Will Reducing CO_2 Emissions in Truck Transport Increase Traffic Fatalities? Evidence from Eleven Countries

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ABSTRACT

The model built in this paper demonstrates a means of measuring tradeoffs among desirable and undesirable outputs of heavy truck freight transportation. We use shadow prices to determine the costs of regulating CO2 emissions relative to the cost of heavy truck related fatalities and the benefit of freight hauled. The technique presented in this paper provides a means of measuring tradeoffs in public policy decisions.

INTRODUCTION

Increasingly, accountability for environmental performance is expected at the level of both individual companies and supply chains, (Nagurney, et al., 2007) and throughout national economies. One consequence of this, the study of transportation has increasingly become related to the issue of sustainability. Although the concept of sustainability is often related primarily to environmental concerns, in transportation it has evolved to include other factors. These include air quality, fatalities, resource depletion, and congestion (Black and Sato, 2007). Tyteca (1997) has called for viewing "environmental performance in a more global framework, related to economic or socio-economic welfare" (p. 184). Such a view can potentially inform decisions concerning environmental regulation.

This paper focuses on two negative externalities of transportation, CO_2 emissions and fatalities, within the heavy truck sector of eleven OECD countries. Noting the concern for both these externalities, the question then becomes one of how to analyze potential tradeoffs in the use of resources to reduce either CO_2 emissions or truck related fatalities. We present a model that allows us to determine if reducing CO_2 emissions in truck transport increase traffic fatalities.

BACKGROUND

Concerns about the environmental consequences of greenhouse gas emissions have focused the attention of scientists, economists, and policy-makers on devising policies to reduce those emissions. As a result of the high level of carbon dioxide (CO_2) generated by transportation, these emissions, in particular, are receiving a high level of attention. Global estimates are that transportation accounts for 25% of global CO_2 emissions with an expectation this percentage will increase (Olsthoorn, 2003). In the U.S., the transportation sector contributed approximately 31% to CO_2 emissions in 1990, rising to 33.5% in 2006 (Energy Information Agency, 2007). That this increase is expected grows from the understanding that CO_2 levels are linked to growth in fuel usage, in particular, the growing demand for freight hauled via heavy trucks. As more economic development and growth occurs, demand for fuel will also increase and with it exacerbation of the environmental problems (Marcotullio, et. al, 2005).

However, CO_2 emissions are not the only negative externality of transportation. As noted in Black and Sato (2007), the World Health Organization estimates that by 2020 the third largest cause of death will be transportation related (WHO, 2002). Further, as globalization intensifies, so too has the importance of large trucks in transportation. As a result, "the function and safety of conventional transportation infrastructures are challenged by increased allowable vehicle masses and speeds" (Itoh, et. al, 2007). To cope with these challenges, safety oriented activities must be implemented that include transportation engineering, motor vehicle manufacturing (Hauer, 2005), structure design of road barriers (Itoh, et. al, 2007), and safety campaigns implemented by both the trucking industry and governmental agencies (Moore, et. al., 2005).

In this paper we model the joint production of CO_2 emissions, traffic fatalities caused by truck accidents, and tons of goods shipped by truckers in eleven countries during 2000 to 2003. We use the directional output distance function to represent the technology of production address this question: will reducing CO_2 emissions in truck transport increase traffic fatalities? To answer this question we estimate the directional output distance function assuming that CO_2 emissions are freely (strongly) disposable and assuming that CO_2 emissions are only weakly disposable. A consequence of weak disposability is that the opportunity cost of reducing undesirable outputs is that some desirable output must also be foregone. If truck transporters can freely dispose of CO_2 emissions, then some of the resources they employ can be used to reduce traffic fatalities or expand the shipment of goods. However, when CO_2 emissions are regulated, resources that might have gone into reducing fatalities or increasing the shipment of goods are instead used to reduce emissions. The difference in the directional output distance functions estimated under the strong and weak disposability assumptions will provide an estimate of the costs of reducing CO_2 emissions.

METHOD

The directional distance function was introduced by Chambers, Chung, and Färe (1996, 1998) as an extension of Luenberger's (1992, 1995) benefit and shortage functions. The directional distance function serves as an inefficiency measure for multi-output, multi-input production technologies and has recently been used to model the joint production of desirable and undesirable outputs.

Let $y \in R_+^M$ represent a vector of M desirable outputs and let $b \in R_+^J$ represent a vector of jointly produced undesirable outputs. Desirable and undesirable outputs are produced from N inputs represented by $x \in R_+^N$. We assume there are k=1,…,K decision-making units. The technology of production is given by the production possibility set:

$$P(x) = \{(y,b): \quad x \text{ can produce } (y,b)\}. \qquad (1)$$

The production possibility set contains the desirable and undesirable outputs that can be jointly produced given inputs. We assume that this set is closed, bounded, and convex. We also assume that $P(x)$ satisfies strong disposability of desirable outputs and inputs, weak disposability of undesirable outputs, and desirable and undesirable outputs are null-joint. These assumptions are written as:

$$\begin{aligned} &i. \quad (y,b)\in P(x) \text{ and } y'\le y, \text{ then } (y',b)\in P(x)\\ &ii. \quad (y,b)\in P(x) \text{ and } x'\ge x, \text{ then } (y,b)\in P(x')\\ &iii. \quad (y,b)\in P(x) \text{ and } 0\le\theta\le 1, \text{ then } (\theta y,\theta b)\in P(x)\\ &iv. \quad (y,b)\in P(x) \text{ and } b=0, \text{ then } y=0. \end{aligned} \tag{2}$$

Strong disposability of desirable outputs and inputs implies that if a desirable and undesirable output vector is producible from a given amount of input, then it is possible to produce either less desirable output (2i), or, produce the same amount of desirable and undesirable outputs using more inputs (2ii). Weak disposability (2iii) implies that the opportunity cost of reducing undesirable outputs is that some desirable output must be foregone. Finally, desirable and undesirable outputs are null-joint (2iv) if the only way to produce zero undesirable output is to also produce zero desirable output.

We use the directional output distance function to transform the set representation of the technology given by (1) and (2) to a functional representation. Let $g^y=(g_1^y,...,g_M^y)$ and $g^b=(g_1^b,...,g_J^b)$ be directional scaling vectors for desirable and undesirable outputs. The directional output distance function seeks the maximum expansion in desirable outputs and contraction in undesirable outputs, given inputs. This function is written as:

$$\vec{D}_o(x,y,b;g^y,g^b)=\max_{\beta}\{\beta: \quad (y+\beta g^y, b-\beta g^b)\in P(x)\}. \tag{3}$$

Efficient decision-making units (DMUs) cannot simultaneously expand desirable outputs in the g^y direction while contracting undesirable outputs in the g^b direction. Thus, efficient DMUs have $\vec{D}_o(x,y,b;g^y,g^b)=0$. A DMU that is inefficient can simultaneously expand desirable outputs in the g^y direction and contract undesirable outputs in the g^b direction. Inefficient DMUs have $\vec{D}_o(x,y,b;g^y,g^b)>0$, with a higher value indicating greater inefficiency.

The properties of the directional output distance function are inherited from the production possibility set. These properties include:

$$\begin{aligned} &i. \quad \vec{D}_o(x,y,b;g^y,g^b)\ge 0 \text{ if and only if } (y,b)\in P(x)\\ &ii. \quad \vec{D}_o(x,y',b;g^y,g^b)\ge \vec{D}_o(x,y,b;g^y,g^b) \text{ for } (y',b)\le (y,b)\in P(x)\\ &iii. \quad \vec{D}_o(x,y,b';g^y,g^b)\ge \vec{D}_o(x,y,b;g^y,g^b) \text{ for } (y,b')\ge (y,b)\in P(x)\\ &iv. \quad \vec{D}_o(x,\theta y,\theta b;g^y,g^b)\ge 0 \text{ for } (y,b)\in P(x) \text{ and } 0\le\theta\le 1.\\ &v. \quad \vec{D}_o(x,y+\alpha g^y,b-\alpha g^b;g^y,g^b)=\vec{D}_o(x,y,b;g^y,g^b)-\alpha. \end{aligned} \tag{4}$$

The directional output distance function provides a complete characterization of the technology in that it will be non-negative for feasible output vectors (5i). Property (5ii) corresponds to strong disposability of desirable outputs. Holding inputs and undesirable outputs constant, firms that produce less desirable output are no more efficient. Property (5iii) is a monotonicty condition for undesirable outputs and states that holding desirable outputs and input constant, firms that produce more undesirable output are no more efficient. Property (5iv) corresponds to weak disposability of desirable and undesirable outputs. If an output vector (y,b) is feasible, then proportional contractions in that output vector are also feasible. Finally, the directional output distance function satisfies a translation property (5v) which states that if desirable outputs are expanded by αg^y and undesirable outputs are contracted by αg^b, then the level of inefficiency as measured by the directional output distance function declines by α.

Figure 1 illustrates the production possibility set when a given level of input is used to produce one desirable output and one jointly produced undesirable output. Four DMUs are represented by points A, B, C, and D. We assume a piece-wise linear non-increasing returns to scale technology so the origin is feasible. The production possibility set is bounded by the line segments 0ABDX0. The vertical extension DX models strong disposability of desirable outputs. In addition, weak disposability is represented in that any point in the set can be scaled back toward the origin along a ray from the origin. The negatively sloped portion of the frontier, BD, indicates congestion in the undesirable output. When the undesirable output is congesting, its production has become so great as to reduce the desirable output. Traffic accidents that cause highways to be closed while the accident is attended to are an example of congestion caused by an undesirable output. The directional scaling vector is represented by the ray $0g^1$. The DMUs represented by points A, B, and D form the frontier technology. The DMU represented by point C produces (y_C, b_C) inside the frontier and is inefficient. If DMU C were to become efficient it could produce at point E. For this DMU, the directional output distance function is $\vec{D}_o(x, y, b; g^y, g^b) = \frac{CE}{0g}$. We note that a DMU might be deemed efficient for one directional vector, but not for other directional vectors. For instance, the DMU represented by D can feasibly contract the undesirable output, holding the desirable output constant (moving due west), but it cannot feasibly expand the desirable output holding the undesirable output constant (moving due north). The due west directional vector would corresponds to $g^y = 0$ and $g^b > 0$ while the due north directional vector corresponds to $g^y > 0$ and $g^b = 0$.

We estimate the directional output distance function using linear programming methods called DEA (data envelopment analysis). The DEA production possibility set is represented by

$$P(x) = \{(y, b) : \sum_{k=1}^{K} z_k y_{km} \geq y_m,\ m = 1, \ldots, M,\ \sum_{k=1}^{K} z_k b_{kj} = b_j,\ j = 1, \ldots, J,$$
$$\sum_{k=1}^{K} z_k x_{kn} \leq x_n,\ n = 1, \ldots, N,\ \sum_{k=1}^{K} z_k \leq 1,\ z_k \geq 0,\ k = 1, \ldots, K\}, \tag{5}$$

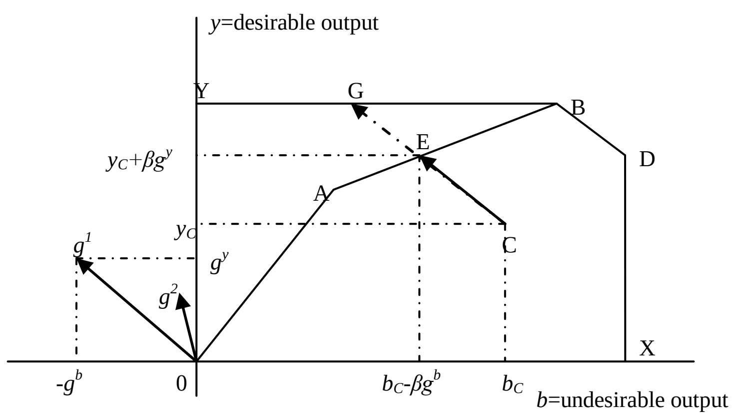

Figure 1: The Production Possibility Set and Directional Output Distance Function

where the z_k are intensity variables that form linear combinations of the *K* observed quantities of inputs, and desirable and undesirable outputs. Constraining the intensity variables to sum to no greater than one imposes non-increasing returns to scale. The inequality constraints for the *M* desirable outputs and the *N* inputs impose strong disposability. Weak disposability of undesirable outputs is obtained from the equality constraints for the *J* undesirable outputs.

For DMU "o" the DEA directional output distance function takes the form:

$$\vec{D}_o(x,y,b;g^y,g^b)=\max_{\beta,z}\{(y,b):\sum_{k=1}^{K} z_k y_{km} \geq y_{mo}+\beta g_m^y,\ m=1,...,M,$$
$$\sum_{k=1}^{K} z_k b_{kj} = b_{jo}-\beta g_j^b,\ j=1,...,J, \sum_{k=1}^{K} z_k x_{kn} \leq x_{no},\ n=1,...,N, \tag{6}$$
$$\sum_{k=1}^{K} z_k \leq 1,\ z_k \geq 0,\ k=1,...,K\}.$$

To capture the effects of regulations that limit emissions of CO_2, we compare a DEA technology where the undesirable output is freely disposable with the technology where the undesirable output is only weakly disposable. The DEA technology where undesirable outputs are freely disposable is represented by 0YBX0. For the DMU represented by C, the directional output distance function assuming strong disposability of the undesirable output is $\vec{D}_o(x,y,b;g^y,g^b)=\frac{CG}{0g^1}$. Taking the difference between the directional output distance function estimated assuming strong disposability (SD) and weak disposability (WD) and multiplying by the directional vector yields the opportunity cost of the regulation. Suppose undesirable outputs *j*=2,…,*J* are currently regulated, but undesirable output *j*=1 is unregulated. Then the opportunity cost of regulating undesirable output 1 is the foregone desirable output and extra undesirable output that occur because limited resources have to be used to reduce the now regulated undesirable output. This opportunity cost vector can be represented as

$$\text{Opportunity cost}=[\vec{D}_o(x,y.b;g^y,g^b \mid SD)-\vec{D}_o(x,y.b;g^y,g^b \mid WD)]\cdot g\ . \tag{7}$$

In addition to measuring efficiency we can use the directional output distance function to estimate the shadow price of undesirable outputs. Let $p\in R_+^M$ represent desirable output prices and let $q\in R_+^J$ represent undesirable output prices. The revenue function takes the form:

$$R(x,p,q)=\max_{y,b}\{py-qb:\quad (y,b)\in P(x)\}, \tag{8}$$

where $py=p_1y_1+...+p_My_M$ are the revenues earned from desirable outputs and $qb=q_1b_1+...+q_Jb_J$ are the charges (negative revenues) from producing undesirable outputs. In problem (8), the DMU chooses desirable and undesirable outputs that are feasible given inputs and the technology and given desirable and undesirable output prices. Given property (5i) we can write the revenue function as

$$R(x,p,q)=\max_{y,b}\{py-qb:\quad \vec{D}_o(x,y,b;g^y,g^b)\geq 0\}. \tag{9}$$

Chambers, Chung, and Färe (1998) showed that the Lagrangian multiplier associated with (9) is $\lambda=pg^y+qg^b$. This multiplier gives the expansion in revenues and contraction in the charges to undesirable outputs if the constraint associated with the directional output distance function is relaxed by one unit. While desirable output prices are usually observed from market transactions, undesirable outputs are usually not traded in markets and have unobserved prices. To obtain undesirable output prices we use the revenue function and the physical tradeoff between desirable outputs and undesirable outputs. Färe et al. (2005) show that the directional output distance function can be recovered from the revenue function as

$$\vec{D}_o(x,y,b;g^y,g^b)=\min_{p,q}\left\{\frac{py-qb}{pg^y+qg^b}\right\}. \tag{10}$$

The first-order conditions to problem (10) are

$$\frac{\partial \vec{D}_o(x,y,b;g^y,g^b)}{\partial b_j} = \frac{q_j}{pg^y + qg^b}, \quad j = 1,...,J,$$
$$\frac{\partial \vec{D}_o(x,y,b;g^y,g^b)}{\partial y_m} = -\frac{p_m}{pg^y + qg^b}, \quad m = 1,...,M. \tag{11}$$

Taking ratios in (11) and rearranging we can obtain the shadow prices of the undesirable outputs as

$$q_j = -p_m\left(\frac{\partial \vec{D}_o(x,y,b;g^y,g^b)/\partial b_j}{\partial \vec{D}_o(x,y,b;g^y,g^b)/\partial y_m}\right), \quad j = 1,...,J. \tag{12}$$

The DEA directional output distance function was specified in (6). Fukuyama and Weber (2008) specify a dual DEA directional output distance function that can be used to estimate shadow prices using (12). For DMU "o" the dual DEA directional output distance function takes the form:

$$\begin{aligned}
&\vec{D}_o(x,y,b;g^y,g^b) = \min_{v,u,\sigma,\omega}\{\sum_{n=1}^{N} v_n x_{no} - \sum_{m=1}^{M} u_m y_{mo} - \sum_{j=1}^{J} \sigma_j b_{jo} + \omega : \\
&\sum_{n=1}^{N} v_n x_{nk} - \sum_{m=1}^{M} u_m y_{mk} - \sum_{j=1}^{J} \sigma_j b_{jk} + \omega \geq 0,\ k = 1,...,K, \\
&\sum_{m=1}^{M} \mu_m g_m^y - \sum_{j=}^{J} \sigma_j g_j^b = 1, \quad \mu_m \geq 0,\ m = 1,...,M, \\
&\quad v_n \geq 0,\ n = 1,...,N; \quad \sigma_j \leq 0,\ j = 1,...,J,\ \omega \geq 0\}.
\end{aligned} \tag{13}$$

The constraints that $\mu_m \geq 0$ and $\sigma_j \leq 0$ are the monotonicity conditions set forth in properties (5ii) and (5iii). Shadow prices of the undesirable outputs can be obtained from the estimated parameter of (13) using the shadow pricing formula given by (12):

$$q_j = -p_m \frac{\sigma_j}{u_m}, \quad j = 1,...,J. \tag{14}$$

Thus, given knowledge of the market price of one of the desirable outputs, say the m^{th}, the shadow prices of the undesirable outputs can be inferred from the market price and the tradeoff between the desirable and undesirable output.

DATA AND EMPIRICAL ESTIMATES

Data on the trucking industry were gathered from IRTAD, the International Road Traffic Accident Database (www.irtad.net) and OECD in Figures, Organization for Economic Co-operation and Development database. All data in both databases are self-reported by member countries from 28 or the 30 OECD member countries. A problem with self-reporting is that, while many countries report various data on truck transport, the data are often reported at irregular intervals and the variables reported are not the same across countries. Consequently, we examine the trucking industry in eleven countries for the years 2000 to 2003. Missing data confined our data set to 35 observations. We assume that the trucking industry uses inputs of fuel, labor, and the road system to produce a desirable output of transported goods. In addition, two undesirable by-products are generated by the truck transport industry: traffic fatalities involving trucks and CO_2 (carbon dioxide) emissions.

Fuel is measured in Mtoe, million tons of oil equivalent. Labor is measured in 1000s of workers. The length of transportation networks is measured in kilometers. Emissions of CO_2 are in millions of tons. Truck fatalities equal the number of fatalities involving a heavy truck in each year. Freight transported is in billion ton kilometers per year. We constructed a price per ton of freight transported one kilometer as the ratio of income generated by the truck transport sector divided by the number of tons transported. Appendix A1 lists the observations.

Descriptive statistics on the inputs, outputs, and the price of the desirable output are presented in Table 1. To estimate efficiency we need to choose a directional vector for desirable and undesirable outputs. We consider two alternatives. First, we choose $g^y = (\bar{y}) = 257.1$ and $g^b = (\bar{b}_1, \bar{b}_2) = (260.3, 992.2)$ as a common directional vector for all observations. This choice of directional vector means that our estimate of $\vec{D}_o(x_k, y_k, b_k; \bar{y}, \bar{b})$ for each country in each year will equal the percent increase in freight transported one kilometer and percent decline in CO_2 emissions and truck related fatalities relative to the means of truck freight, CO_2 emissions, and fatalities. Our second choice of directional vector equals the value of each country's desirable and undesirable outputs. That is, $g^y = (y_k)$ and $g^b = (b_{1k}, b_{2k})$ meaning that $\vec{D}_o(x_k, y_k, b_k; y_k, b_k)$ will give the each country's proportional expansion in freight transported and proportional contraction in CO_2 emissions and truck related fatalities.

Tables 2 and 3 report the estimates for the two choices of directional scaling vectors. For our first model, where $g^y = (\bar{y}) = 257.1$ and $g^b = (\bar{b}_1, \bar{b}_2) = (260.3, 992.2)$, the mean estimate of inefficiency is $\vec{D}_o(x, y, b; \bar{y}, \bar{b}) = 0.013$ which means that freight transported one mile could increase by $0.013x257.1 = 3.3423$ billion tons, CO_2 emissions could decrease by $0.013x260.3 = 3.384$ million tons, and truck relate fatalities could decrease by $0.013x992.2 = 12.9$ if the average country were to become efficient and produce on the frontier of their production possibility set. In model 1, sixteen observations were efficient and produced on their production possibility frontier. These sixteen observations included Belgium in 2002, Canada in 2003, the Czech Republic in 2000, 2002, and 2003, Finland in 2002, Germany in 2000 to 2003, South Korea in 2000 and 2002, and the US in 2000 to 2003. The least efficient country was France in 2003.

For the second model, with $g^y = (y_k)$ and $g^b = (b_{1k}, b_{2k})$, the mean estimate of efficiency is $\vec{D}_o(x, y, b; y_k, b_k) = 0.196$ which indicates that average inefficiency is about 20%. The frontier countries are the same as in model 1, except for South Korea, which is no longer on the frontier for this alternative directional vector, and in fact, has the highest inefficiency. South Korea is an interesting case in that it has the highest ratio of the two undesirable outputs to desirable output. South Korea has 132 fatalities per billion ton kilometers as opposed to the average directional vector of 3.8 fatalities per billion ton kilometers. For CO_2 emissions, South Korea emits 9 million tons of CO_2 per billion ton kilometers of freight transported as opposed to the average directional vector of 1.01 million tons of CO_2 per billion ton kilometers of freight transported. The results for South Korea for models 1 and 2 indicate that the country lies on a negatively sloped portion of the production possibility frontier at a point like D in Figure 1. If South Korea is located at point like D, then it cannot simultaneously expand desirable outputs and contract undesirable outputs in a direction such as g^2, but it can simultaneously expand desirable outputs and contract undesirable outputs in a direction such as g^1.

Now, we turn our attention to the shadow price estimates of CO_2 emissions and fatalities involving a heavy truck. In each case the shadow price indicates the decrease in the value of freight shipped necessary to reduce either CO_2 emissions or fatalities by one unit. In model 1, the shadow price of CO_2 equals 0.56. Since CO_2 emissions are measured in millions of tons and truck shipments in billions of ton kilometers, to reduce CO_2 emissions by 1 ton, \$560 ((=1billion/1 million)x\$0.56) in freight value must be foregone, holding inputs constant. The model 2 estimate is higher, at \$1.46 million in foregone freight value. The difference in the two estimates can be attributed to differences in the directional vectors used to scale outputs to the frontier. As seen in Figure 1, if the directional vector scales firm C's outputs to the frontier along line segment AB, there will be a different shadow price than if the directional vector scales outputs to the frontier along line segment 0A.

The shadow price of traffic fatalities is \$0.745 in model 1 and \$0.128 in model 2. Thus, model 1 suggests that to reduce one fatality involving a heavy truck, between \$128 million (model 2) and \$745 million (model 1) in the value of freight must be foregone. The US, which is on the frontier in both models, has a shadow price of approximately \$134 million.

Finally, what effect will regulations requiring reductions in CO_2 emissions have on traffic fatalities with heavy truck involvement? To address this question we estimated the directional output distance function twice, once assuming that traffic fatalities and CO_2 emissions are weakly disposable and a second time assuming that traffic fatalities are weakly disposable but CO_2 emissions are freely disposable. Taking the difference in the two distance functions and multiplying by the directional vector provides an estimate of the opportunity costs of regulating CO_2. Holding inputs constant, regulating CO_2 emissions would result in an average reduction of 4.78 (model 2) to 5.42 (model 1) billion ton kilometers in freight shipped and 20.9 (model 1) to 29.5 (model 2) extra fatalities per year.

To test whether the opportunity costs of regulating CO_2 are significant we test the null hypothesis that the directional output distance function estimated under strong disposability of CO_2 emissions equals the directional output distance function estimated under weak disposability of CO_2 emissions. Figures 2 and 3 graph the kernel distributions of inefficiency as measured by the directional output distance function for the two disposability assumptions. The linear programming method provides nonparametric estimates of the directional output distance function and results in non-normal distributions of inefficiency. We tested the hypothesis using a battery of nonparametric tests. The Kruskal-Wallis, Median, Savage, and Van der Waerden tests all have a chi-square distribution, while the Kolmogorov-Smirnov test examines differences in the empirical distribution functions. Based on the results of these tests we cannot reject the null hypothesis. That is, the regulated and unregulated technologies give the same estimates of inefficiency. Therefore, our simulated effects of regulating CO_2 indicate no significant increase in traffic fatalities nor decline in truck shipments.

CONCLUSIONS

The model built in this paper demonstrates a means of measuring tradeoffs among desirable and undesirable outputs of heavy truck freight transportation. We have shown how to measure the cost of regulating a negative externality, CO_2 emissions, from heavy truck transport relative to both another negative externality, truck related fatalities, and a positive externality, tons of freight hauled. The results indicate that the increased regulation of CO_2 emissions will not result in a significant decrease in freight hauled or a significant increased in traffic fatalities involving large trucks. Calculating shadow prices of regulations using the modeling techniques presented in this paper provide a means of informing public policy decisions by measuring the costs of possible regulations.

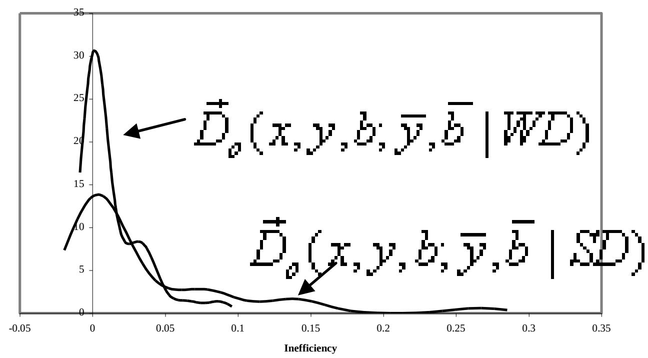

Figure 2: Kernel Distribution functions of Inefficiency under strong disposability and weak disposability for CO_2 emissions Model 1 $g^y = \bar{y} \quad g^b = (\bar{b}_1, \bar{b}_2)$

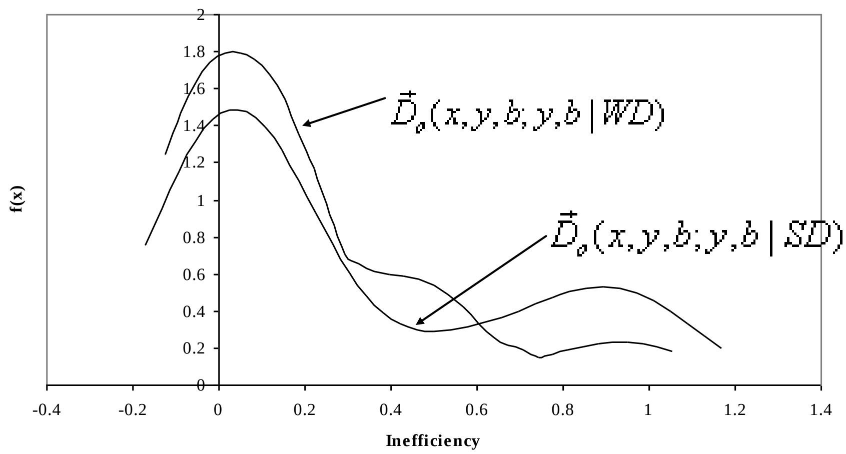

Figure 3: Kernel Distribution functions of Inefficiency under strong disposability and weak disposability for CO_2 emissions. Model 2: $g^y = y_k \quad g^b = (b_{1k}, b_{2k})$

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Tables and Appendix available upon request.