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A DIRECT ESTIMATE OF THE TECHNIQUE EFFECT: CHANGES IN THE POLLUTION INTENSITY OF US MANUFACTURING 1990 – 2008

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ABSTRACT

From 1990 to 2008, the real value of US manufacturing output grew by one-third while the pollution emitted from US factories fell by two-thirds. What accounts for this cleanup? Prior studies have documented that a relatively small share can be explained by changes in the composition of US manufacturing – a shift towards producing relatively more goods whose production processes involve less pollution. Those studies attribute the unexplained majority to "technique", a mix of input substitution, process changes, and end-of-pipe controls. But because that technique effect is a residual left over after other explanations, any errors or interactions in the original calculation could inflate the estimated technique. In this paper I provide the first direct estimate of the technique effect. I combine the National Emissions Inventories with the NBER-CES Manufacturing Industry Database for each of over 400 manufacturing industries. I aggregate across industries using analogs to the Laspeyres and Paasche price indexes for each of six major air pollutants. The calculations using this direct estimation of the technique effect support the research findings using indirect measures. From 1990 to 2008, production technique changes account for more than 90 percent of the overall cleanup of US manufacturing.

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A Direct Estimate of the Technique Effect:
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1. Introduction

From 1990 to 2008, the real value of US manufacturing output grew by 35 percent while the pollution emitted from US factories fell by 52 to 69 percent, depending on the pollutant. This tremendous decrease in the pollution-intensity of US production has two possible causes: composition or technique. Either US manufacturers produced proportionally more goods whose production processes involve less pollution, or manufacturers adopted technologies that enabled production of the same goods with less pollution – cleaner fuels, energy efficiency, end-of-pipe abatement equipment, or other production process changes.

Economists have noticed this trend for some time, but all of the research to date parsing the cleanup of manufacturing into those two components – composition and technique – has involved careful documentation of composition changes in the manufacturing sector, with any leftover pollution reductions being attributed to technique changes. Most find that composition changes do not explain even half of the cleanup of manufacturing and that therefore technology changes must explain the majority. If true, this is welcome news. If composition changes had explained the US manufacturing cleanup that would raise logical follow-up questions: Where are those polluting factories going? Could those other places replicate the US cleanup without finding even more polluted places to offshore their polluting industries? But if technique changes explain the US cleanup, that process could be easily replicable by follow-on countries that adopt technologies developed elsewhere.

For carbon pollution the importance of these distinctions is compounded. Any US cleanup that results from composition changes due to shifting US manufacturing abroad has no climate mitigation benefits, because carbon emitted overseas is just as damaging as carbon emitted domestically. But any US cleanup that results from technique changes represents real reductions in global pollution and real climate benefits. So the conclusion that most of the cleanup stems from technique represents good news.

But the estimates of the technique effect to date also leave room for worry. Prior estimates have relied on emissions intensities from a single year, 1987, and the technique effect has only been measured as a residual, a left-over-amount of cleanup after the other plausible explanations are exhausted. Its magnitude could be the product of peculiarities of the 1987 emissions inventory, some accounting or measurement error, or unaccounted interactions among other trends. Those concerns would be alleviated if the technique effect were estimated more directly as changes over time in the emissions intensities of industries, holding the composition of those industries constant. The data for that calculation are now available.

In what follows I provide the first direct estimate of the technique effect. I use the six iterations of the National Emissions Inventories between 1990 and 2008, listing the amount of pollution emitted by each of over 400 manufacturing industries. I combine those data with the NBER-CES Manufacturing Industry Database to generate pollution per dollar of output for each of those industries, deflated by industry-specific producer price indexes. I then aggregate across industries using analogs to the Laspeyres and Paasche price indexes to get a single measure of cleanup for each of six major air pollutants. Those index measures describe aggregate declines in pollution per dollar of output for the whole manufacturing sector from 1990 to 2008, abstracting away from composition changes. In the end, the calculations using this direct estimation of the technique effect support the research findings using indirect measures. From 1990 to 2008, pollution per dollar of output from US manufacturing declined by 64 to 77 percent. More than 90 percent of this cleanup can be attributed to technique changes, directly.

2. What we know so far

Several recent studies have estimated the effect of changes in the composition of the manufacturing sector by disaggregating output changes among various industries and projecting their separate emissions using fixed industry-specific measures of pollution-intensity.[1] The standard approach notes that total pollution from manufacturing (P) can be calculated as

$$P = \sum_i p_i = \sum_i v_i\, z_i = V \sum_i \theta_i\, z_i \qquad (1)$$

where p_i represents pollution from industry i, v_i is the value of output, z_i is the emissions intensity or pollution per dollar of output, and θ_i is (v_i/V) the share of each industry in total manufacturing output.

The composition effect can be seen by calculating the predicted total pollution from manufacturing ($\hat{P}$) holding those emissions intensities in the last term in (1) constant ($\bar{z}$).

$$\hat{P} = V \sum_i \theta_i\, \bar{z} \qquad (2)$$

Any changes in $\hat{P}$ over time are due solely to changes in the overall scale (V) of manufacturing or its composition (θ). And any difference between $\hat{P}$ and actual pollution P must be due to changes in emissions intensities – or technique.

Figure 1 depicts the basic idea for sulfur dioxide (SO2). Line (1) plots the total inflation-adjusted output of the US manufacturing sector from 1990 to 2008, indexed so that 1990=100.

[1] See, for example, Brunel (2014), Levinson (2009), Cole (2000, 2004), Ederington et al. (2004), Kahn (2003), and Hettige et al. (1992).

This is the scale effect, which increased 35 percent. Line (2) plots the total manufacturing emissions of SO2, originally in tons but indexed so that 1990=100. SO2 pollution declined 65 percent, which means that SO2 per dollar of manufacturing output declined by 74 percent. Table 1 contains the data behind lines (1) and (2) in Figure 1 for SO2, along with the data for four other major air pollutants. Pollution per dollar of manufacturing output fell by 64 to 77 percent, depending on the pollutant, a cleanup that in each case must be explained by some combination of composition and technique.

Line (3) of Figure 1 depicts predicted SO2 pollution ($\hat{P}$) from equation (2), based solely on changes in the composition and scale of manufacturing. That prediction ($\hat{P}$) rises 23 percent, nearly as much as manufacturing overall, which means that the composition effect can only explain about 12 percent of the decline in SO2 per dollar of manufacturing output.[2] Indirectly, 88 percent most of the cleanup of SO2 must be attributable to the residual – the "technique effect."

In Levinson (2009) I estimate (indirectly) that from 1987 to 2001, between 60 and 95 percent of the cleanup of US manufacturing was attributable to technique. Brunel (2014) replicates this analysis for the European Union from 1995 to 2008 and finds that air pollution from manufacturing declined there as well, and that little or none of that cleanup can be explained by changes in the composition of Europe's manufacturing sector. Most, therefore, she attributes to changes in technique. Martin (2014) shows that declining greenhouse gas emissions in India have been due more to productivity gains within industries than reallocations among productive and unproductive industries. And Shapiro and Walker (2014) take a more ambitious structural approach that leads to similar conclusions. Trends in US manufacturing pollution are

[2] Manufacturing rose 35 percent, and SO2 pollution fell 65 percent, so pollution per dollar of output fell 74 percent. (1-(0.35)/(1.35)). Pollution predicted from composition ($\hat{P}$) grew 23 percent, so composition accounts for 12 percent of the 74 percent decline in pollution per dollar: (1.35 –1.23)/(1.35 – 0.35).

not explained by the scale or composition industries within manufacturing, and so must be driven by changes in technique.

But all of this work that credits most of the manufacturing cleanup to technique does so as a residual source of improvement after the composition and scale changes have been accounted for. And this approach has several problems. Most importantly, it assumes there are no interactions between scale, composition and technique – that changing the scale of an industry (v_i) does not affect its pollution intensity (z_i) for example. Any such interactions would all be erroneously included in the remainder term and attributed to technique effects in this approach.

Second, because the time-varying measures of pollution intensity I use here were not available, all of the prior approaches use emissions intensities from a single year – most often the 1987 Industrial Pollution Projection System (IPPS) developed by the World Bank (Hettige et al, 1995). If over time the faster-growing industries cleaned up more, in percentage terms, then using base-year pollution intensities for $\bar{z}$ in equation (2) misses that change and overstates the role of technique. If the slower-growing industries cleaned up more, then using base-year $\bar{z}$ understates the role of technique. In this paper I address both shortcomings by estimating the technique effect directly using time-varying measures of pollution intensity.

3. Data and the Indexes

To estimate industry-specific pollution intensities I combine two sets of data. The first is the US EPA's National Emissions Inventory (NEI). The NEI is a national aggregation of emissions data from state, local, and federal sources, compiled intermittently from 1990 to 2008.[3] Pollutant coverage varies, but coverage of six major air pollutants has been mostly consistent since the beginning: carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide

[3] The NEI data are from 1990, 1996, 1999, 2002, 2005, and 2008.

(SO2), particulate matter smaller than 10 microns and 2.5 microns (PM10 and PM2.5), and volatile organic compounds (VOCs). The NEI reports the amount of each pollutant emitted per year for each source, along with the industry to which that source belongs.[4]

The second dataset is the NBER-CES Manufacturing Industry Database.[5] That contains the annual output of each industry, along with industry-specific price deflators. I merge the two datasets by industry and year, and divide aggregate pollution by value shipped to get an industry-specific measure of pollution intensity for each of the three NEI years.[6] Before describing the results, it's worth highlighting some key data challenges: changing industry definitions, price indexes, base-year index choices, and industry composition issues.

Changing industry definitions: SIC and NAICS

The 1990, 1996, and 1999 NEI data are categorized according to four-digit Standard Industrial Classification (SIC) codes, while the 2005 and 2008 NEI data are categorized according to six-digit North American Industrial Classification System (NAICS) codes.[7] Each is a hierarchical numerical taxonomy of industries, with similar industries grouped into separate classifications. To match the two I rely on the NBER-CES Manufacturing Industry Database, which publishes industry data according to both industry codes along with a concordance between the two.

For half of the 473 six-digit NAICS codes, the match is one-to-one with a corresponding four-digit SIC code.[8] For the others, I matched the pollution from SIC and NAICS industries

[4] More information about the NEI can be found here: http://www.epa.gov/ttnchie1/trends/.
[5] http://www.nber.org/nberces/
[6] As I describe later, similar results come from using value added rather than value shipped.
[7] The 2002 NEA is listed both ways.
[8] For example, SIC 3061, "Molded, Extruded, and Lathe-Cut Mechanical Rubber Goods," has simply been relabeled as NAICS 326291, "Rubber Product Manufacturing for Mechanical Use."

according to the share of value shipped in each.[9] In what follows, I report calculations both ways: converting the early NEI data to NAICS categories, and converting the more recent NEI data to SIC codes.

Price indexes

In order to assess whether pollution per dollar of output has declined, I need real values of output. But prices changed between 1990 and 2008 differently for different industries. For energy intensive industries like petrochemicals and copper smelters, prices tripled for reasons unrelated to the characteristics of the products. A barrel of oil or a bar of copper was the same product in 2008 as it was in 1990, just more expensive. If I were to use the overall producer price index (PPI) rather than industry-specific price indexes, I would exaggerate the size of these pollution-intensive industries in 2008 and overstate the technique effect. For these industries, using industry-specific price indexes is important.

For industries like computers and semiconductors, the price indexes fell by up to 99 percent, due to changes in the products themselves. A computer in 2008 was not the same product as in 1990, though manufacturing it might well involve similar quantities of pollution. Industry-specific price indexes inflate the growth of these relatively clean industries, understating the technique effect. To be conservative, in what follows I report results using industry-specific price deflators.

[9] For example, the concordance reports that 92 percent of the value shipped from SIC code 3313, "Electrometallurgical Products, Except Steel," can now be classified as NAICS 331112, "Electrometallurgical Ferroalloy Product Manufacturing." So I assign 92 percent of the pollution from SIC 3313 to NAICS 331112 as well.

Index issues: Laspeyres and Paasche

Directly estimating the technique effect involves a very standard index problem: what weight do we assign to each industry, given that the industries' shares of total output changed from 1990 to 2008? As with any index problem, there are two basic choices. We can create the index of change by comparing actual 1990 emissions to what the current emissions would have been, had the individual industries' emissions intensities changed from 1990 but each industry's output remained as it was in 1990.

$$I_L = \frac{\sum_i z_{it} \times v_{i,1990}}{\sum_i z_{i,1990} \times v_{i,1990}} \tag{3}$$

where z_{it} is the emissions intensity for industry *i* in year *t*, and v_{it} is the value shipped from industry *i* in year *t*. This would be analogous to a Laspeyres price index, with pollution intensities in place of prices. Hence the subscript *L*.

Alternatively, we can create the index by comparing actual current emissions to what the 1990 emissions would have been, had each industry's output in 1990 been as it is currently.

$$I_P = \frac{\sum_i z_{it} \times v_{it}}{\sum_i z_{i,1990} \times v_{it}} \tag{4}$$

This is the analog to a Paasche price index, subscripted *P*.

For prices, the Laspeyres index overstates inflation and the Paasche index understates inflation, assuming people adjust to changing relative prices by consuming more of the goods whose prices grow least. In this pollution context, the relative sizes of the two indexes depend on whether the manufacturing sector has shifted towards or away from industries whose pollution intensities have fallen the most. If between 1990 and 2008 the manufacturing sector produced relatively less output in industries with the fastest-falling pollution intensities, the Laspeyres index will be smaller than the Paasche index and suggest a larger technique effect. If output grew more in those industries with the fastest-falling pollution intensities, Laspeyres will be larger than Paasche and suggest a smaller technique effect.

Although I am using the indexes in equations (3) and (4) to answer the same question as others have addressed, the approach here is fundamentally different. Rather than holding technique fixed, examining predicted pollution ($\hat{P}$) from changes in scale and composition as in equation (2), and attributing the rest to technique, I do the reverse. I hold composition of output fixed and show how pollution per dollar of output for the aggregate manufacturing sector has changed.

Intra-industry composition effects

One final note deserves mention here. The use of changes in the emissions intensities of six-digit NAICS codes cannot entirely identify the technique effect, separate from any change in industry composition. This is because the disaggregate industry definitions are themselves heterogeneous. In other words, within each 6-digit NAICS code there are sub-industries with varying degrees of pollution intensity. Over time, the composition of sub-industries within any six-digit NAICS code may change, potentially altering the pollution intensity of the six-digit industry – the z_i. While this approach would attribute the change in that industry's pollution intensity to "technique," as described it may be due to an undocumented change in composition.

4. Results

Table 2 reports the Laspeyres and Paasche indexes of pollution intensity for the whole manufacturing sector, calculated according to equations (3) and (4) for the whole time period. Sulfur dioxide emissions per dollar of output fell 68.3 percent to 0.317 by the Laspeyres index and 71.4 percent to 0.286 according to the Paasche index. The indexes for the other four air pollutants fell similar amounts, ranging from 58 to 78 percent. These are direct estimates of the technique effect – the drop in pollution intensity of the US manufacturing sector, holding its composition constant.

Line (4) of Figure 1 plots this technique effect for SO2 using the Laspeyres index, by multiplying the index value (0.317 for 2008) by total real manufacturing output ($5491 for 2008) and indexing the result so that 1990=100. This SO2 prediction based on technique and scale alone, holding composition fixed, declines almost as much as actual pollution, depicting the degree to which the overall cleanup stems from technique rather than composition.

Finally, Table 3 puts the two calculations together and calculates the share of the cleanup of manufacturing depicted in Figure 1 and documented in Table 1 that is due to the technique effect reported in Table 2. Column (1) just reports the total cleanup of manufacturing from Table 1 – the gap between manufacturing growth and pollution depicted in Figure 1. Columns (2) and (4) report the percentage declines in the Laspeyres and Paasche indexes. And columns (3) and (5) take the ratio of the two – the share of total cleanup of manufacturing in column (1) that is explained by the industry-by-industry cleanup indexes in columns (2) and (4). Those shares all exceed 90 percent.

For volatile organic compounds (VOCs), the share explained by technique using the Paasche index exceeds 100 percent, which bears some explaining. How can technique account for more than 100 percent of the cleanup? From 1990 to 2008 the US manufacturing sector shifted towards industries that in 1990 had production processes that generated a lot of VOCs, which means that the composition effect was negative.[10] A version of Figure 1 drawn for VOCs shows line (3) rising above line (1). If each industry kept its 1990 pollution intensity, VOC emissions would have grown even faster than overall manufacturing, because the sector shifted towards more pollution-intensive products.

For comparison with prior research, in the last column of Table 3 I report the share of the cleanup of each pollutant from the technique effect using the earlier method, as a residual after calculating the composition effect. In the context of Figure 1 this is like calculating the technique effect from the difference between lines 2 and 3 instead of between lines 1 and 4. In most cases, the technique share of the cleanup is even larger when measured directly, suggesting that if anything, the prior literature that explained the technique effect as a residual understated its role. The cleanup of US manufacturing is almost entirely explained by declines in pollution intensity among individual 6-digit industries, not by changes in the relative shares of those industries.

One other notable feature of Tables 2 and 3 is that for each pollutant, the Laspeyres index declined slightly less than the Paasche index, suggesting a smaller decline in pollution intensity. That means that over these periods, pollution intensities declined the most in US manufacturing industries that grew as a share of total output. The distinction is small, but it runs counter to conventional wisdom. On average US manufacturing industries that cleaned up the most did not shrink as a share of the whole sector, they grew.

[10] For example, NAICS code 334413, "Semiconductor and Related Device Manufacturing."

Robustness Checks

Table 4 recalculates the indexes by converting the 2008 NEI data to an SIC-code basis, rather than converting 1990 NEI to a NAICS-code basis. The results are largely the same, differing by a percentage point at most.

Table 5 recalculates the pollution intensities (the z_i's) as pollution per dollar of value added rather than value shipped. There are some slight differences: for some pollutants the technique effect appears larger using value added; for others the technique effect is slightly smaller. But the overall conclusion remains, that technique accounts for 90 percent or more of the cleanup of US manufacturing.

Conclusions

This simple exercise demonstrates a remarkable change over the past two decades. Air pollution emitted by US manufacturers has fallen by two-thirds, and that cleanup has almost entirely come from reductions in emissions intensity of each of the more than 400 industries that comprise the manufacturing sector rather than from shifts in the shares of those industries in overall manufacturing output – from technique rather than composition.

Although simple, the result is newsworthy for two reasons. First, it supports past research that came to the same conclusion via different methods. Prior studies have held emissions intensities constant, predicted pollution changes due to composition changes, and attributed the remainder to technique. Here I hold industry composition constant and predict pollution changes due to technique directly. As a consequence, the finding here is not subject to the same concerns, that the residual labeled "technique" may be a function of unaccounted interactions or peculiarities of the base-year emissions intensities.

Second, the finding runs counter to perceptions about the effects of environmental cleanup on US manufacturing. While I don't assess the cause of that cleanup here, one natural speculation would be that it has resulted from environmental regulations. If so, those regulations have not worked by reducing the share of polluting industries in the US manufacturing sector – driving those industries overseas or reducing consumption of those industries' products. Instead, they have worked by reducing the emissions intensities on an industry-by-industry basis. That finding should be welcomed by anybody concerned that US regulations might appear to be succeeding, but only by reducing the menu of products available to American consumers or by shifting pollution from the US to other countries. The results here directly refute that concern.

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Table 1. Pollution and Output from US Manufacturing

	1990	2008	Percent change	Change in pollution per dollar of shipments
	(1)	(2)	(3)	(4)
Manufacturing value shipped (billion $2008)	$4,076	$5,491	+34.7%	
Pollution (1000 tons)				
Sulfur dioxide (SO2)	3,541	1,235	−65%	−74%
Carbon monoxide (CO)	5,292	1,829	−65%	−74%
Nitrogen oxides (NOx)	1,914	928	−52%	−64%
Particulates (PM10)	998	363	−64%	−73%
Fine Particles (PM2.5)	570	276	−52%	−64%
Volatile organic compounds (VOCs)	2,094	656	−69%	−77%

Source: NBER-CES Manufacturing Industry Database www.nber.org/nberces. EPA National Emissions Inventory

Table 2. Indexes of Pollution per Dollar Shipped. 1990-2008

Pollutant	**Laspeyres**	**Paasche**
	(1)	(2)
Sulfur dioxide (SO2)	0.317	0.286
Carbon monoxide (CO)	0.306	0.279
Nitrogen oxides (NOx)	0.422	0.380
Particulates (PM10)	0.314	0.295
Fine Particles (PM2.5)	0.417	0.389
Volatile organic compounds (VOCs)	0.268	0.219

Table 3. Share of Cleanup from Technique. 1990-2008

		Direct Effect				
		Laspeyres		**Paasche**		**Indirect**
Pollutant	Cleanup of Manufacturing [From Table 1 Col. (4)]	Technique [From Table 2]	Technique share	Technique [From Table 2]	Technique share	Technique Share
	(1)	**(2)**	**(3)** [(2)/(1)]	**(4)**	**(5)** [(4)/(1)]	**(6)**
SO2	–0.74	–0.683	92%	–0.721	96%	88%
CO	–0.74	–0.694	93%	–0.620	97%	89%
NOx	–0.64	–0.578	90%	–0.705	97%	93%
PM10	–0.73	–0.686	94%	–0.611	97%	89%
PM2.5	–0.64	–0.583	91%	–0.714	95%	89%
VOCs	–0.77	–0.732	95%	–0.781	102%	110%

Table 4. SIC-based Indexes. 1990-2008

	Laspeyres		**Paasche**	
Pollutant	Technique	Technique share	Technique	Technique share
	(1)	(2)	(3)	(4)
SO2	–0.680	92%	–0.715	97%
CO	–0.692	93%	–0.720	97%
NOx	–0.578	90%	–0.620	97%
PM10	–0.684	94%	–0.706	97%
PM2.5	–0.580	91%	–0.613	96%
VOCs	–0.734	96%	–0.785	102%

Table 5. By Value Added rather than Value Shipped. 1990-2008

	Laspeyres		**Paasche**	
Pollutant	Technique	Technique share	Technique	Technique share
	(1)	(2)	(3)	(4)
SO2	–0.715	97%	–0.740	100%
CO	–0.667	90%	–0.699	94%
NOx	–0.584	91%	–0.616	96%
PM10	–0.644	88%	–0.657	90%
PM2.5	–0.520	81%	–0.538	84%
VOCs	–0.709	92%	–0.746	97%

Figure 1. US Manufacturing Output and Sulfur Dioxide