Efficiency, Production, and Resource Consumption

A Historical Analysis of Ten Activities

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Abstract

This work explores the historical effectiveness of efficiency improvements in reducing mankind's impact on the earth. Ten activities are analyzed, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and refrigeration. The data and analyses presented here show that historically, over long time periods, improvements in efficiency have not succeeded in outpacing increases in production. The result has been sizeable increases in energy-related resource consumption for all ten sectors. However, there do exist a few examples of shorter, decade-long time periods in which efficiency improvements were able to outpace production increases. In these cases, during times of relatively small increases in production, efficiency mandates, price pressures, and industry upheaval led to periods of reduced resource consumption. These cases suggest that with appropriate incentives, including, for example, efficiency mandates and price mechanisms, future resource consumption, and its associated environmental effects, could be controlled and even reduced.

Keywords: efficiency, production, resource consumption, *IPAT* identity, rebound effect

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Introduction

Efficiency improvements are often touted as effective and unobtrusive means of reducing mankind's impact on the earth. For many, and perhaps in particular for engineers, the idea that reductions in environmental impact can be achieved through technology-based solutions is especially attractive. As such, improving efficiency is often mentioned as a critical component of design for environment (DfE) or green engineering approaches (Graedel and Allenby 1998, Anastas and Zimmerman 2003). Such efficiency improvements have also frequently been embraced as "win-wins", in that they allow for both economic and environmental progress to occur (DeSimone and Popoff 1997, OECD 1998, WBCSD 2000).

Although improving efficiency may appear to be a promising approach to reducing environmental impact, it is important to point out that such improvements have been taking place for centuries. While these improvements have clearly helped to drive economic and social progress, where have they led us with regards to the environment? Perhaps more importantly, what do past efficiency improvements say about efficiency as a means of reducing environmental impact in the future? This paper addresses these very questions, and makes recommendations about the use of efficiency improvements as a means of reducing mankind's impact.

The IPAT Identity

One way to examine the relationship between efficiency improvements and environmental impact is to use the *IPAT* identity. This identity, first developed in the 1970s, is commonly used to help isolate and quantify the multiple factors that contribute to mankind's impact on the earth. The *IPAT* identity disaggregates impact (I) into the product of population (P), affluence (A), and technology (T). It can be written as

$$Impact = Population \; x \; \frac{Production}{Population} \; x \; \frac{Impact}{Production} \quad , \tag{1}$$

where affluence is represented as production over population and technology is represented as impact over production. While this disaggregation allows one to focus on individual aspects of sustainability, it is important to note that these terms are not independent (Ehrlich and Holdren 1972).

In discussing the role of efficiency improvements in modifying mankind's impact on the earth, the technology term in (1) is of particular interest. This technology term represents environmental intensity, the inverse of which is environmental efficiency, and can be written as

$$Technology = \frac{Impact}{Production} = \frac{1}{Efficiency} \quad . \tag{2}$$

The efficiency term shown in (2) is in fact an eco-efficiency, a ratio of economic value to environmental load (Ehrenfeld 2005).[1] The quantification of economic value and environmental load can range greatly, from dollar figures to production quantities in the case of economic value, and from amounts of resources consumed to amounts of emissions outputted in the case of environmental load.[2]

It is clear from (2) that those who tout efficiency improvements as a means of reducing environmental impact are in fact advocating improving the technology term in the *IPAT* identity. Graedel and Allenby affirm this focus on efficiency improvements, commenting that the technology term, "…appears to offer the greatest hope for a transition to sustainable development, especially in the short term, and it is modifying this term that is among the central tenets of industrial ecology." (Graedel and Allenby 2003).

While many variants on the *IPAT* identity exist, the variant used in this paper combines population and affluence into a single term that represents total production. Thus, (1) simplifies to

$$Impact = Production \ x \ \frac{Impact}{Production} \quad , \tag{3}$$

or, using (2),

$$Impact = Production \ x \ \frac{1}{Efficiency} \quad . \tag{4}$$

From (4) it is clear that in order for efficiency improvements to successfully reduce impact, the rate of improvement in efficiency must exceed the rate of increase in production. At the same time, in order to maintain economic growth, the rate of change in production must be positive. Thus, in order for this "win-win" scenario to occur, the inequality

$$\frac{\Delta e}{e} > \frac{\Delta P}{P} > 0 \,, \tag{5}$$

where e represents efficiency and P now represents production, must be true.[3]

Historical Trends in Efficiency and Production

Historical efficiency and production data were compiled to examine if past improvements in efficiency have been able to outpace past increases in production. If this had indeed been the case, (5) would have been satisfied, and reductions in impact would have occurred. The data presented here covers ten activities, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and refrigeration.

For each of the activities analyzed, production is measured in units produced, while efficiency is measured in units produced per unit of energy-related resource consumed. Thus, given (4), impact is measured in terms of energy-related resource consumption, and has units ranging from liters, in the case of fuel consumption, to kWh, in the case of electricity consumption. While this measure of impact could be converted into emissions, such as the mass of carbon dioxide emitted, and further converted into environmental effects, such as global warming potential, it is instead, for simplicity, left in units of energy-related resource consumption.

It should be noted that for each of the ten activities analyzed, the boundaries of the analysis can be quite varied. Geographically, some activities are analyzed from a global perspective, while others include only US data. In general, activities lacking geographic limits, such as pig iron production, which can take place anywhere in the world, global data was used. For activities with geographic limits, such as motor vehicle travel, US data was used. Perhaps the larger difference in analyses stems from the system boundaries established for each activity. For some activities, such as for aluminum production, the boundary is drawn at the process-level. Such analyses generally consider technological improvements to a single process. For other activities analyzed here, including freight rail travel, the boundary is drawn at the industry-level. Thus, these industry-level analyses include a broader range of innovations, from multiple process improvements to operational changes. It will be shown that despite the varied boundaries in the analyses presented here, the overall patterns in efficiency, production, and resource consumption are pervasive.

Figure 1 plots worldwide production of pig iron, measured as the mass of pig iron produced, and efficiency, measured as the mass of pig iron produced per unit of energy consumed in smelting.[4] Figure 2 plots worldwide aluminum production, measured as the mass of aluminum produced, and efficiency, measured as the mass of aluminum produced per unit of electricity consumed in the Hall-Heroult process.[5] Figure 3 plots worldwide nitrogen fertilizer production, measured as the mass of nitrogen produced, and efficiency, measured as the mass of nitrogen produced per unit of energy consumed in the Haber-Bosch process.[6] The data plotted in Figures 1 through 3 show almost continuous increases in both efficiency and production.

Figures 4, 5, and 6 show efficiency and production data for electricity generation from coal, oil, and natural gas in the US. These figures plot US production of electricity, measured in units of electricity produced, and efficiency, measured in units of electricity produced per mass or volume of fossil fuel consumed. In each of these three figures, despite significant disturbances in both efficiency and production, the general trends show both efficiency and production increasing over time.[7, 8, 9]

Figures 7 through 10 plot efficiency and production data for freight rail travel, passenger air travel, motor vehicle travel, and refrigeration. These cases differ from those presented in Figures 1 through 6 in that while the previous examples showed efficiency during the production phase, the data presented here shows efficiency during the use phase.[10]

Figure 7 plots the efficiency and production of freight rail travel by US Class I railroads.[11] Production is measured in revenue tonne-kilometers of freight rail travel, while efficiency is measured in revenue tonne-kilometers of freight rail travel per volume of fuel consumed.[12] Figure 8 plots the efficiency and production of passenger air travel by US airlines. Production is measured in available seat kilometers of passenger air travel, while efficiency is measured in available seat kilometers of passenger air travel produced per volume of fuel consumed.[13] As in Figures 1 through 6, Figures 7 and 8 again show efficiency and production increasing in parallel.

Figure 9 shows efficiency and production data for motor vehicle travel in the US.[14] Production is measured in vehicle-kilometers of motor vehicle travel produced, while efficiency is measured in vehicle-kilometers of motor vehicle travel produced per volume of fuel consumed.[15] Figure 10 shows production and efficiency data for residential refrigeration in the US.[16] Production is measured in hours of refrigeration produced, while efficiency is measured in hours of refrigeration produced per unit of electricity consumed. Figures 9 and 10 both show an earlier period of declining efficiency, followed by a more recent period of improving efficiency.[17] Throughout these changes in efficiency, production in both activities has continued to increase.

FIGURE 1: Worldwide Pig Iron Production (*P*) and the Energy Efficiency of Pig Iron Smelting (*e*) [a]

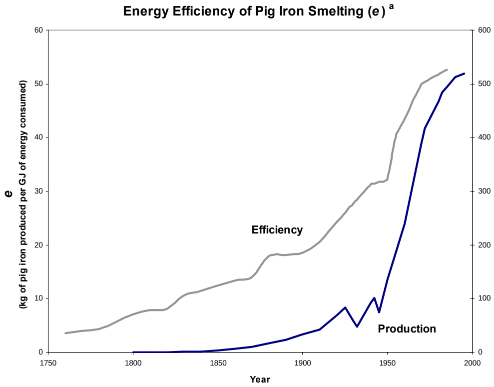


FIGURE 2: Worldwide Primary Aluminum Production (*P*) and the Energy Efficiency of the Hall-Heroult Process (*e*) [b]

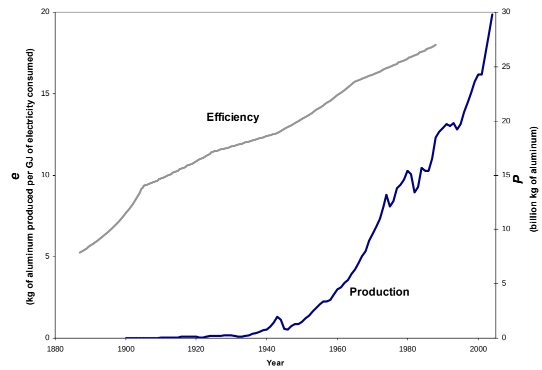


FIGURE 3: Worldwide Nitrogen Fertilizer Production (*P*) and the Energy Efficiency of the Haber-Bosch Process (*e*) [c]

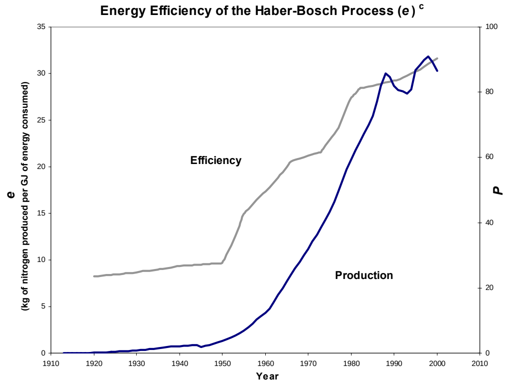


FIGURE 4: Electricity Generation from Coal (*P*) and the Efficiency of Electricity Generation from Coal (*e*) (US data) [d]

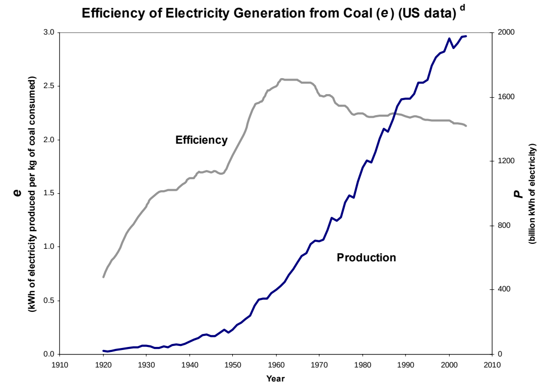


FIGURE 5: Electricity Generation from Oil (*P*) and the Efficiency of Electricity Generation from Oil (*e*) (US data) [d]

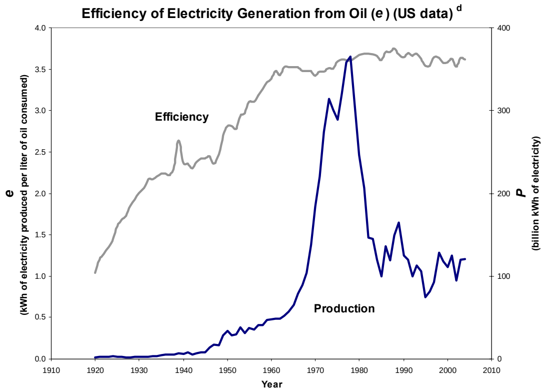


FIGURE 6: Electricity Generation from Natural Gas (*P*) and the Efficiency of Electricity Generation from Natural Gas (*e*) (US data) [d]

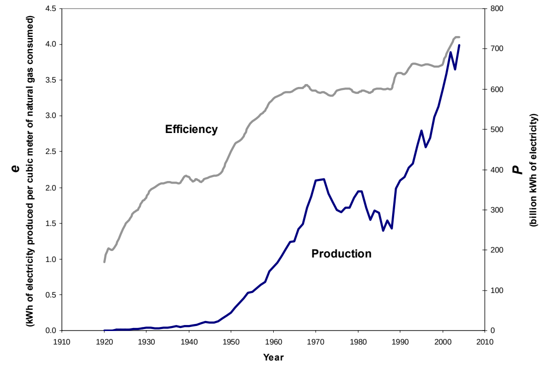


FIGURE 7: Freight Rail Travel (*P*) and the Energy Efficiency of Freight Rail Travel (*e*) (US Class I railroads) [e]

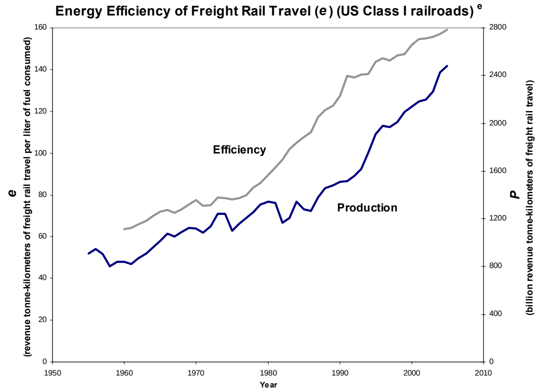


FIGURE 8: Passenger Air Travel (*P*) and the Energy Efficiency of Passenger Air Travel (*e*) (US airlines) [f]

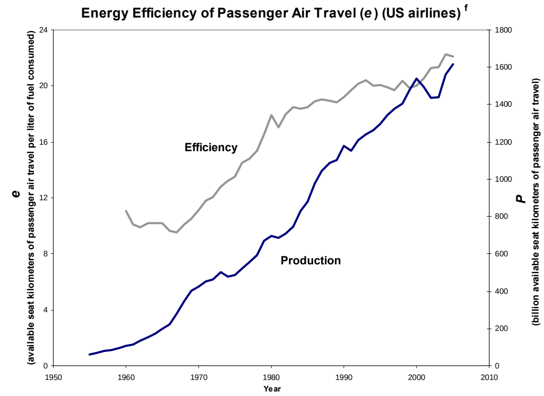


FIGURE 9: Motor Vehicle Travel Produced (*P*) and the Efficiency of Motor Vehicle Travel (*e*) (US data) [g]

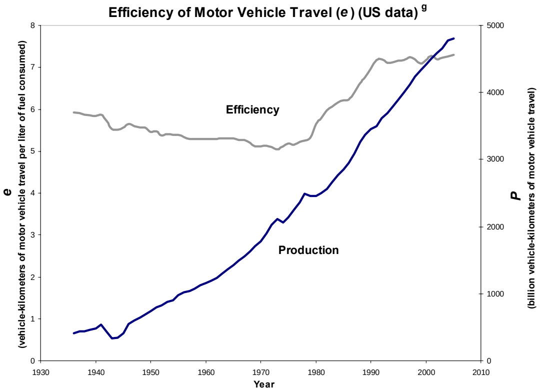


FIGURE 10: Refrigeration Produced (*P*) and the Efficiency of Refrigerators (*e*) (US data) [h]

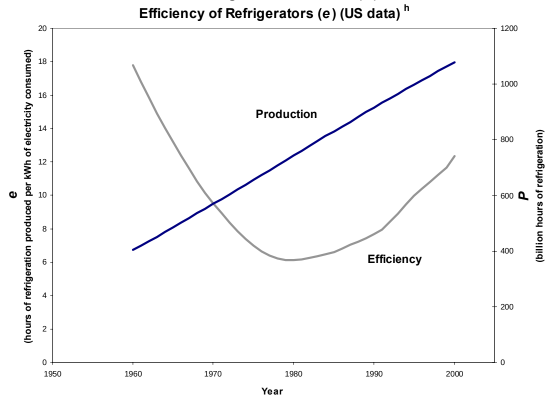


Table 1 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in production, $\Delta P/P$, for the ten activities analyzed in Figures 1 through 10. Positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in production indicate production increases. The historical data clearly show that in each of these industries, the average annual $\Delta P/P$ exceeded the average annual $\Delta e/e$, meaning that, on average, (5) was not satisfied. Thus, despite significant improvements in efficiency, the impact of each of these activities, as calculated using (4), has increased. Figures in Appendix A clearly show this overall increase in impact over the time periods analyzed here.

Activity	Time Period	Average Annual *Δe/e*	Average Annual *ΔP/P*	Average *ΔP/P* / Average *Δe/e*
Pig Iron	1800-1984	1.1%	4.1%	3.7
Aluminum	1900-1987	1.0%	11.1%	11.4
Nitrogen Fertilizer	1915-2000	0.9%	9.6%	10.2
Electricity				
from Coal	1920-2005	1.3%	5.8%	4.5
from Oil	1920-2005	1.5%	6.9%	4.5
from Natural Gas	1920-2005	1.8%	9.6%	5.4
Freight Rail Travel	1960-2005	2.0%	2.5%	1.2
Passenger Air Travel	1960-2005	1.3%	6.5%	4.9
Motor Vehicle Travel	1936-2005	0.3%	3.9%	13.0
Refrigeration	1960-2000	-0.9%	2.5%	---

Table 1: Average annual *Δe/e*, average annual *ΔP/P*, and the ratio of the two for ten activities over different time periods. In these activities, increases in production outpace improvements in efficiency by factors ranging from 1.2 to 13.0.

The values in Table 1 can also be shown graphically by plotting the average annual change in production versus the average annual change in efficiency, as shown in Figure 11. The solid diagonal line in Figure 11 is the line of constant impact, representing the condition in which the average annual *Δe/e* is equal to the average annual *ΔP/P*. Points above this line represent periods of increasing impact, where (5) is not satisfied, while points below this line represent periods of decreasing impact, where (5) is satisfied. From Figure 11, it is clear that in each of the ten cases examined above, (5) is not satisfied.

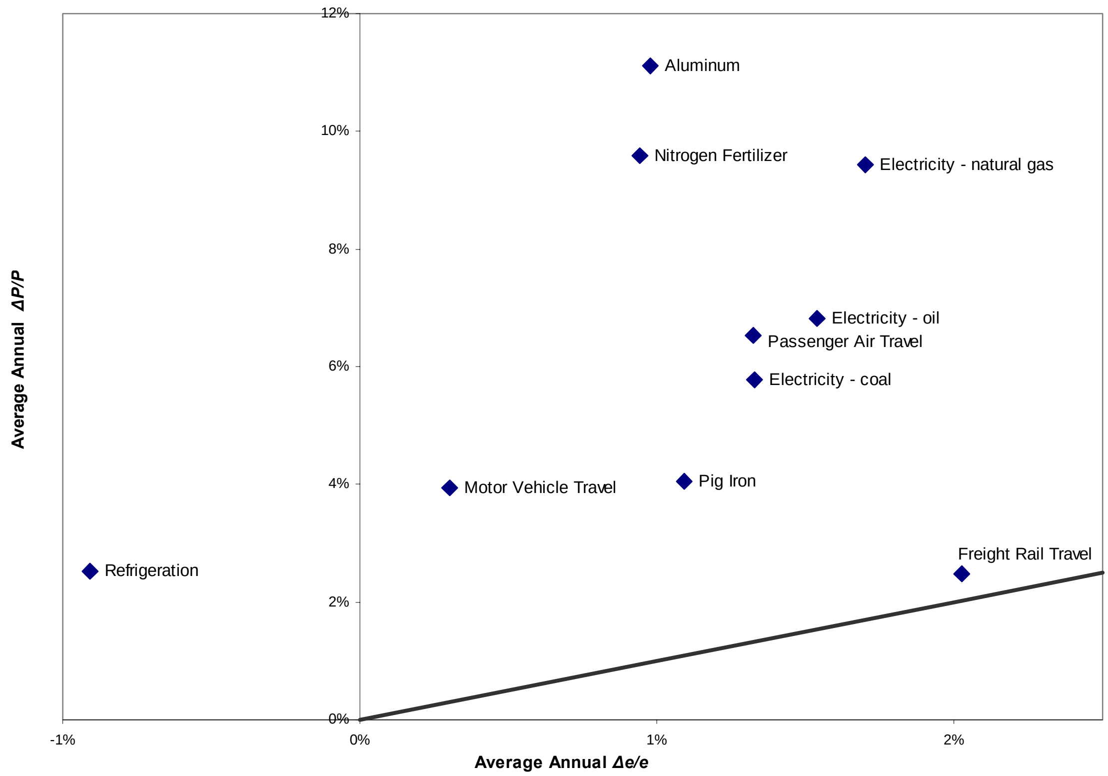


Figure 11: Average annual $\Delta P/P$ versus average annual $\Delta e/e$ for ten activities.

The fact that improvements in efficiency have not been able to outpace increases in production over the long term is perhaps not surprising, particularly given mankind's increasing impact on the earth. However, this inability of past efficiency improvements to reduce impact does bring into question the effectiveness of efficiency improvements as a means of reducing impact in the future.

Decade-by-Decade Analysis

While the long time periods presented above may appear to show little hope for efficiency improvements, a decade-by-decade analysis of these activities reveals a few time periods in which improvements in efficiency did outpace increases in production, resulting in periods of decreasing impact. Two such examples occur in the cases of freight rail travel and passenger air travel. Table 2 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in production, $\Delta P/P$, for freight rail travel and passenger air travel, both overall and on a decade-by-decade basis. As before, positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in production indicate production increases.

Activity	Time Period	Average Annual *Δe/e*	Average Annual *ΔP/P*
Freight Rail Travel	1960-2000	2.0%	2.5%
	1960-1969	1.7%	3.0%
	1970-1979	1.3%	1.8%
	1980-1989	3.7%	1.4%
	1990-1999	1.9%	3.6%
	2000-2005	1.2%	2.9%
Passenger Air Travel	1960-2005	1.3%	6.5%
	1960-1969	-1.6%	15.6%
	1970-1979	4.7%	5.3%
	1980-1989	1.4%	5.2%
	1990-1999	0.6%	3.0%
	2000-2005	1.8%	1.6%

Table 2: Average annual *Δe/e* and average annual *ΔP/P* for freight rail travel and passenger air travel over different decades. The time periods in which average annual *Δe/e* outpaced average annual *ΔP/P* are highlighted.

Figures 12 and 13 provide graphical displays of the data in Table 2. As in Figure 11, the dark diagonal lines in Figures 12 and 13 represent lines of constant impact, where the average annual *Δe/e* is equal to the average annual *ΔP/P*. Points above this line represent periods of increasing impact, where (5) is not satisfied, while points below this line represent periods of decreasing impact, where (5) is satisfied.

FIGURE 12: Average Annual ΔP/P versus Average Annual Δe/e for Freight Rail Travel (US Class I railroads)[e]

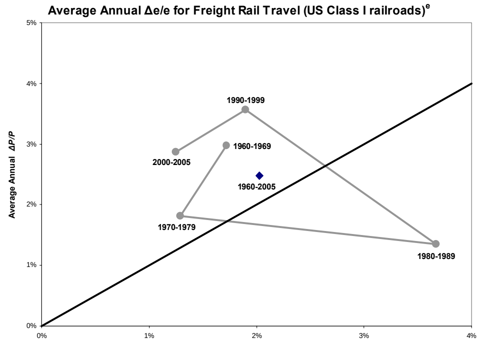
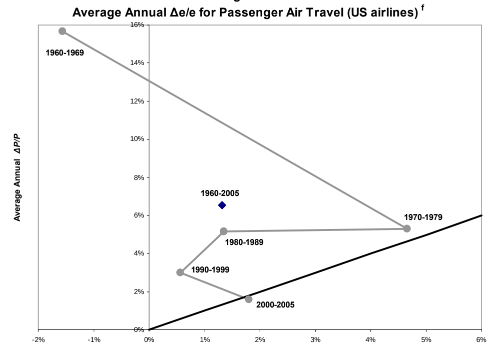


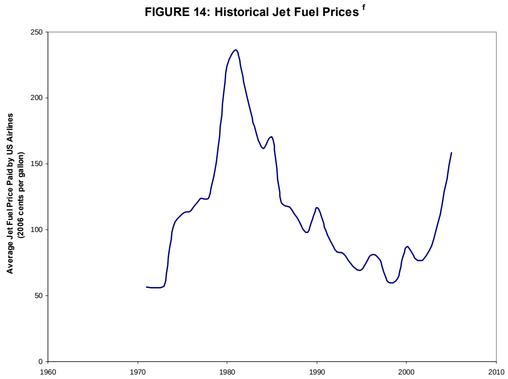
FIGURE 13: Average Annual ΔP/P versus Average Annual Δe/e for Passenger Air Travel (US airlines)[f]



As can be seen in Table 2 and in Figures 12 and 13, both freight rail travel and passenger air travel did have periods in which improvements in efficiency outpaced increases in production. In the case of US freight rail travel, the 1980s marked the only period in which (5) was satisfied. This period featured relatively slower growth in production, and relatively faster improvements in efficiency. In general, the 1980s marked a renaissance in US freight rail travel, as the financial health of the industry improved considerably (Pauly et al. 1980, Duke et al. 1992, Braeutigam 1993). This industry revitalization was driven by various factors, the most important of which was government legislation that deregulated the rail industry. In particular, the Staggers Rail Act of 1980, which, among other things, gave rail companies the freedom to set their own rates and to shut down unprofitable rail lines, helped the rail industry to both increase revenue and reduce costs (Duke et al. 1992, Braeutigam 1993).[18] These actions also had important impacts on fuel efficiency, as fewer lines, now carrying more freight, proved to be more efficient (Business Week 1984, Flint 1986).[19]

In the case of passenger air travel by US airlines, a shorter, more-recent time period, namely 2000-2005, featured average annual $\Delta e/e$ values that exceeded average annual $\Delta P/P$ values. This period of declining impact can be attributed to both increased improvement in efficiency and decreased growth in production. In the case of efficiency, the increase in average annual improvement was driven in large part by increasing jet fuel prices, as seen in Figure 14. In an industry where fuel costs can at times represent over a quarter of operating costs, increases in jet fuel prices often lead to both operational changes, which improve efficiency in the short-term, and technological changes, which improve efficiency in the long-term (ATA 2007).[20] In the case of production, the decrease in average annual growth was due to a two to three year decline in passenger air travel, as seen in Figure 8, which was driven by numerous factors, including the economic slowdown in the early 2000s, the events of September 11th, 2001, the start of military action in Iraq, and the outbreak of severe acute respiratory syndrome (SARS) in Asia. This decrease in average annual production growth also followed a general trend of declining growth, as seen in Table 2. Whether or not this recent reduction in impact for passenger air travel will continue throughout the rest of this decade, remains to be seen.

FIGURE 14: Historical Jet Fuel Prices [f]



It is also interesting to note the time period from 1970 to 1979, during which the average annual *Δe/e* values for passenger air travel nearly exceeded the average annual *ΔP/P* values, as seen in Figure 13. Although (5) was not satisfied, this was a period of relatively stable impact in the industry, as measured by the volume of fuel consumed. This period was marked by both a slower rate of production growth and an increased rate of efficiency improvement, as compared to the previous decade. This increase in the rate of efficiency improvement was again driven in large part by increasing jet fuel prices (Morrison 1984). Although there are of course other influences on fuel efficiency besides fuel prices, in the case of passenger air travel, the two periods of increased efficiency improvement, namely the 1970s and the early 2000s, directly correspond to the two time periods in which real jet fuel prices were increasing.

Another case in which improvements in efficiency did outpace increases in production on a decade-by-decade basis, is refrigeration. For comparison, a related case, but one in which (5) was not met, namely motor vehicle travel, is also examined. Table 3 summarizes the average annual change in efficiency, *Δe/e*, and the average annual change in production, *ΔP/P*, for refrigeration and motor vehicle travel, both overall and on a decade-by-decade basis.

Activity	Time Period	Average Annual *Δe/e*	Average Annual *ΔP/P*
Refrigeration	1960-2000	-0.9%	2.5%
	1960-1969	-5.9%	3.6%
	1970-1979	-4.9%	2.8%
	1980-1989	1.9%	2.2%
	1990-1999	4.6%	1.7%
Motor Vehicle Travel	1936-2005	0.3%	3.9%
	1940-1949	-0.5%	5.3%
	1950-1959	-0.5%	5.2%
	1960-1969	-0.3%	4.3%
	1970-1979	0.4%	3.8%
	1980-1989	2.4%	3.2%
	1990-1999	0.5%	2.5%
	2000-2005	0.5%	1.8%

Table 3: Average annual *Δe/e* and average annual *ΔP/P* for refrigeration and motor vehicle travel over different decades. The time period in which average annual *Δe/e* outpaced average annual *ΔP/P* is highlighted.

Figures 15 and 16 provide a graphical display of the data in Table 3. The dark diagonal lines in these figures again represent lines of constant impact, where the average annual *Δe/e* is equal to the average annual *ΔP/P*.

FIGURE 15: Average Annual *ΔP/P* versus Average Annual *Δe/e* for Refrigeration (US data) [h]

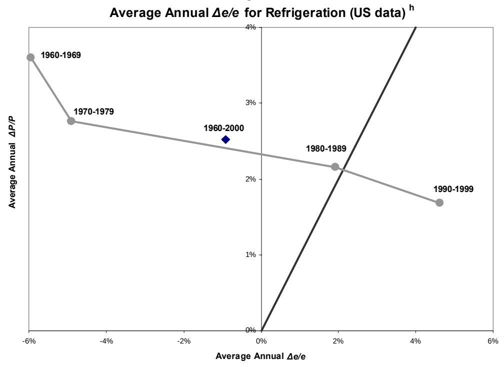
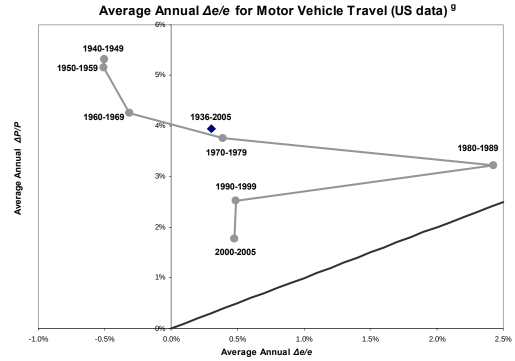


FIGURE 16: Average Annual *ΔP/P* versus Average Annual *Δe/e* for Motor Vehicle Travel (US data) [g]



From Figure 15, it is clear that residential refrigeration in the US did succeed in crossing below the line of constant impact. The efficiency trends show that prior to the 1980s, refrigerator efficiency decreased.[21] However, after this period, efficiency improved considerably, driven primarily by a series of state and federal efficiency mandates on appliances.[22] Throughout these periods of changing efficiency, production of refrigeration hours increased, albeit at a progressively slower rate, as both the number of American households and the hours of refrigeration used per household increased.[23]

Unlike in the case of refrigeration, motor vehicle travel in the US has never crossed below the line of constant impact, meaning that (5) has never been satisfied. The efficiency data shows an extended period of declining efficiency from the 1940s through the 1960s, as motor vehicles became larger and more powerful.[24] In the 1970s, consumer concerns about gasoline supplies, along with government legislation in the form of Corporate Average Fuel Economy (CAFE) standards, marked the beginning of an extended period of improving efficiency.[25] In the 1980s, when the average annual efficiency improvement peaked, motor vehicle travel did move closer to the line of constant impact, as shown in Figure 16. However, more recently, consumer demand and the lack of updated legislation have allowed the average annual efficiency improvements to decline considerably in magnitude.[26] Meanwhile, throughout these periods of changing efficiency, the number of vehicle-miles of motor vehicle travel produced has increased considerably, as both the number of motor vehicles and the miles traveled per motor vehicle have increased. As in the cases of passenger air travel and refrigeration, the rate of increase in vehicle-miles produced has decreased in each decade, which, if the trend continues, could possibly make future impact stabilization or reduction easier to achieve.

These decade-by-decade analyses show that in the cases of freight rail travel, passenger air travel, and refrigeration, there did exist periods in which efficiency improvements successfully outpaced production increases, meaning that (5) was satisfied and a reduction in impact occurred. However, it is important to point out that in each of the three cases, the production increases were at their lowest level of any of the decades observed, while the efficiency improvements were at their highest or second highest observed. Looking forward, it is critical to understand the circumstances that enabled efficiency improvements to outpace production increases in these three cases. If these conditions can be identified and recreated, there exists the possibility that future efficiency improvements could also lead to successful reductions in impact.

Behind Changes in Efficiency and Production

Before examining the circumstances behind these cases in greater detail, the means by which changes in efficiency and production come about, will first be explored. Understanding how these changes are realized helps to explain the complexity of actually satisfying (5).

Efficiency

Improvements in efficiency can be attributed to a number of different factors, from technological innovations to learning effects to market effects.

Technological Innovation

Technological innovation is frequently behind both evolutionary and revolutionary improvements in performance. Often, such performance improvements, when plotted over time, are said to follow an S-shaped technology curve (Ulrich and Eppinger 2000). Such curves typically show limited performance improvement at the start of a new technology, as companies and industries first become aware of an innovation and begin working on it (Otto and Wood 2001). As the technology becomes more widely disseminated and more resources are applied to the problem, a period of rapid improvement ensues (Ibid.). Finally, there is a plateau in performance, as technologies mature and reach their practical and/or thermodynamic limits (Ibid.). In the mature region of the S-curve, further efficiency improvements can sometimes occur by switching to a new technology, which corresponds to jumping to a new S-curve (Foster 1986, Grübler 1998).

For example, consider the case of nitrogen fertilizer production. The invention of the Haber-Bosch process for ammonia synthesis, developed and commercialized in the early 1900s, represented a revolution in nitrogen production, and a jump to a new S-curve.[27] While other industrial methods of nitrogen production did already exist, the Haber-Bosch process was significantly more energy efficient (Tamaru 1991). By the mid-1920s, it had become the most common means of producing nitrogen (Smil 2001).

Following its invention, efficiency improvements in the Haber-Bosch process have roughly followed an S-shaped technology curve, as can be seen in Figure 3. These efficiency improvements have been realized through a broad range of technological innovations, including the use of natural gas instead of coal as a feedstock, the design of improved reactors, the recovery of waste heat, the use of centrifugal compressors instead of reciprocating compressors, and the development of improved catalysts, among others (Dybkjaer 1995, Smil 1999, Smil 2001). As the Haber-Bosch process nears its 100th anniversary, efficiency improvements may be reaching a plateau. Such leveling would not be surprising, as the process is nearing its stoichiometric efficiency limit of 39.4 kg of nitrogen produced per GJ of energy consumed (Smil 2001).

Learning Effect

Efficiency improvements can also come about through improvements in the application of existing technologies. This type of efficiency improvement can be attributed to learning and/or experience, and is often referred to as “learning by doing” or “learning by using” (Grübler 1998, Ruttan 2001). Learning is typically said to occur when the unit cost of production decreases as cumulative experience, often measured as cumulative output, increases (Argote and Epple 1990). Originally identified in the aircraft industry, learning effects have been seen in many different activities, from shipbuilding to power plant construction (Searle 1945, Joskow and Rose 1985). The improvements in efficiency resulting from learning can be quite impressive. For example, in the case of Liberty ships built for the US and its allies for use in World War II, between December 1941, the delivery date of the first Liberty ship, and December 1942, the average number of man-hours per ship decreased 45% and the average days per ship decreased 76% (Searle 1945). Overall, across ten different shipyards, the average number of labor hours required to build a Liberty ship decreased by around 20% for each doubling of output (Ibid.).

In the case of learning effects, production drives efficiency. Thus, while (5) shows that in order to reduce impact, the rate of efficiency improvements must exceed the rate of production increases, the existence of learning effects means that these two measures are often in fact positively correlated.

Market Effect

While longer-term efficiency improvements are largely driven by technological innovation and learning effects, shorter-term efficiency changes can come about through market dynamics, such as through dips or surges in demand. In some cases, short-term efforts to scale-back production, can lead to an improvement in efficiency, as operations are streamlined and less-efficient equipment is shelved. Conversely, short-term efforts to scale-up production, can lead to a decline in efficiency, as all available equipment, including less-efficient equipment, is brought into use. In general, this negative correlation between production and efficiency appears to be brought about by dynamic markets, and is most commonly seen in industries with high capital costs and/or long lead-times for capital equipment.

As an example, consider the case of passenger air travel in the early 2000s. With the precipitous decline in passenger air travel during this time, airlines, facing a surplus of capacity, scaled-back operations by removing excess aircraft from service (Perez et al. 2003, Setaishi 2003, Wong 2003). In general, the planes that were the most costly to operate, which often corresponded to the planes that were the least fuel efficient, were parked, thereby increasing overall fuel efficiency in the short-term.[28] Thus, in this situation, sharp decreases in production drove short-term efficiency gains, as airlines adapted to changing market conditions (McCartney and Carey 2003).

While in the recent case of passenger air travel, efficiency improved as production decreased, the opposite can also occur. Consider the case of freight rail travel in the late 1980s and early 1990s, a period marked by increases in the production of revenue tonne-kilometers of freight rail travel. This increase in production led to an increase in demand for locomotives, which was in turn met by increasing the production of new, more-efficient locomotives, as well as by increasing the repair and refurbishment of older, less-efficient locomotives, some of which had previously been idled (Holusha 1989, Kruglinski 1993). Thus, this surge in production pushed older, less-efficient machines back into use, contributing to a decrease in average annual efficiency gains.

Over longer time periods, more new locomotives were brought into use to meet the surging demand. However, in the short term, production and efficiency were negatively correlated.

Production

Much like changes in efficiency, changes in production can also be attributed to many different factors, including consumers, consumer demand, and efficiency.

Consumers and Consumer Demand

It is clear that consumers have a large impact on production. As the population of consumers increases, and/or as the affluence of consumers increases, production typically increases to meet this surging demand.[29] In fact, in this work, production is defined as the product of population and affluence, where affluence is represented as production over population. Using this definition, it is not surprising that increases in population and affluence have, over time, driven increases in production.

Changing consumer taste can also play an important role in production. For example, in the case of passenger air travel, the number of available seat kilometers produced has been affected by changes in consumer preferences, as consumers have increasingly chosen air travel over other transportation options, including bus, train, and boat travel. Of course, these changing consumer attitudes have themselves been driven by various factors, including technological innovations that have led to improvements in the safety, cost, and convenience of air travel. Had air travel not improved, it is likely that consumer preferences, and production increases to keep pace with consumer preferences, would not have changed as dramatically.[30]

Rebound Effect

Another mechanism by which efficiency drives production is through the rebound effect. As early as 1865, W. Stanley Jevons observed that improvements in efficiency can in fact lead to increases in production. Observing coal mining in the United Kingdom, Jevons wrote,

> "It is wholly a confusion of ideas to suppose that the economical use of a fuel is equivalent to a diminished consumption. The very contrary is the truth." (Jevons 1865).

This idea, alternately known as "Jevons' Paradox," the "rebound effect," and the "take back effect," has been the subject of much debate in the economics and energy policy literature (Herring 1998, Hertwich 2005, Herring 2006). At its root however, is the idea that efficiency improvements lead to a decrease in the effective price of a good or service. This price reduction, given a sufficient price elasticity of demand, leads to increased demand.

The mechanisms behind the rebound effect can be explained at both the microeconomic and macroeconomic level. At the microeconomic level, the decrease in the effective price of a good or service resulting from an improvement in efficiency leads to both a substitution effect and an income effect. In the case of the substitution effect, in which the level of utility remains constant, more of the now less-expensive good or service is consumed instead of other goods and services (Pindyck and Rubinfeld 2001, Lovell 2004). In the case of the income effect, in which the level of utility increases, more of all goods and services are consumed, reflecting an increase in real purchasing power (Ibid.). In both cases, exactly how much more is consumed depends on the price elasticity of demand for these goods and services. While the substitution effect always leads to greater consumption, the income effect can lead to either an increase or a decrease in consumption, depending on the type of good.[31] In most cases however, there is an overall increase in consumption, as the substitution effect is typically larger in magnitude than the income effect (Pindyck and Rubinfeld 2001). At the macroeconomic level, efficiency improvements lead to broader effects, including economy-wide changes in the price of other goods and services and factor substitution in economic growth (Brookes 1990, Brookes 2000, Greening et al. 2000). Efficiency improvements can in fact drive economic growth, which in turn can lead to an increase in overall production (Brooks 1990, Saunders 1992, Saunders 2000, Ayres et al. 2003, Stern 2004).

In large part, the debate about the rebound effect comes down to a debate about the size of the rebound. Some argue that the size of the rebound is insignificant, meaning that efficiency improvements of a given amount will lead to impact reductions of approximately the same amount (Lovins 1988, Grubb 1990, Grubb 1992). Others argue that the size of the rebound is sufficiently large to be of significance and that in some cases, an improvement in efficiency can in fact lead to an increase in impact (Khazzoom 1980, Khazzoom 1982, Khazzoom 1987, Khazzoom 1989, Brookes 1990, Brookes 1992). While efforts have been made to quantify the rebound effect, these measurements only take into account the microeconomic effects, also known as the direct rebound effect, not the macroeconomic or indirect rebound effects.

The size of the direct rebound effect can vary greatly, depending on the price elasticity of demand, which in turn depends on many factors, including the economic actors involved, the goods or services in question, and the length of time since the efficiency improvement. In a survey of measured direct rebound effects in the US, some categories, such as appliances or "white goods", showed essentially no rebound, while other categories, including automobile transport, showed noticeably larger rebound (Greening et al. 2000). In the case of automobile transport, the rebound effect, expressed as the percentage increase in consumption resulting from a 100% improvement in efficiency, was estimated to be between 10 and 30% (Ibid.). Research into the magnitude of the direct rebound for other goods and services has, in some cases, shown larger rebounds, particularly among lower-income populations (Milne and Boardman 2000, Roy 2000). While many of the measurements of direct rebound, including the ones mentioned above, have focused on rebound in the residential and transportation sectors, there have also been some attempts to measure rebound in industry. Estimates of direct rebound in industry resulting from improvements in energy efficiency vary, depending on country, energy prices, and measurement approach, but generally range from 0 to 25% (Berkhout et al. 2000, Greening et al. 2000, Bentzen 2004). Accurate measurements of the size of the complete rebound effect, including direct and indirect effects, are difficult given the many factors involved and the broad range of macroeconomic consequences of efficiency improvements (Greening et al. 2000, Smil 2003).

Discussion

There are clearly many factors that contribute to changes in efficiency and production. It is also clear that efficiency and production are coupled, meaning that the terms in (5) are not independent. Thus, in order to reduce impact, one cannot simply focus on a single term in (4), but must instead approach this as a system problem.

Looking at the periods of impact reduction in the cases of freight rail travel, passenger air travel, and refrigeration, it is apparent that different circumstances drove each case. For freight rail travel, the period of impact reduction in the 1980s was attributable to a major upheaval in the industry, driven by deregulation. For passenger air travel, price pressures, namely increases in jet fuel prices, led to a period of declining impact in the early 2000s. For refrigeration, government efficiency mandates led to impact reduction in the 1990s. Of these different circumstances, it appears that two of them, namely price mechanisms and efficiency mandates, are reproducible, and thus represent potential approaches for future impact reduction.

Efficiency Mandates

In attempting to use efficiency mandates to realize impact reductions, the size of the rebound effect can be critical to success. With little or no rebound, both direct and indirect, efficiency mandates can lead to a case in which (5) is satisfied. However, with more considerable rebound, efficiency mandates may, at best, lead to impact reductions that are smaller in magnitude than expected; at worst, efficiency mandates may lead to larger overall impact. In fact, efficiency mandates could lead to larger impacts more quickly than without efficiency mandates.

Residential refrigeration appears to be an ideal candidate for efficiency mandates, as appliances exhibit essentially no direct rebound (Greening et al. 2000). As the efficiency of refrigerators improves, the effective price of refrigeration decreases. In response, consumers can increase their utilization of refrigerators and/or increase their ownership of refrigerators (Khazzoom 1982). However, since refrigerators typically run constantly, increasing utilization is difficult. Increasing ownership is possible through the use of additional refrigerators, but over 80% of US households still find one refrigerator to be sufficient (US DOE 2001). With low price elasticities of demand in both utilization and ownership, there is little rebound. Thus, efficiency mandates have worked very well in the case of residential refrigeration.[32]

Efficiency mandates for other goods and services with little rebound may also prove successful. For example, efficiency mandates on other appliances may lead to impact reductions, as the direct rebound on “white goods” is essentially zero (Greening et al. 2000). Motor vehicle travel, with a direct rebound effect between 10 and 30%, may also represent a case in which efficiency mandates can lead to impact reduction (Ibid.). While the existence of rebound effects may erode some of the overall impact reduction, efficiency mandates on motor vehicles may still prove to be successful. Indeed, past efficiency mandates on motor vehicles did play a role in helping to move motor vehicle travel closer to impact reduction in the 1970s and 1980s, as can be seen in Figure 16. In general, applying efficiency mandates to activities with little to no rebound seems to be a viable approach to satisfying (5), and thus reducing impact.

Price Pressures

Price pressures also appear to be a promising approach to realizing impact reductions, although the exact effect depends largely on the short-run and long-run price elasticities of demand. In the case of durable goods, which have high short-run price elasticities of demand and lower long-run price elasticities of demand, price increases can lead to sizeable decreases in demand in the short term, but a recovery in demand in the long term. For non-durable goods, which have low short-run price elasticities of demand and higher long-run elasticities of demand, price increases can lead to limited decreases in demand in the short term, and efficiency improvements in the long term. While these efficiency improvements resulting from price increases can eventually lead to increases in demand through the rebound effect, the short-term decrease in demand that price pressures induce may serve to balance out this later increase in demand. In this regard, efficiency improvements that come about through price mechanisms may have an advantage over efficiency improvements that come about through efficiency mandates.

In the case of passenger air travel, price pressures, in the form of increased jet fuel prices, did help lead to a period of impact reduction. With no real substitutes for jet fuel, passenger airlines were forced to find other means by which to compensate for rising fuel prices, from passing on higher costs to consumers through measures such as fuel surcharges, to improving fuel efficiency through measures such as reducing aircraft weight (Pindyck and Rubinfeld 2001, Sharkey 2004, Heimlich 2007). Thus, in this case, the low short-run price elasticity of demand for jet fuel did help to spur efficiency improvements in the longer term (Pindyck and Rubinfeld 2001).

Using price pressures to reduce the impact of other goods and services may also prove successful. For example, in the case of automobile travel, the price elasticity of demand for motor fuel follows that of most non-durable goods. Thus, increases in the price of motor fuel could lead to a small drop in demand in the short term, and efficiency improvements in the long term (Pindyck and Rubinfeld 2001, Krueger 2005). Interestingly, the real price of motor fuel in the US has been on the rise recently, increasing by about 66% over the five-year span from early 2001 to early 2006 (Krauss et al. 2007). However, despite this increase, there has been little change in demand for fuel, and only a slow shift towards more fuel-efficient motor vehicles (Hughes et al. 2006, Krauss et al. 2007). While these price increases have not yet decreased demand and/or spurred efficiency enough to satisfy (5), it remains to be seen whether or not these market-driven price pressures will continue in the future, and whether or not they will someday be sufficient to bring about an overall reduction in impact.

While the price pressures in the cases of airline passenger travel and motor vehicle travel came from market forces, other price pressures may need to be legislated, perhaps through taxation. Although introducing new taxes is politically difficult, it may prove to be an effective approach to reducing impact. Of course, the size of the price increase does play an important role, both in terms of political feasibility and in terms of effect. Thus, much care must be taken to apply appropriate price pressures to allow for impact reduction without hindering economic growth. For cases in which considerable price increases may be necessary, efficiency mandates may prove to be the more politically-feasible approach (Hughes et al. 2006).

Updates

In order to continue to realize impact reductions over the long term, it appears that both efficiency mandates and price pressures should be updated regularly. Without constant updating, the rate of efficiency gains will revert back to previous levels, and old dynamics may return. For example, in the case of motor vehicle travel, the failure to update past efficiency mandates, among other factors, reversed a trend towards increasing rates of efficiency improvement. Instead, the old dynamics returned, with average annual production growth outpacing average annual efficiency improvements by a sizeable margin. On the other hand, in the case of refrigeration, continually-updated efficiency mandates eventually led to impact reduction. In the case of price mechanisms, the increases in the rate of efficiency improvement in passenger air travel during periods of increasing fuel prices, and the decreases in the rate of efficiency improvement during periods of decreasing fuel prices, also seem to suggest the importance of continually applying price pressures.

Conclusion

Historically, past efficiency improvements have not proven to be successful in reducing mankind's impact on the earth. Of the over 75 decades examined across ten activities, only three decades had rates of efficiency improvement that outpaced rates of production increase. In these three cases, efficiency mandates, price pressures, and industry upheaval contributed to these periods of decreasing impact. Based upon this evidence, it does appear that efficiency mandates and price pressures, given certain conditions, may prove effective in reducing impact. However, efficiency improvements without external pressures or mandates, do not appear to lead to impact reductions.

It seems that much of the debate over the effectiveness of efficiency improvements in reducing impact comes down to a matter of system boundaries. To engineers, who generally draw their system boundaries at the level of an individual product or process, the beneficial effects of efficiency improvements on the environment seem clear. However, to economists, who generally draw their system boundaries at the level of the society or the economy as a whole, the beneficial effects of efficiency improvements on the environment is much less clear. Khazzom captures this issue of system boundaries with the succinct comment,

> "For the laboratory engineer, a 3-percent improvement in efficiency will always mean, as it should, a 3-percent reduction in energy, since the engineers's (sic) basic assumption is that the appliance will be used to derive the same amount of service as before. But this result cannot be extended mechanically from the laboratory to society. Consumers cannot be assumed to be oblivious to the economic consequences of changing efficiency." (Khazzom 1980).

As engineers, it is critical to understand how product- and process-level efficiency improvements play out in the larger system. While working on such efficiency improvements is worthwhile from an economic and social perspective, it is not necessarily worthwhile from an environmental perspective. Instead, as the many links between efficiency and production have shown, improvements in efficiency can in some cases simply lead to more production and greater impact. While engineers should continue to pursue efficiency improvements, such improvements may need to be combined with appropriate conditions or policies in order to realize impact reduction.

The true message for engineers and others who encourage efficiency-based solutions to our environmental problems, is that product- and process-level efficiency improvements, in the absence of external pressures or mandates, do not equate to system-level impact reductions. Thus, improving efficiency should not be thought of as a goal by itself. Instead, the true goal must be to reduce environmental impact.

Appendix A

Figures A1 through A10 show increasing impact for the activities shown in Figures 1 through 10.

FIGURE A1: Impact (*I*) of Worldwide Pig Iron Production [a]

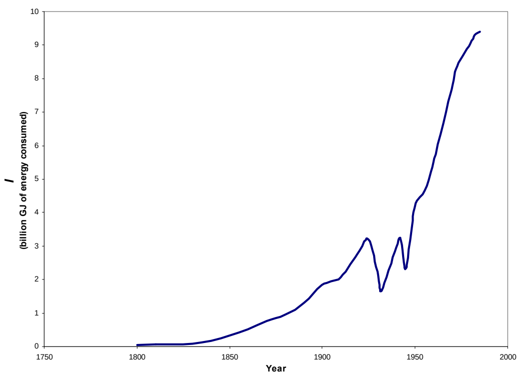


FIGURE A2: Impact (*I*) of Worldwide Primary Aluminum Production [b]

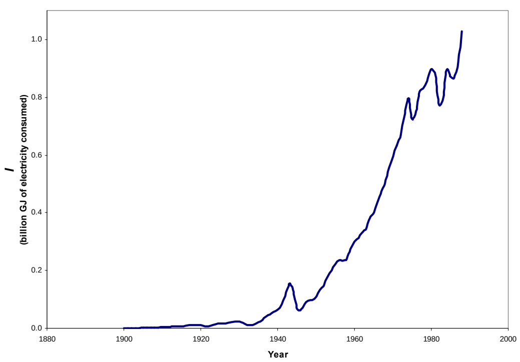


FIGURE A3: Impact (*I*) of Worldwide Nitrogen Fertilizer Production [c]

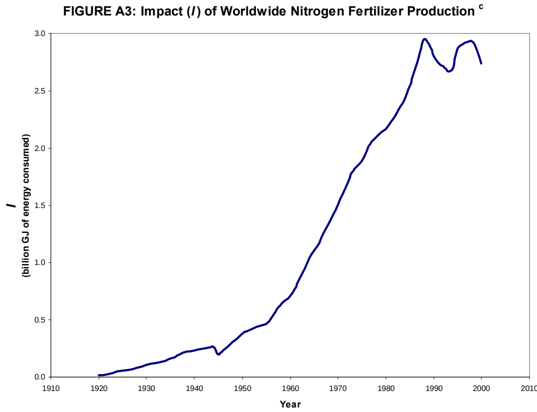


FIGURE A4: Impact (*I*) of Electricity Generation from Coal (US data) [d]

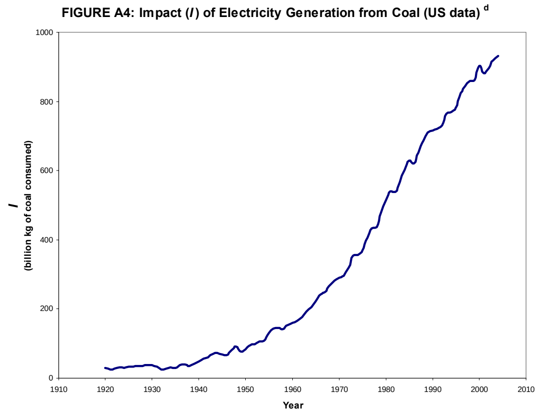


FIGURE A5: Impact (*I*) of Electricity Generation from Oil (US data) [d]

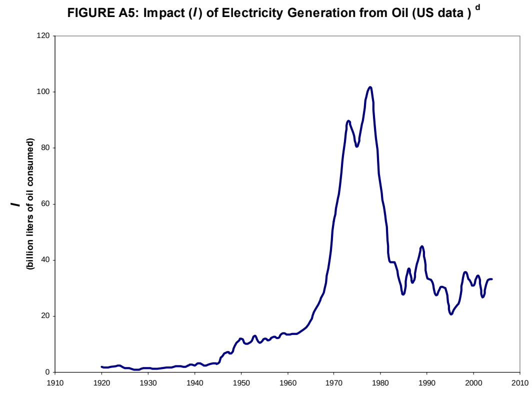


FIGURE A6: Impact (*I*) of Electricity Generation from Natural Gas (US data) [d]

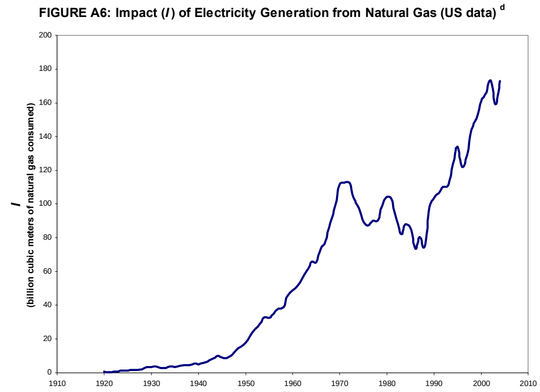


FIGURE A7: Impact (*I*) of Freight Rail Travel (US Class I railroads) [e]

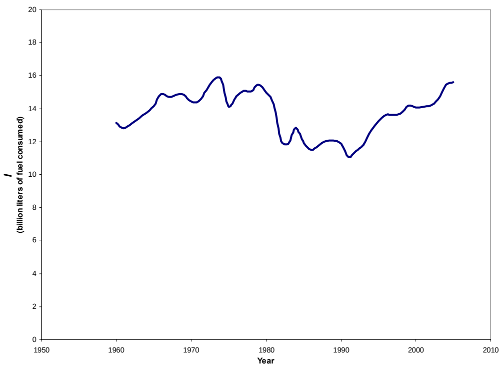


FIGURE A8: Impact (*I*) of Passenger Air Travel (US airlines) [f]

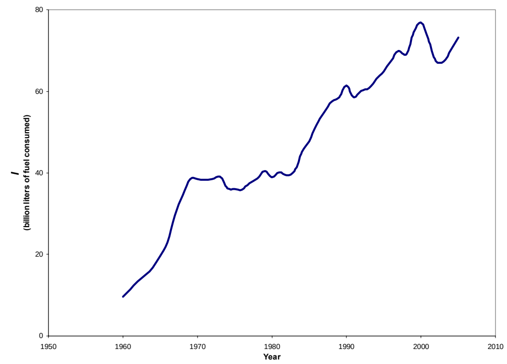


FIGURE A9: Impact (*I*) of Motor Vehicle Travel (US data) [g]

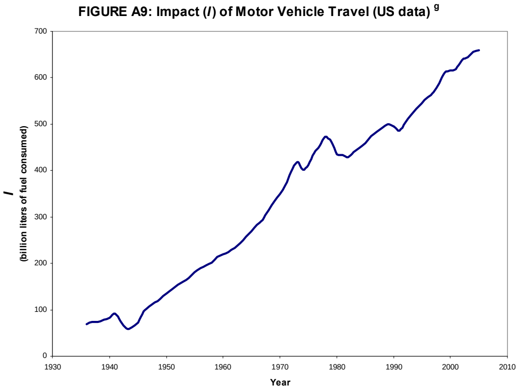
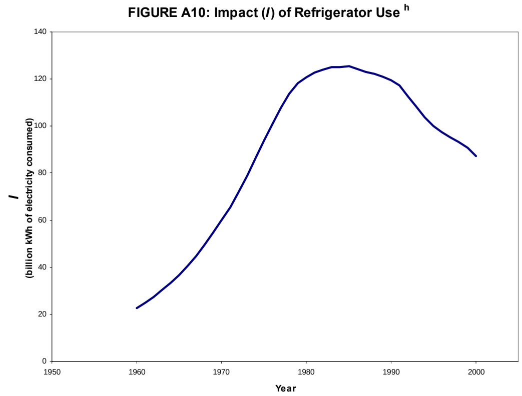


FIGURE A10: Impact (*I*) of Refrigerator Use [h]



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Notes

1. The efficiency described here is different from the typical engineering efficiency. While engineering efficiency is often defined as output over input for a single variable, for example energy output over energy input, eco-efficiency is typically a ratio of two variables, for example production output over energy input. In this paper, "efficiency" refers to eco-efficiency.

2. Since efficiency is simply production over impact, this characterization of efficiency also provides a characterization of production and impact. Production is thus measured in terms of dollar figures or production quantities, while impact is measured in terms of resource consumption or emissions output. While this measure for production is quite typical, this measure for impact may not be. In this work, the use of the term "impact" to measure resource consumption is different from the use of this term in life cycle assessment, where "impact" is used to measure environmental effects, such as global warming potential or ozone depletion potential. In the vernacular of life cycle assessment, the "impacts" measured here would typically be considered "inventories".

3. For the remainder of this paper, *P* will represent total production, not population.

4. The efficiency data used in the pig iron analysis comes from the UK (1760-1910), the US (1910-1940), and Japan (1940-1985), and thus represents some of the most efficient technology available for pig iron smelting at a given time. The actual global average efficiency would be lower, given the technologies in use in less technologically-advanced countries.

5. The Hall-Heroult process, independently invented in 1886 by Charles Hall in the US and Paul Heroult in France, is the process by which aluminum oxide, produced from bauxite, is reduced, producing aluminum. The Hall-Heroult process is the primary method of aluminum production.

6. The Haber-Bosch process, invented by Fritz Haber and commercialized by Carl Bosch in the early 1900s, is the process by which ammonia is synthesized from nitrogen and hydrogen. The Haber-Bosch process is the primary method of nitrogen fertilizer production. The efficiency data used in the nitrogen fertilizer analysis represents the most efficient technology available at a given time. Thus, the actual global average efficiency would be lower, given the technologies in use in less technologically-advanced plants.

   The noticeable drop in nitrogen fertilizer production in the late 1980s and early 1990s can be attributed primarily to the decline of the Soviet Union. In 1988, the Soviet Union was the world's largest producer of ammonia, with over 15 billion kilograms of nitrogen produced (Smil 2001). However, by 1996, the former Soviet states combined for only about half of the production quantity of 1988 (Ibid.).

7. In the case of electricity generation from coal, shown in Figure 4, the efficiency trends demonstrate an extended period of improving efficiency followed by an extended period of

slowly declining efficiency. This long downward trend in efficiency is attributable to various factors, including fuel substitution and power plant efficiencies.

The increased use of low-sulfur bituminous coal provides one likely explanation for the decline in the efficiency of electricity generation from coal. As part of the 1970 Clean Air Act, controls on certain emissions from power plants, including sulfur dioxide, nitrogen oxides, and particulates, were established. Such legislation led to the implementation of various emission reduction strategies at coal-fired power plants, from implementing flue-gas desulfurization units to switching to low-sulfur coal (Ellerman et al. 2000). This low-sulfur coal, which is primarily found in the Western US, also has lower heating values. Thus, the use of Western low-sulfur coal resulted in lower overall electricity generation efficiencies, as measured in units of electricity produced per mass of coal consumed. It should be noted that efficiency could have been measured with respect to an environmental load other than resource consumption. For example, efficiency could have been measured in units of electricity produced per mass of sulfur dioxide emitted. In this case, efficiency may have increased, not decreased, as a result of the Clean Air Act.

Another possible explanation for this downturn in efficiency is the plateauing of power plant efficiencies. The 1970 Clean Air Act, as described above, established stricter pollution controls on power plants. However, existing power plants were exempt from these new regulations. This resulted in many companies choosing to maintain old power plants that were exempt from these regulations, instead of building new power plants that would be subject to these regulations. This had the effect of locking-in existing equipment and efficiencies. It is also interesting to note that around this same time, the thermal efficiency of steam turbines, a critical component of power plants, was beginning to plateau, after almost a century of improvement (Smil 1999).

8. Figure 5, which plots efficiency and production data for electricity generation from oil, shows large fluctuations in production but relatively steady improvements in efficiency. This variation in production is due to both price and supply volatility for oil, as well as to various policy interventions.

   In the late 1960s, electricity generation from oil increased dramatically, primarily because of low oil prices, but also due to environmental reasons, as oil burns more cleanly than coal. With the oil embargo of 1973, oil prices increased dramatically. However, due to severe shortages in other fuels used for electricity generation, namely natural gas, the use of oil for electricity generation continued well into the 1970s. In 1978, the Powerplant and Industrial Fuel Use Act was passed, restricting the construction of power plants that used oil or natural gas. This, along with the Iranian oil shock of 1979, led to a rapid decline in the production of electricity from oil. Since then, electricity generation from oil has fluctuated considerably, but the general trend has been to move away from the use of oil for this purpose.

9. In the case of electricity generation from natural gas, shown in Figure 6, there are significant fluctuations in production but relatively steady improvements in efficiency. As in the case of electricity generation from oil, this variation in electricity production from natural gas is due to both price and supply volatility for natural gas, as well as to various policy interventions.

In the 1950s and 1960s, government price regulation of natural gas led to declines in production and increases in demand (Tugwell 1988). This combination brought about severe natural gas shortages in the 1970s. During these times of limited supply, homes and businesses were given priority over electricity generation facilities. Thus, electricity generation from natural gas during the 1970s and into the 1980s was quite volatile. This uncertainty of supply, along with the 1978 Powerplant and Industrial Fuel Use Act, which, as discussed previously, restricted the construction of power plants that used oil or natural gas, brought about an overall decline in electricity generation from natural gas during the 1970s and 1980s. The repeal of parts of the Powerplant and Industrial Fuel Use Act in 1987, combined with falling natural gas prices, helped to bring about a resurgence in the use of natural gas for electricity generation that has continued to this day.

10. When looking at products during the use phase, it is perhaps more common to look at the amount of goods or services consumed by the customer, not the amount of goods or services produced by the product. For example, in the case of refrigerators, it is perhaps more common to consider the hours of refrigeration consumed, not the hours of refrigeration produced. However, if one assumes that supply meets demand, the number of hours of refrigeration consumed is equal to the number of hours of refrigeration produced. Referring to the output of the use phase as goods and services produced, instead of as goods and services consumed, does not change the results. In fact, if the affluence term in (1) were to be represented as consumption per population instead of production per population, and if the technology term in (1) were to be represented as impact per consumption instead of impact per production, (4) could be written as

$$Impact = Consumption \ x \ \frac{1}{Efficiency} .$$

In order to reduce impact while maintaining economic growth, (5) would then become,

$$\frac{\Delta e}{e} > \frac{\Delta C}{C} > 0 ,$$

where *e* represents efficiency and *C* represents consumption.

11. In the US, freight railroads are categorized using a system designated by the Surface Transportation Board. This classification system has three categories, Class I, Class II, and Class III, which are based on operating revenue. In 2005, Class I railroads had operating revenues of $319.3 million or more, Class II railroads had operating revenues between $25.5 million and $319.2 million, and Class III railroads had operating revenues less than $25.5 million (AAR 2006). These monetary cut-offs are adjusted annually for inflation.

In 2005, there were only seven Class I railroads in the US, including railroads such as Norfolk Southern, Union Pacific, and CSX Transportation. Although limited in number, Class I railroads accounted for 68% of all US freight rail mileage and 93% of all US freight rail revenue in 2005 (Ibid.).

12. Revenue tonne-kilometer (RTK) is a measure of production for freight railroads. RTK values can be obtained by multiplying the number of revenue-generating tonnes of freight by the distance, in kilometers, that each paid tonne of freight travels. One RTK represents one revenue-generating tonne of freight traveling one kilometer.

    Efficiency of freight rail travel is measured in RTKs of freight rail travel per volume of fuel consumed, where the fuel consumed is diesel. While other types of fuel have been used for freight rail travel, by 1960, over 97% of the locomotives used by Class I railroads in the US were diesel (AAR 1965). Since then, diesel has remained the most popular fuel for freight rail.

13. Available seat kilometer (ASK) is a measure of production or capacity for airlines. ASK values can be obtained by multiplying the number of seats available for passengers by the distance, in kilometers, that each of those seats is flown (Bazargan 2004). One ASK represents one seat traveling one kilometer. It should be noted that ASK is independent of load factor, meaning that it is independent of how many seats on an airplane are occupied.

14. The term “motor vehicle”, refers to virtually all vehicles on the road, including passenger cars, motorcycles, buses, and trucks.

15. Vehicle-kilometer is a measure of production for motor vehicles. Vehicle kilometer values can be obtained by multiplying the number of motor vehicles by the distance, in kilometers, that each vehicle travels. One vehicle-kilometer represents one vehicle traveling one kilometer.

16. The noticeable smoothing of the data in the case of refrigeration is due to both limited data, in the case of production data, and fleet averaging, in the case of efficiency data. For annual production data, values between limited data points were obtained using a third order polynomial with an r-squared value of approximately 0.99996. The annual efficiency data for refrigeration is a measure of the average efficiency of the refrigerators in service in a given year. This value is obtained by using both the efficiency data for new refrigerators in a given year and data about the age distribution of the refrigerator fleet in a given year (Rosenfeld 1999, US DOE 1993, US DOE 1997, US DOE 2001).

17. In the cases of motor vehicle travel and refrigeration, earlier trends of declining efficiency were reversed in large part due to government efficiency mandates. While the efficiency of other activities, including electricity generation, freight rail travel, and passenger air travel, were clearly also affected by legislation, motor vehicle travel and refrigeration were unique in that in these cases, efficiency itself was explicitly legislated. These cases, and the efficiency mandates that contributed to these cases, will be discussed later in greater detail.

18. Giving rail companies the ability to set their own rates and to shut down unprofitable rail lines had a number of important ramifications. First, the ability to set their own rates made the rail industry much more competitive with trucking, as rail was now able to negotiate individual contracts for each customer (Williams 1985, Flint 1986). This ability to set rates also allowed rail companies to fill trains will low-rate cargo in order to avoid empty mileage, which in some years could account for 40% of total miles (Flint 1986). This reduction in empty mileage helped to improve both profitability and fuel efficiency. The fact that rail

companies could now close down unprofitable sections of track allowed for a reduction in operating costs, which also improved profitability.

Another factor driving the revitalization of the industry was the increase in oil prices in the 1970s, which had two important effects. The high oil prices made transport by freight rail, which is more fuel efficient per tonne-kilometer than transport by truck, more attractive, thus helping rail to gain market share (Pauly et al. 1982, Williams 1985, Railway Age 1990, Duke et al. 1992). The high oil prices also helped to increase demand for domestic coal. Railroads, which provided the most effective means of transporting coal from Western mines to US factories and utilities, thus benefited greatly (Pauly et al. 1980).

19. The deregulation of the rail industry led to many other efficiency improvements. The ability to set rates allowed rail companies to fill trains that may have previously run empty on return trips with low-rate cargo, thus improving efficiency (Flint 1986). The ability to close unprofitable rail lines allowed companies to discontinue service on less-traveled sections of track, sections that had in some cases deteriorated to the point that trains were forced to travel as slowly as 10 miles per hour (Pauly et al. 1980). The closing of rail lines, along with a recession-related equipment surplus in the early 1980s, allowed some older, less-efficient equipment to be removed from service (AAR 1983).

    Other operational and technological changes also led to further efficiency improvements. For example, operational changes by train engineers, including reducing unnecessary braking and reducing acceleration rates, led to noticeable improvements (Railway Age 1990, Shedd 1984). Changes in train dispatching, including the increased use of computers in scheduling and routing trains, also led to efficiency improvements (Shedd 1984, Omaha World-Herald 1984, Houston Chronicle 1986). In equipment, new innovations in cargo haulers, including the use of piggyback trains, in which containers and trailers, and sometimes double-stacked containers and trailers, are carried on flat rail cars, increased the type and amount of freight that could be transported by a single train (Williams 1985, Flint 1986, Duke et al. 1992). Other changes in equipment, including the introduction of high-efficiency, microprocessor-controlled locomotives, and the use of advanced wheel slip-control systems, also improved fuel efficiency, although such improvements generally took longer to manifest themselves at the fleet level (Shedd 1984, Houston Chronicle 1986).

20. There are many different approaches to improving fuel efficiency in passenger air travel, from improvements in aircraft and engine technology to operational changes. While each of these approaches can improve fuel efficiency, the time scales over which these improvements are realized can differ greatly. In the case of changes to aircrafts and engines, the long lifespan of aircraft, typically around 25 years, results in a considerable lag in technology (IPCC 1999, Lee at al. 2001). In general, it takes about 10 to 15 years for the US aircraft fleet to reach the efficiency levels of a new aircraft (Lee at al. 2001). This lag, along with considerable time spent in development, certification, and production, means that an increased interest in fuel efficiency by the air travel industry may not manifest itself in the aerodynamic and engine efficiency of the aircraft fleet for quite some time. Some have estimated this time delay between initial development and actual impact at the fleet level to be as much as 25 years (Ibid.).

While improvements to aircraft and engines take some time to manifest themselves, there are operational changes that can yield more immediate results. Improvements in air traffic management, including reducing air and ground delays, improving flight routing, and, more recently, reducing vertical separation minimums, can lead to considerable increases in fuel efficiency (IPCC 1999, Lee et al. 2001, ICF 2005, McCartney 2006). Other common operational approaches to improve fuel efficiency include reducing aircraft weight, by removing unnecessary equipment such as magazines and seat-back phones, and reducing aircraft drag, by lowering cruising speeds and implementing stricter repair and maintenance programs (McCartney 2006, Heimlich 2007). Together, these various operational changes can lead to immediate improvements in fuel efficiency. It is important to point out that increasing passenger load factors, a technique that has been employed frequently by airlines in recent years, improves efficiency on a revenue passenger kilometer (RPK) basis, but not on the available seat kilometer (ASK) basis used here. The number of ASKs, multiplied by the passenger load factor, yields the number of RPKs.

21. This decrease in efficiency was due to various factors, including additional refrigerator features and increased refrigerator size.

22. Starting in the 1970s, states, in particular California, began mandating minimum efficiency requirements on new household appliances (Gellar 1995). These requirements were updated over time, ensuring that efficiency improvements would continue. In 1987, with a patchwork of state requirements already in place, the National Appliance Energy Conservation Act created federal minimum efficiency requirements for residential appliances, including refrigerators (US DOE 2004). Since then, the efficiency standards for refrigerators have been updated multiple times, ensuring that efficiency improvements continued (IEA/OECD 2003).

23. While the number of hours of refrigeration an individual refrigerator provides is generally limited by the number of hours in a year, American households have increasingly added second refrigerators, thereby increasing the total hours of refrigeration used each year by a single household.

24. This period of declining efficiency was due in large part to market demand, as an increasingly affluent post-World War II public demanded larger, more powerful motor vehicles with more accessories (Hirsh 1999).

25. The period of improving efficiency, which began in the mid-1970s, was brought about by both market and legislative drivers. The oil crises of the 1970s introduced gasoline availability concerns and higher gasoline prices to drivers in the US, thereby stimulating consumer interest in improved motor vehicle fuel efficiency. Legislatively, Corporate Average Fuel Economy (CAFE) standards, which, beginning in 1978, mandated a minimum average fuel economy for a manufacturer’s fleet of vehicles, also drove automakers to improve fuel efficiency. Combined, these factors had a noticeable effect on the efficiency of motor vehicle travel in the US.

26. The recent stabilization of automobile efficiency is due in part to the fact that CAFE standards have not been updated for over a decade. Consumer demand for larger vehicles and better performance has also contributed to this plateau in fuel efficiency (Wald 2006).

27. Prior to the development of the Haber-Bosch process, the industrial methods available for producing nitrogen included the fixation of atmospheric nitrogen using calcium carbide at high temperatures to produce calcium cyanamide ($CaC_2 + N_2 \rightarrow CaCN_2 + C$), and the fixation of atmospheric nitrogen by electrical discharge to produce nitric oxide ($N_2 + O_2 \leftrightarrow 2NO$) (Tamaru 1991, Smil 2001).

28. It is true that in some cases, the planes that are the most costly to operate are not those with the worst fuel efficiency, but instead the planes that are of a different make or model from the majority of other planes in an airline's fleet (Wong 2003). In general, large cost savings can be realized, both in operation and in maintenance, by having a limited variety of planes.

29. Increases in affluence leading to increases in demand, and thus increases in production, applies in the case of normal goods. In the case of inferior goods, for which consumption decreases as income increases, increases in affluence lead to decreases in demand, and thus decreases in production.

30. Vaclav Smil offered his own humorous insights into the benefits of improvements in air travel and, more specifically, improvements in the efficiency of aircraft engines. In a 2007 lecture entitled "Transforming Energy Techniques", Smil commented,

> "These new big gas turbines, these, you know, GE and Rolls Royce things, they are marvels of engineering – much more efficient, much lighter, much more durable. The single most durable machine on this planet. You notice the plane goes, two hours they refuel it, goes back, and keeps doing it for seven months before they even look at the bloody engine. They don't even look at it! The most marvelous machine ever. But what is happening? These old inefficient turbojets. In 1960, who was flying? If somebody was flying, 'Oh, he *flew* somewhere! Amazing! First person in our family who flew somewhere,' right? Now? There is (sic) 78 discount airlines in Western Europe alone really. And people are flying – where is the number one destination in the continent? 45 million people fly to Las Vegas for what, you know, to spend money which they don't have really. This is what the efficient engine has brought us. People frivolously flying into the middle of the desert without any water to spend money which they don't have, really, right. So that's the benefit of efficient engines, ok." (Smil 2007).

31. In the case of normal goods, the income effect increases demand. However, in the case of inferior goods, for which consumption decreases as income increases, the income effect decreases demand.

32. Although data is difficult to find, it would be interesting to examine overall trends in refrigeration, not just trends in residential refrigeration, as are analyzed here. Given the increase in the US of dining and food service outside the home, the overall production of refrigeration, including both the service sector and the residential sector, may have grown at a faster rate than for the residential sector alone (Herring 2007). Significantly faster growth rates in the overall production of refrigeration could eclipse the rate of efficiency improvement, thus leading to an overall increase in impact.