THE CONCEPTUAL FRAMEWORK

As noted already in the introduction, we deviate from the earlier production economic approaches in that we focus on environmental pressures rather than specific undesirable outputs. This crucial point will be elaborated upon next.

Undesirable outputs of production might include air emissions such as carbon-dioxide and methane. Both these emissions contribute to the same environmental problem: the green house effect. Numerous studies have investigated the effects of different green house gases, and conversion factors are available for translating the amounts of different green house gases into carbon-dioxide equivalents. Since we are ultimately concerned about the green house effect rather than the amount of carbon-dioxide in the atmosphere as such, and since different green house gases can be aggregated based on scientifically sound conversion factors, we believe it is most appropriate to build the eco-efficiency analysis on aggregated measures of environmental themes such as climate change.[2]

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[2] To our knowledge, only one earlier study has proposed to use environmental pressure (or impact) categories in the activity analysis (and DEA) framework: see (Dyckhoff and Allen, 2001).

The aggregated carbon-dioxide equivalents are obviously inadequate for measuring the ultimate environmental impact: the social costs of climate change. Rather, such measures only represent the pressure on the ecosystem. To a certain extent, the forests are capable of sequestrating the extra carbon-dioxide emitted to the atmosphere. The problem occurs when the green house gas emissions exceed the carrying capacity of the ecosystem, and extra carbon-dioxide stocks start to accumulate causing drastic, unpredictable changes in climate conditions. The relationship between the environmental pressure and the real environmental impact can be very complex, nonlinear, and difficult to predict. Moreover, it seems practically impossible to attribute the effects of climate change (such as loss of life due to heavy storms or flooding) to specific firms that have emitted a certain amount of green house gases. Therefore, we do not attempt to measure the ultimate environmental impacts, but find it most appropriate to work at the level of environmental pressures.

The most significant problem in eco-efficiency measurement concerns the aggregation of various environmental pressures. Like in the case of green house gases, we believe that it is often possible and meaningful to aggregate individual pollutants that contribute to the same environmental theme in the same aggregate measure for the overall environmental pressure using some *a priori* conversion factors. By contrast, pressures on different environmental themes referring to different types of environmental deterioration are incommensurable, meaning that these pressures cannot be aggregated unanimously by using objective conversion factors.

To illustrate the relationship between “environmental pressures” and “pollutants”, consider the main environmental pressures due to road transportation listed in Table I (we will return to this example in Section 5 below). We note that some adverse environmental effects from road transportation are directly measurable by a single indicator (e.g. dispersion of particles), while other pressures (e.g. climate change, acidification) are influenced by several emissions. To assess a given pressure, different undesirable outputs arising in the production activity can often be aggregated by using well-defined conversion factors. For example, different types of air emissions contributing the climate change can be fairly accurately summarized by converting different emissions to CO_2 equivalents. By contrast, there is no unambiguous way of summarizing all the different environmental pressures in a single overall environmental index. For example, we cannot simply add green-house gases measured in CO_2 equivalents to particle emissions measured in tons of TPM. Moreover, it is very difficult (if not impossible) to express some generally accepted weights that would reflect the relative importance of the pressures. While this example pertains to the case of road transportation, which in industrialized countries is one of the main sources of air emissions, the similar type of aggregation possibilities and problems are faced equally well in other industries and at all levels of aggregation.

Table 1: The main environmental pressures due to road transportation

Environmental pressure	Specific emissions	Unit of measurement
Climate change	CO_2, CH_4, N_2O, CO	tons of CO_2 equivalents / year
Acidification	NO_x, SO_2	tons of acid equivalents / year
Smog formation	HC	tons of HC / year
Dispersion of particles	TPM	tons of TPM / year
Noise	Sound waves	dB

To overcome this incommensurability problem, we propose to define eco-efficiency, which is genuinely a multiple dimensional concept, in a multiple dimensional Euclidean space, following the approach of Koopmans (1951). To this end, it is necessary to introduce some notation. We denote the economic value added of the production activity by v, assuming that the economic value added is known or can be calculated directly from the input and output quantities and their prices. Suppose the production activity under consideration induces M different environmental pressures, the severity of which is measured by variables $\mathbf{z} = (z_1 \ldots z_m)$. For simplicity, all environmental pressures are assumed to be harmful (i.e., $\mathbf{z} \geq 0$).

In general, there are many ways of generating economic value added, some of which are more harmful for the environment than others. As mentioned, a comprehensive eco-efficiency measure should take into account the various substitution possibilities between environmental pressures. This is because reducing one pollutant may come at the cost of increasing another. To characterize the substitution possibilities at the most general level, we introduce the pollution generating technology set

$$(1) \qquad T = \left\{ (v, \mathbf{z}) \in \mathbb{R}_+^{1+M} \,\middle|\, \text{value added } v \text{ can be generated with damage } \mathbf{z} \right\},$$

which includes all possible technically and economically feasible combinations of value added v and environmental damage $\mathbf{z}$. For the purposes of the present conceptual discussion, we assume the set T to be known. We return to the issues related to the estimation of the set in Section 4 below.

Adapting the Koopmans' (1951) definition of efficiency to the present context, we propose to diagnose a production activity as eco-efficient if and only if it is impossible to decrease any environmental pressure without simultaneously increasing another pressure or decreasing the economic value added.[3] This definition is value-free, it treats all environmental pressures equally, and approaches eco-efficiency from the general multiple dimensional perspective. The set of efficient activities forms a subset of T, the so-called efficient frontier. There can be a large (or even infinite) number of alternative efficient points. Since the choice of a target point from the efficient frontier involves a normative judgment, we leave it for the policy makers.

Figure 1 illustrates the set T and its efficient frontier graphically in the case of two environmental pressures. The axes represent the index of environmental pressure. The gray area represents the set of possible levels of environmental pressures that arise from production of a given economic value added v. The south-west edge of this set represents the efficient frontier, where one cannot decrease either of the two environmental pressures without increasing the other or decreasing the economic value added. The points in the interior of T are eco-inefficient: it is technically feasible to reduce the level of at least one pressure without restricting the economic activity.

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[3] This definition is inspired by the more famous efficiency concept by Pareto, and it is often referred to as Pareto-Koopmans efficiency.

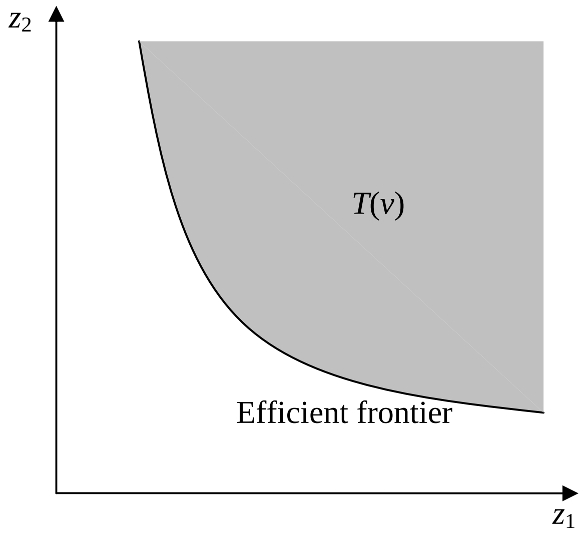

Figure 1. Illustration of technology set T and its efficient frontier

To complete the presentation of the conceptual framework, it is illustrative to relate our multi-dimensional concept of eco-efficiency to the notion of sustainability. In terms of the environmental pressures, the concept of sustainability is best represented in terms of the carrying capacity of the ecosystem. Like in the case of technological possibilities, also the ability of the ecosystem to deal with one type of pressure depends on the level of other pressures; there are tradeoffs between alternative pressures. Analogous to the technology set *T*, we may introduce a sustainability set *S* defined as

$$(2) \qquad S = \left\{ \mathbf{z} \in \mathbb{R}_{+}^{M} \,\middle|\, \text{the ecosystem can sustain damage } \mathbf{z} \right\}.$$

It is worth to emphasize that whereas the technology set *T* can be meaningfully defined at the micro-level of individual firms as well as at the aggregate country or global level, the sustainability set is only meaningful at the aggregate levels.

Suppose the sets *T* and *S* overlap at the aggregate level. In such circumstances it is possible to achieve sustainability by operating eco-efficiently at the economic activity level that yields value added *v*. The entire eco-efficient frontier may not be contained in the sustainability set *S*; eco-efficiency as such does not guarantee sustainability but also the specific combination of pressures matters. Conversely, a certain degree of eco-inefficiency may be tolerated if the mixture of pressures is appropriate; however, by improving efficiency it would be possible to increase the economic value added. Thus, eco-efficiency is neither necessary nor sufficient condition for sustainability. The choice of the most appropriate point in the intersection of *T* and *S* involves a normative judgment, and is generally a responsibility of policy makers.

The situation is more difficult if sets *T* and *S* do not overlap. In such circumstances it is impossible to reach the sustainability set at the level of value added *v*, but the gap must be bridged by reducing the level of economic activity, and thus also the value added *v*. Eco-efficiency would still be important: efficient operation guarantees that the maximal economic value added is obtained that can be produced in a sustainable fashion.

In practice, empirical estimation of set *S* is difficult, if not impossible. The notion of sustainability appears meaningful only at a relatively high level of aggregation, and thus we can hope to observe only a small number of different combinations of pressures. Moreover, even if we observed environmental pressures as aggregate level, it is difficult to determine which observations are sustainable in the long run and which ones are not. By contrast, technology *T* can be estimated at different levels varying from production units within a firm to the global level. Moreover, sophisticated, generally applicable methods exist for such estimation (we return to this point in more detail Section 4 below). Therefore, we next focus on operationalizing the presented conceptual framework for eco-efficiency; estimation of the carrying capacity is left as a challenge for ecologists.

3. GENERALIZED MEASURE OF ECO-EFFICIENCY

This section generalizes the usual ratio measures of eco-efficiency by drawing insights from production theory (Shephard, 1970; Färe and Primont, 1995). We are interested in evaluating the eco-efficiency of *N* comparable production activities. Let V_n denote the economic value added and $\mathbf{Z}_n$ environmental pressures of the production activity *n*. For transparency, the capital symbols V_n, $\mathbf{Z}_n$ refer to observed data of firm *n*, while arbitrary (theoretical) values of value added and environmental pressures are denoted by lower case *v* and *z*, respectively.

The standard approach in ecological literature (see, e.g. Schmidheiny and Zorraquin, 1996) is to define eco-efficiency as a ratio

$$(3) \qquad \textit{Eco-efficiency} = \frac{\textit{Economic value added}}{\textit{Environmental pressures}}.$$

Following this definition, we further define *eco-efficiency* (*EE)* formally as the ratio of economic value added to the index of environmental pressure, that is

$$(4) \qquad EE_n = \frac{V_n}{D(\mathbf{Z}_n)},$$

where *D* is the damage function that aggregates the *M* environmental pressures into a single environmental damage score. We base our approach for this definition, thus approaching eco-efficiency from a more aggregated perspective than the earlier environmental performance studies (see, e.g. Färe et al. 1989; Färe et al., 1996; Boyd and McClelland 1999). This definition is also reason for technical differences between our approach and other studies that utilize production theory for measuring eco-efficiency or environmental performance, as we shall see below. Due to these reasons, it is worth taking a more detailed look at the numerator and the denominator of the ratio (4).

First, note that if the total value added (i.e., the numerator) is known for all firms in the sample, we do not need detailed data on individual inputs and outputs (or their prices).[4] Hence, data requirements can be quite different compared to the traditional productive efficiency studies, where input and output quantities play a central role. In particular, if we measure eco-efficiency of a firm, the economic value added can be thought of as the total revenue minus the cost of intermediate inputs. Thus, in contrast to the firm-level economic efficiency analyses, the costs of labor and capital inputs are not subtracted from the revenue; these items are expenditures for the owners of the firm, but represent income (wages and rents) for the society. In other words, the primary production factors do not appear in the measure of eco-efficiency, even though they are important cost factors in the technical and economic efficiency analysis.

In contrast to economic inputs and outputs, environmental pressures do not typically have prices or other unambiguous values. This presents a challenge for constructing the environmental damage index $D(\mathbf{Z}_n)$. To build up an encompassing ”total” eco-efficiency ratio of form (4), a natural approach is to take a weighted average (or sum) of the various environmental pressures, that is,

$$D(\mathbf{z}) = w_1 z_1 + w_2 z_2 + ... + w_m z_m \, , \tag{5}$$

where w_i represents the weight accorded to environmental pressure i. In fact, the damage index D must be a weighted sum of $\mathbf{z}$ in order to satisfy desirable properties of units invariance, weakly increasing, and continuous; see Proposition 2 in Ebert and Welsch (2004). Now the essential question is, how the weights w_i (i = 1, ..., m) should be chosen or determined.

In general, the weight of each pressure should depend on the importance of the pressure. However, it is not possible to determine such priorities without subjective valuation. With regard to environmental pressures, subjective valuation is extremely complicated. Not surprisingly, even specialists seem unable to reach a consensus about the appropriate weighting scheme (see, e.g. DeSimone and Popoff, 1997). Hence, we argue that the use of objective weighting is more reasonable in the context of eco-efficiency measurement.

In this paper we propose to employ a so-called *benefit of the doubt* weighting scheme. This approach applies weights that maximize the relative eco-efficiency of the evaluated activity in comparison with the maximum attainable eco-efficiency. Formally, the eco-efficiency for firm k is calculated as

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[4] The economic value added may be difficult to measure in some applications. This problem may arise particularly in the case of public sector firms and non-for-profit organizations. In these kinds of circumstances we need to rely on some proxy indicator for the value added measure.

$$
\begin{aligned}
&\max_{w} \overline{EE}_n = \frac{V_n}{w_1 Z_{n1} + w_2 Z_{n2} + \ldots + w_M Z_{nM}} \\
&s.t. \\
&\frac{v}{w_1 z_1 + w_2 z_2 + \ldots + w_M z_M} \le 1 \;\forall (v,z) \in T \\
&w_m \ge 0 \;\forall m = 1,\ldots,M.
\end{aligned} \tag{6}
$$

That is, we employ weights w_m ($m = 1,\ldots, M$) that maximize the eco-efficiency ratio, subject to the condition that the highest attainable efficiency score does not exceed the maximum index value of one when the same weights are applied across all other activities. Since individual weights cannot be negative, eco-efficiency scores for all activities lie within the interval [0, 1], where the value of one represents the best performance.

An interesting feature of the benefit of the doubt weighted eco-efficiency index (6) is that it gives the upper bound for the family of indices of type (3), that is, $\overline{EE}_n = \max_{w} \left\{ EE_n \,\middle|\, EE_i \le 1 \;\forall i \right\}$. This means that the most favorable weights are chosen for each activity: using any other weights will necessarily decrease the eco-efficiency score of the evaluated activity. Since weights vary among activities, this method does not favor any single environmental pressure over another.

Another important feature of the benefit of the doubt weighting is its intimate relation with the Shephard (1953, 1970) distance function approach employed in the literature of productive efficiency analysis. Interestingly, it is relatively easy to show that the distance function perspective and the weighting perspective are equivalent approaches. Due to this duality property, the problem (6) has an equivalent dual formulation as

$$
\begin{aligned}
&\min_{\theta,\alpha} \overline{EE}_n = \theta \\
&s.t. \\
&(V_n, \theta \mathbf{Z}_n) \in \alpha T \\
&\alpha, \theta \ge 0
\end{aligned} \tag{7}
$$

where α is the scaling parameter. This duality result is a direct corollary of Proposition 1 in Kuosmanen et al. (2004).[5] The minimization problem (6) reduces all environmental pressures in equal proportions, until it reaches the boundary of the feasible set T. The scaling parameter α makes the comparison invariant to the scale of activity. Specifically, the economic value added and the environmental pressures may depend on the total amount of output due to the economies or diseconomies of scale. The scaling parameter α implies that we compare the evaluated activity to the frontier performance in the optimal scale. Or interpreted alternatively, we measure eco-efficiency per unit of value added, rather than efficiency of the activity as a whole.

The properties of the distance function are well known in the production theory (e.g. Färe et al., 1994; Russell 1998). These axiomatic properties directly imply that the eco-

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[5] For more general discussion about duality theory of distance functions, see Färe and Primont, 1995.

efficiency measure (7) is homogenous of degree one in economic value added V_n, homogenous of degree minus one in environmental pressures $\mathbf{Z}_n$, and upper semi-bounded and upper semi-continuous in all variables. Importantly, this measure is units invariant (or dimensionless), which means that the choice of units of measurement (e.g. measurement of value added in U.S. dollars or Euro) does not influence its value. As noted in Ebert and Welsch (2004), for units invariance is a desirable property any meaningful environmental index should satisfy; yet many indices described in the literature fail this basic property.

Both the benefit of the doubt weighting method and the distance function can be illustrated by figures. Suppose only two detrimental environmental pressures (z_1 and z_2) are generated in production. We plot the pressures per unit of economic value added (i.e., z_1/V and z_2/V) on the vertical and horizontal axis to obtain graphs in Figure 2. The left graph describes the distance function problem and the right one the weighting problem. The efficient frontier is the boundary of technology set *T* and describes substitution possibilities between environmental pressures when value added (or output) remains at the same level. Thus all the points above the frontier are inefficient. In addition, straight lines in the right figure are environmental "isocost" lines, in which the environmental cost level does not change. However, the higher the isocost line lies, the greater are the costs and damage to the environment.

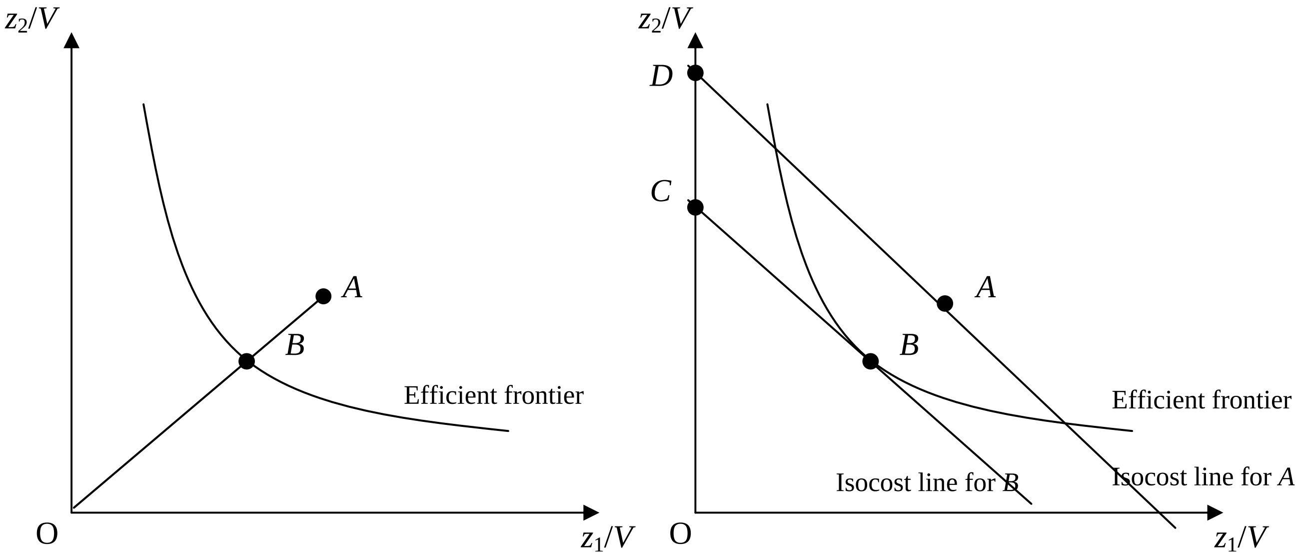

Figure 2. Distance function approach (left figure) and the benefit of the doubt weighting (right figure).

Let us evaluate efficiency of point *A*. The distance function measures radial distance from point *A* to the reference point *B* on the efficient frontier, where both environmental pressures are reduced in equal proportions. Eco-efficiency score is calculated as the ratio $\theta = |OB| / |OA|$, where $|OB|$ and $|OA|$ represent the lengths of the line-segments *OB* and *OA*, respectively. On the other hand, in the weighting problem, weights (w_1, w_2) of the environmental pressures are set to maximize the eco-efficiency of the evaluated activity, or alternatively interpreted, environmental costs of producing *V* units of economic value added are minimized. Thus the optimal solution is given by the isocost line that is feasible, but as low as possible. This means that the optimal weights are given by a point where the isocost line is at a tangent to the efficient frontier. At the optimal prices, point *B* has an equal environmental cost to that of point *C*. Similarly, costs of points *A* and *D* are equal. Thus, the cost efficiency is the ratio $|OC|/|OD|$. When the efficient frontier is convex, this ratio will always be equal to θ: the benefit of the doubt method gives the same eco-efficiency score than the distance function approach.

As a final note, we should add that although benefit of the doubt weighting method does not require prior information or normative judgment about relative weights, such information can easily be incorporated in the analysis in the form of weight restrictions. For example, if we have information that certain environmental pressure *i* is considered at least twice as detrimental as another pressure *j*, we can allow for this by imposing weight restriction $w_i \geq 2w_j$ to (6).[6] Using these kinds of weight restrictions, it is possible to set lower and upper bounds to relative weight of environmental pressures. These bounds can be incorporated in the original model by simply adding linear constraints to the problem (6). Of course, the weight restrictions should be appropriately justified by appropriate normative grounds (e.g. all pressures should count with a positive weight (e.g. one or five percent) in the total index) or widely held subjective opinion (e.g. use stated preference techniques such as contingent valuation to determine a distribution of weights *w* among individuals, and restrict weights in (5) to lie within the 95 or 99 percent confidence interval obtained in the subjective valuations).

4. ACTIVITY ANALYSIS APPROACH

So far we have assumed the technology set *T* to be known. This is unrealistic in empirical applications. In practice, we need to estimate the technology from the sample of *N* comparable activities. The most straightforward way of estimating *T* is the so-called activity analysis approach (Koopmans, 1951), also known as Data Envelopment Analysis (DEA: Charnes et al., 1978).[7] This approach specifies technology by using mathematical programming techniques. It is worth noting that the method does not require any *a priori* arbitrary assumption as on how to set the weights of various environmental pressures.

Let us start from the primal problem (6). Instead of comparing performance of activity *n* with the theoretical optimum, we compare it with the “best-practice” observed in the sample. Formally, the empirical eco-efficiency measure can be calculated as

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[6] It is advisable to use *relative* weight restrictions, i.e., impose bounds on weight of pressure *i* that depend on the weights of other pressures. The problem with absolute weight restrictions (e.g. $w_i \geq 0.1$) is that the weights *w* are also used for normalizing the pressures *Z* such that the eco-efficiency ratio is less than or equal to unity for all firms (cf. the constraint in (5)). The absolute restrictions interfere with this normalization function of weights, and unlike the relative weight restrictions, are not invariant to units of measurement.

[7] In addition to the present approach, the technology set can also be estimated using parametric econometric techniques of productive efficiency analysis. We follow the non-parametric route in this paper because of the direct link to the distance function and the benefit of the doubt –weighting formulations of Section 3.

$$
(8) \qquad \begin{aligned}
&\max_{w} \widehat{EE}_n = \frac{V_n}{w_1 Z_{n1} + w_2 Z_{n2} + \ldots + w_M Z_{nM}} \\
&s.t. \\
&\frac{V_k}{w_1 Z_{k1} + w_2 Z_{k2} + \ldots + w_M Z_{kM}} \le 1 \ \forall k = 1,\ldots,N \\
&w_m \ge 0 \ \forall m = 1,\ldots,M
\end{aligned}
$$

This problem simply substitutes the unknown technology set *T* of problem (6) by the discrete set of empirical observations drawn from that set (after all, all observations must be technically and economically feasible). It is worth emphasizing that we do not impose assumptions about the topological shape of set *T*; we only assume that all observations were drawn from this set.

Unfortunately, this is a fractional linear programming problem involving a non-linear objective function and non-linear constraints, which makes it computationally hard. However, the problem is easy to linearize by taking the inverse of the eco-efficiency ratio and solving the reciprocal problem

$$
(9) \qquad \begin{aligned}
&\min_{w} \widehat{EE}_n^{-1} = \frac{1}{V_n}(w_1 Z_{n1} + w_2 Z_{n2} + \ldots + w_M Z_{nM}) \\
&s.t. \\
&\frac{1}{V_k}(w_1 Z_{k1} + w_2 Z_{k2} + \ldots + w_M Z_{kM}) \ge 1 \ \forall k = 1,\ldots,N \\
&w_m \ge 0 \ \forall m = 1,\ldots,M
\end{aligned}
$$

This problem is linear in terms of the unknown parameters w_m and can be solved by standard linear programming algorithms. The eco-efficiency measure is obtained by taking the inverse of the optimal solution to (9).[8]

We can also calculate the eco-efficiency measure using the distance function approach. Problem (8) has an equivalent dual formulation, which can be written as

$$
(10) \qquad \begin{aligned}
&\min_{\lambda} \widehat{EE}_n = \theta \\
&s.t. \\
&\theta Z_{nm} \ge \sum_{k=1}^{N} \lambda_k Z_{km} \ \ \forall m = 1,\ldots,M \\
&V_n \le \sum_{k=1}^{N} \lambda_k V_k \\
&\lambda_k \ge 0 \ \forall k = 1,\ldots,N,
\end{aligned}
$$

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[8] Linearization is also possible in the more general case that involves multiple economic values, say V_1 and V_2, applying the Charnes-Cooper transformation to the resulting fractional linear programming problem. See Charnes et al. (1978) for further details.

where $\lambda_k, k = 1,...,n$, can be interpreted as intensity weights of firm *k*. Using these weights, problem (10) forms a linear combination of the observed value added – damage vectors, which gives the reference point $(V_n, \theta\mathbf{Z}_n)$ against which the performance of activity *n* is compared. In other words, problem (10) measures the equiproportionate reduction potential of all environmental pressures relative to the envelopment set

$$(11) \qquad cmc(\hat{T})_{DEA} = \left\{ (v,z) \in \mathbb{R}_{+}^{1+M} \,\middle|\, v \le \sum_{k=1}^{N} \lambda_k V_k ; z \ge \sum_{k=1}^{N} \lambda_k Z_k ;\ \lambda_k \ge 0\ \forall k = 1,...,N \right\},$$

which approximates the convex monotonic conical hull (*cmc*(.)) of the true but unknown *T* with the convex monotonic conical hull of the observed value added – damage vectors. This means that the size of the firm or production activity, measured by absolute levels of value added and environmental pressures, does not matter in this problem; we are only interested about the ratio of the value added to the environmental pressure. In DEA literature (10) is interpreted as a constant returns to scale model.

Because of similarities, it is worthwhile to compare the above dual linear programming problem with the standard input oriented DEA problem. In fact, from technical point of view, we can interpret (10) as the DEA input efficiency problem which uses environmental pressures as inputs and economic value added as output. However, while DEA typically needs to assume that the true but unknown technology set *T* is a convex monotonic cone, in our approach this is unnecessary; compare the primal formulation (8) with the dual formulation (10). The topological shape of the dual envelopment set follows from the primal specification of the eco-efficiency index as a ratio where environmental pressures are aggregated into a damage index by taking a weighted sum of different pressures. By contrast, the DEA literature usually takes the dual distance function problem as the starting point. Specifically, to interpret (10) as an empirical estimate for *T*, the assumptions of convexity, monotonicity, and constant returns to scale are required.

5. APPLICATION

5.1. *Motivation*

In this section we illustrate how the presented approach can be applied in practice. We consider a real-world case of eco-efficiency measurement in road transportation in Finland. Eco-efficiency of road transportation is a highly relevant topic: in most industrialized countries, road transportation is a major contributor to global green-house effect, transboundary acidification problem, as well as to particle emissions and smog formation that affect the air quality locally. Other undesirable side-effects of transportation include noise and the loss and fragmentation of biological habitat under the road network. As yet, road transportation uses almost exclusively non-renewable oil-derived products as its primary source of energy. These multiple incommensurable environmental pressures present a challenge for eco-efficiency assessment.

In sparsely populated Finland, road transportation has a more central role than in any other country of the European Union: the country has a small population of 5.2 million, but a rather vast land area of 338,000 square-kilometers. Outside bigger cities, road transportation forms the only economically viable option for moving people and cargo from one place to another. According to the Finnish Road Association,[9] as much as 94 percent of all passenger transports and 64 percent of all freight transports take place on the road network. As a result, road traffic is one of the most significant sources of emissions in the country. For instance, 16 percent of Finland's carbon dioxide emissions and 52 percent of the carbon monoxide emissions in year 2002 were generated by road transportation. In light of these figures, it is no surprise that eco-efficiency of road transportation is of great concern in Finland.

A number of earlier studies have employed the presented frontier methodologies in the efficiency analysis of the transportation sector. Performance assessment has been done at the disaggregated level: earlier studies have investigated urban transit companies (see, e.g. Kerstens 1996; Tulkens 1993), ferry services (Førsund 1992), maintenance patrols (Cook et al. 1991) and trucks in road construction and maintenance (Odeck and Hjalmarsson, 1994), among other topics. However, all of the above mentioned studies measure only purely technical efficiency, excluding the environmental pressures of transport. The purpose of the following application is to account for various environmental pressures and, in particular, demonstrate how the presented frontier approach can be applied in the eco-efficiency evaluation of road transportation.

5.2. *Setup*

In our application, all 432 municipalities of continental Finland are considered as "firms" that produce transportation services causing pressures to the environment.[10] It is worth to emphasize that municipalities are not production units of transportation in the usual sense: according to the Finnish Information Centre of Automobile Sector,[11] 86 percent of the road traffic volume consists of passenger cars. Thus, private households usually make production decisions, not the municipal decision makers. The reason for treating municipalities as firms is that our data are reported at municipal level. Even though municipalities themselves have relatively little power to influence eco-efficiency of road transportation, it is interesting to investigate whether there are differences in eco-efficiency across them, in terms of the road transportation that takes place within the boundaries of the municipality. Moreover, based on the municipal level data, we can estimate an aggregate efficiency improvement potential at the national level, assuming the performance in one municipality could be replicated in other municipalities of the country. Such national level efficiency improvement potential is more relevant information for the governmental policy makers.

Our data represent synthetic model results obtained from the 2002 edition of the LIISA model developed by VTT Building and Transport.[12] This model provides estimates of fuel consumption, emissions, and vehicle mileage in all municipalities of Finland, based on data from a sophisticated road and traffic monitoring system. For example, the LIISA model takes into account the emission effects of the road type, the vehicle type, the type of engine, the age of vehicle, start-ups, cold driving, and idling. Of course, the resulting municipal level data are not accurate figures but merely reasonable estimates. In addition to the usual

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[9] http://www.tieyhdistys.fi/

[10] The 16 municipalities of the autonomous province of Åland are excluded. Åland consists of an archipelago (approximately 6,500 islands and skerries) in the Baltic Sea; it had only 913 kilometers of public roads in 1999.

[11] http://www.autoalantiedotuskeskus.fi/

[12] http://lipasto.vtt.fi/lipastoe/liisae/

measurement errors, these data are also subject to possible estimation errors arising from the LIISA model. This should be born in mind when interpreting of our results.

In the context of road transportation, the measurement of the economic value added is rather complicated. In principle, the value added could be calculated with the simple formula: *average mileage price* (€/km) · *total mileage* (km) – *average fuel price* (€/l) · *total fuel consumption* (l). Unfortunately, we do not have relevant data for the average mileage price. Moreover, that price will most likely vary across municipalities. A related problem is that our data does not indicate the number of passengers or the amount of freight transported. Rather than making some heroic assumption about that price, we therefore resort to the same approach as with environmental pressures and use a shadow price for the mileage price. That is, our model finds the mileage price that maximizes efficiency of the evaluated municipality; any other price would yield a lower efficiency level.

Table 2. Descriptive statistics of the economic variables and environmental pressures in year 2002

Variable	Mean	Std. dev.	Min.	Max.
Economic variables				
Road transportation mileage (million km)	115.1	185.6	1.0	2337.0
Fuel consumption (tons)	8,335.8	13,885.4	94.0	185,408.0
Environmental pressures				
Climate change (tons of CO_2 equivalents)	27,600.5	45,944.4	315.0	612,352.0
Acidification (tons of acid equivalents)	3.6	5.8	0.0	77.0
Smog formation (tons of HC)	87.1	154.3	2.0	2134.0
Dispersion of particles (tons of TPM)	8.5	14.3	0.0	190.0

Our environmental pressure indicators include various air emissions and gasoline consumption, as already discussed in Section 2. Of the list of main environmental pressures, only noise was omitted due to unavailability of data. Since we are specifically interested in environmental pressures, different pollutants were first aggregated into environmental pressures according to Table 1 of Section 2. Within each theme, pollutants were aggregated by using conversion factors reported by Statistics Netherlands. Descriptive statistics about environmental pressures, mileage, and fuel consumption are provided in Table 2.

5.3. *Results*

Assuming all municipalities employ (or at least have access to) the same transportation technology (*T*), we first estimated eco-efficiency scores separately for all 432 municipalities by employing activity analysis techniques presented in Section 4. The efficiency scores showed considerable variation across municipalities. In total, only eight municipalities were rated with the efficiency score of one (i.e., full efficiency). All these best performing municipalities have relatively small population, and are located in rural areas in different parts of the country. Interestingly, the lowest efficiency score of 77.1 percent was associated with the capital city Helsinki. Figure 3 illustrates the distribution of eco-efficiency scores graphically. The distribution of efficiency scores is well approximated by the normal distribution with mean 0.898 and standard deviation 0.045.

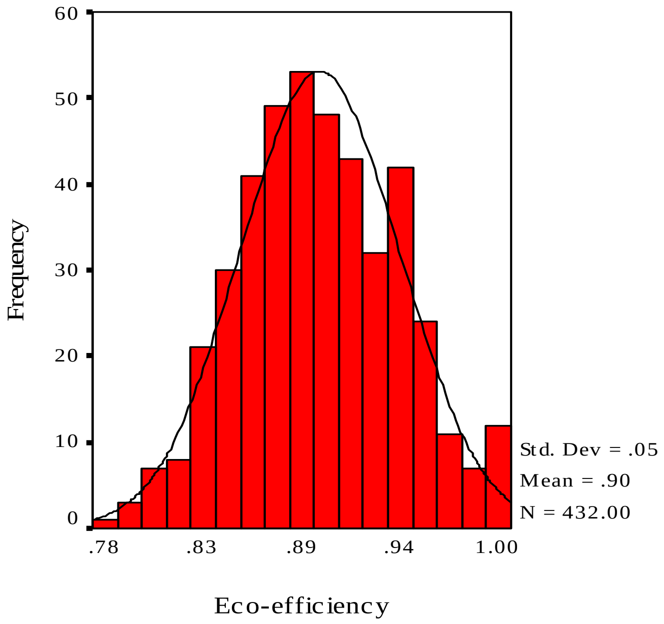

Figure 3. Histogram of eco-efficiency scores

As noted above, the main political interest in eco-efficiency concerns the national rather than municipal level efficiency improvement potential. To measure aggregate eco-efficiency of Finnish road transportation, we resorted to the top-down approach developed by Kuosmanen et al. (2005), and evaluate Finland’s performance, represented by the sum vector $\left(\sum_{n=1}^{N} V_n, \sum_{n=1}^{N} \mathbf{Z}_n \right) \in \mathbb{R}_{+}^{1+M}$, against the technology frontier spanned by individual municipalities. Since the reference technology (10) satisfies constant returns to scale by construction, the national level technology is identical with the municipal level technology. Our activity analysis model indicates that Finland’s overall eco-efficiency in road transportation was 86.8 percent. Thus, if the LIISA model projections are accurate, our model indicates a considerable 13.2 percent reduction potential in all environmental pressures, achievable through efficiency improvements while keeping the transportation mileage and fuel consumption constant. In terms of emission reductions, this would mean a reduction of 1.57 million tons of CO_2 equivalents, 200 tons of acid equivalents, 4960 tons of HC, and 480 tons of TPM per year. As such, the activity analysis model does not identify how such efficiency improvements might be achieved. Yet, the model does provide more information than just the efficiency score, which may provide useful hints for further study.

Firstly, the dual problem (10) indicates that the efficient target point for Finland was obtained as the linear combination of performances of three municipalities: Lemu (with optimal weight λ^*=1761.06), Kuusamo λ^*=16.28), and Muurla (λ^*=10.67).[13] By

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[13] I.e., replicating the performance of municipalities Lemu 1761 times, Kuusamo 16 times, and Muurla 10 times yields Finland’s total mileage with 13.2 percent less environmental pressures.

identifying the efficient benchmark firms, one possible use of the activity analysis model is to facilitate diffusion of best practices from the leading firms to the inefficient ones. In this vein, it would be interesting to investigate in more detail these three benchmark municipalities, and the other five efficient ones, to identify the underlying reasons for their success. However, such detailed qualitative analysis falls beyond the scope of this study.

Secondly, the optimal solution to weighting problem (9) indicates that Finland's overall efficiency score of 86.8 percent is obtained by giving a relatively large weight on acidification. The relative contributions acidification and smog formation to the estimated environmental damage index D were 92.7 and 7.3 percent, respectively, leaving climate change and dispersion of particles only a negligible weight. These benefit of the doubt weights indicate that Finland road transports performed relatively well in terms of emissions related to acidification and smog formation. This is not surprising since these the two environmental themes have been subject to considerable public attention and governmental regulation already for two decades, which has also influenced the automobile industry. The detrimental effects of greenhouse gases and particle emissions were more recently noted, and the emphasis of environmental policy in Finland is shifting towards these themes. Both these themes would certainly be warranted a positive weight in the damage index. However, we maintain that the efficiency score of 86.8 should be interpreted as an upper bound (or the most optimistic estimate); applying any other weights would necessarily decrease this efficiency score.

We also note that the relative shadow price of gasoline turned out to be negligible compared to the average mileage price, both for Finland as a whole and almost all municipalities. Thus, differences in fuel consumption had little effect on our results. For sensitivity analysis, we also estimated the model by including the fuel consumption as an environmental pressure (as a proxy for degradation of natural resources) and using the total mileage as a proxy for the economic value added. This produced almost identical results; the shadow price of fuel consumption was equal to zero for almost all municipalities, and the differences in the efficiency scores were less than 0.08 percentage points for all municipalities.

5.4. *Analysis*

We next consider some possible explanations for the observed efficiency differences across municipalities. Firstly, we should emphasize that our measure for economic value added is almost solely based on the total mileage (as the shadow price of the fuel consumption turned out as negligible). It does not account for the passenger or cargo volume or its composition. Thus, we do not expect such life-style aspects as utilization of public transportation or car-pooling to influence our efficiency scores.

Demographic effects might be a possible source for efficiency differences. The weak performance of Helsinki contrasted with the good performance of mote peripheral municipalities might suggest that the population level or population density determine our efficiency scores. To investigate this, we calculated the Pearson correlation coefficient between eco-efficiency scores and total population. This coefficient was –0.149, which means that there only is a weak negative correlation between eco-efficiency of road transportation and the population in the municipalities. The correlation between eco-efficiency scores and population density was not much stronger: -0.182. In conclusion, differences in the size and population density of the municipality seem to explain only a relatively small part in the measured eco-inefficiencies. Congestion may partly explain the weak performance of Helsinki and some other major cities, but it is hardly a significant factor in most of the 432 municipalities. Moreover, Helsinki's neighboring municipalities Espoo and Vantaa, which together form the capital metropolitan area, performed considerably better than Helsinki: Espoo ranked as 199th with efficiency score of 90.1; Vantaa ranked as 339th with efficiency score of 86.1.

Differences in geographic and climate conditions such as temperature, precipitation, elevation, and other suchlike effects might also explain efficiency differences across municipalities. In the present application, however, these factors do not seem very significant. Firstly, Finland is a relatively flat, low-lying country; its highest point Mt. Halti is only 1,328 meters from the sea level; relative altitude variations are usually less than 50 meters even in the hilliest regions of Eastern and Northern Finland. Thus, differences in elevation can be ruled out on the outset. The climate conditions provide potentially a more important explanation. However, when we examine the geographic locations of the twenty most efficient municipalities, we find that they cover the entire geographic spectrum, ranging from the northernmost municipality of Utsjoki, to the archipelago municipality of Merimasku in the south, from Kitee on the eastern border to Alavus in the west, also including Leivonmäki in the very center of the country. In conclusion, the best performing municipalities do not reveal any systematic geographic pattern, and thus the climate conditions do not appear to present a credible explanation.

By these considerations, differences in the vintage and composition of the vehicle stock suggest themselves as the most likely explanation for efficiency differences. Indeed, Finland's vehicle stock is old: according to the Finnish Information Centre of Automobile Sector,[14] the average age of passenger cars scrapped in 2003 was as high as 18.5 years. In these circumstances, replacing the old vehicles with newer, more eco-efficient ones would undoubtedly offer scope for emission reductions. As our activity analysis estimates are based on the observed performance in real municipalities, they do not take into account technical emission reduction possibilities that have not yet diffused to practice, such as electric or hydrogen powered cars. Our relative eco-efficiency measures show the improvement possibilities available with the technology currently in use in the best performing municipalities.

Heavy taxation of cars is generally seen as the main reason for the high age of Finland's vehicle stock: the direct car tax and the value added tax together make approximately 43 percent of the retail price of a new car, depending on the vehicle class. Not surprisingly, the taxation of cars is currently subject to a lot of political debate in Finland, in which the lower emissions of newer car models is one central argument. However, the taxes related to road transportation are an important source of revenue for the government, and too drastic cuts on car related taxes would probably increase the traffic volume and thus generate more emissions.

In conclusion, we hope this application illustrates the practical use of the eco-efficiency measures and the activity analysis model introduced above and the information that can be extracted with these techniques. We also hope our application might provide some insights for further analysis of eco-efficiency in the transportation sector.

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[14] http://www.autoalantiedotuskeskus.fi/

6. CONCLUDING REMARKS

We have proposed a general framework for measuring eco-efficiency of production. Our approach first aggregates individual pollutants and emissions into environmental pressures by using scientifically accepted conversion factors. Next, these environmental pressures and the value added indicator are further exploited to construct a single encompassing eco-efficiency index. We showed that this general eco-efficiency measure can be derived using either the benefit of the doubt weighting method or the distance function approach. Although these approaches draw from conceptually different perspectives, from mathematical perspective they form a perfect dual pair by producing exactly the same results.

Since both the weighting method and the distance function approach assume technology to be known, we yet have to estimate the technology from the sample data. As an estimation method we proposed to utilize the activity analysis or Data Envelopment Analysis method, which specifies technology by using mathematical programming techniques. Contrary to some other methods presented in the literature, the activity analysis approach does not demand any *a priori* arbitrary assumption as on how to set the weights of various environmental pressures. Despite this, *a priori* information about the distribution of weights can be easily incorporated in the model framework when such information is available.

The presented approach was applied to the eco-efficiency evaluation of road transportation in Finland, with the main purpose to demonstrate the application of the method in practice. Based on the municipal level cross-sectional data on transportation mileage, gasoline consumption, and various air emissions in 2002, we estimated the equiproportionate reduction potential of environmental pressures to be 13 percent at the national level. Variations across municipalities were found to be normally distributed, and weakly negatively correlated with the size and the population density of the municipality.

In this paper we have confined attention on eco-efficiency of production activities in a static setting. Promising directions for further research include extensions of the approach towards efficiency evaluation of consumer goods and dynamic eco-efficiency. Consumer durables such as automobiles, home electronics, and computers can be viewed as “production units” which create both desirable economic services as well as undesirable environmental pressures. Therefore, the approach adopted in this paper might be also applied, in a modified form, in the context of product evaluation. Some modification of the approach is also needed if we wish to measure eco-efficiency over time. The most straightforward approach would be to apply Malmquist index approach (Färe et al., 1994), which enables one to distinguish between the changes in environmental pressures that are due to the technical progress and those due to changes in eco-efficiency.

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