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Energy efficiency measures are typically met with a small but often persistent "rebound effect" that manifests itself across various spheres: Install a more efficient air conditioning unit, lose some of the savings by setting the temperature lower. Buy a more fuel efficient car, visit grandma more often.

The rebound effect has troubled energy analysts and economists for over a century. Sometimes it is also called the "Jevons Paradox," after William Jevons who, in the 19th century, hypothesized that efficiency improvements will only backfire and lead us to use more resources overall. In fact, the Jevons Paradox acts in the extreme long run—over decades, centuries, and millennia—and might be better thought of as economic growth, progress.

There is also substantial evidence of a rebound effect in the relative short run—over days, weeks, and months. The magnitudes are much smaller, in order to magnitude closer to 10 percent: after taking into account a rebound effect of such a magnitude, we are still left with 90 percent of original energy efficiency savings.[2] (In contrast to Jevons's extreme long run and the short run observed immediately, we will also introduce the "long run," a measure often applied to months and years, when some conditions such as where someone lives relative to one's work are adjustable.)

An important example is the case of vehicle fuel efficiency improvements through Corporate Average Fuel Economy (CAFE) standards. As miles-per-gallon ratios improve, owners of more fuel-efficient cars may well be driving more as their fuel cost per mile travelled decreases.

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[2] While Jevons was concerned with the implications on Britain's coal resource, Brookes (1979) and Khazzoom (1980) more recently applied Jevons' theory to the area of energy conservation, suggesting that improvements in the energy efficiency of machinery and equipment could in fact have the reverse effect of increasing the energy consumed.

Whether the rebound effect is more than a theory, and the extent to which it might practically occur has significant welfare and policy implications. Energy efficiency improvements form a third of President Obama's proposed energy policy in his "Blueprint for a Secure Energy Future." Furthermore, half of the proposal to improve energy efficiency focuses on the transportation sector. If fuel efficiency in the transportation sector is to be a key pillar of America's energy future, and if we are to invest substantially in fuel-efficient capital, policies such as CAFE standards need to take into account any possible offsetting impact from the rebound effect—and they do. The most commonly used figure is 10 percent.

Overall welfare implications of the rebound effect are equally clear, although they point to a slightly more nuanced conclusion. Improved energy efficiency increases potential welfare for two reasons: by decreasing negative externalities associated with energy consumption, and by allowing consumers to spend their money differently, while still enjoying the same amount of services derived from energy. If some of the money is now spent on increased demand for energy services, that step is similarly welfare-enhancing. Rebound, in short, benefits the consumer. The rebound effect does point to the fact that policies that aim to decrease externalities should ideally be focused on capping or pricing those externalities directly. Pollution caps or taxes know no rebound effect.

This paper reviews the existing research on the rebound effect in the transportation sector, presents a framework for policymakers, and suggests future research that could enhance our understanding of the rebound effect and its implications.

1 Rebound Classified

The "rebound effect" has many different meanings. The Jevons Paradox highlights the long-term, economy-wide view. Others, such as Brookes (1979) and Khazzoom (1980), provide a shorter-term, micro-economic approach. Greening (2000) and Sorrell (2007) bridge the two by tying in general equilibrium effects.

One level of classification distinguishes between direct and indirect rebound effects. The direct effect works through the price of the particular resource: a decrease in marginal cost of an energy service—e.g. driving—increases the quantity demanded for it. This direct effect, in turn, is made up of a substitution effect—households and firms use more of the now cheaper energy service and less of other goods and services—and an income effect—the lower expenditure on the cheaper energy service allows households and firms to consume more of it.

Similarly, the indirect rebound effect can be split into two categories. First is the embodied energy—what is required to increase the efficiency of the energy service in the first place, such as the energy needed to build a more fuel-efficient car engine. Then there are secondary effects such as the energy required to produce the additional goods and services that households and firms consume as a result of the rise in their real income following the improved efficiency of an energy service. That last effect comes close to how Jevons would characterize his paradox, although for the paradox to work, we would have to look at the very long run.

The sum of direct and indirect effects is sometimes known as the "general equilibrium" rebound effect, including all effects from using the good in question as well as other goods and services affected by it. Another word for it is the "economy-wide" rebound effect.

By convention, the rebound effect is expressed as a percentage value. For instance, a 10 percent direct rebound means that although the energy efficiency of a vehicle reduces the fuel used for a particular journey by half, the vehicle owner only decreases his fuel consumption by 45 percent. General equilibrium effects may decrease this number further, although these effects would be second-order, especially in the short run. He consumes additional fuel by driving more on another journey, given the lower marginal cost. If rebound were ever more than 100 percent—i.e. a greater amount of energy is consumed than before the efficiency improvement—it is known as "backfire." That seems extremely unlikely for the transport sector where percentages hover around 5 to 30 percent even in the long term.

2 Fuel Efficiency Policy in the United States

The centerpiece of U.S. transportation fuel efficiency policy are Corporate Average Fuel Economy (CAFE) standards, currently jointly administered by the Department of Transport (DOT) and the Environmental Protection Agency (EPA). CAFE sets minimum fuel economy standards that each auto manufacturer must meet. In any given vehicle model year, the average miles per gallon (mpg) of a fleet sold by a manufacturer must equal or exceed the standard. CAFE was first legislated in 1975 against the backdrop of the oil crisis of the early 1970s. Its main purpose was to reduce U.S. reliance on oil imports by improving the fuel efficiency of cars and light trucks to 27.5 mpg by 1985. In 2007, when CAFE standards were first revised, the fuel economy requirement for cars and light trucks was raised to 35 mpg by 2020.

DOT and EPA under the Obama administration are actively strengthening CAFE. For the first time, medium- and heavy-duty trucks will come under CAFE regulation in 2014, under a new program that requires such vehicles to meet standards for both fuel consumption and greenhouse gas emissions. The two agencies are currently formulating a similar dual standard program that would strengthen requirements for light duty vehicles, in order to attain the President's target of achieving 54.5 mpg by 2025.

Are CAFE standards stringent enough? How does the DOT know the level at which to set the fuel economy standard to achieve its policy goal? The rebound effect plays a part in answering these questions. Depending on the extent of rebound, tightening fuel economy standards could be, in the worst case, self-defeating or counterproductive, or it could require fine-tuning for greater policy efficiency.

3 The Magnitude of the Rebound

While researchers largely agree that the rebound effect exists, they offer a range of views on the key question driving current research, namely, how large is the rebound effect? The direct rebound effect has been best documented, given the relative ease at which the consumption of a particular energy service can be analyzed in isolation. Estimating the indirect rebound effect is considerably more difficult since a whole host of second-order effects must be accounted for.

The direct rebound effect is best estimated using the efficiency elasticity of the demand for useful work, which can be easily obtained mathematically using the efficiency elasticity of demand for energy (Berkhout 2000, Sorrell and Dimitropoulos 2008). However, these two measures require data on energy efficiency, which is often inaccurate or unavailable. Further, the range of energy efficiency values from available data is usually too small to provide sufficient variation for econometric analysis (Sorrell 2007). The rebound effect is thus most commonly estimated with the price elasticity of the demand for useful work or for energy. For fuel efficiency, this is commonly measured as the change in vehicle miles travelled or in gasoline consumed for a unit change in fuel price. Estimates based on such price elasticity measurements could be biased if drivers are not equally sensitive to a decrease in fuel price and an increase in fuel efficiency, or if fuel efficiency is correlated with fuel price.

Table 1 summarizes results from studies quantifying the direct rebound effect in the transport sector. The most comprehensive survey to date identifies an overall long-run range of 10 to 30 percent (Sorrell, 2007). Short-run estimates are at or below 10 percent.

The wide range of estimates can be attributed to factors such as differences in how the rebound effect is defined, the level at which data is aggregated, and the estimation methodologies used. Most studies estimating direct rebound make use of aggregate data, while some use household survey data. Studies based on aggregate data are able to estimate long-term impacts and have largely converged within the range of 5 to 30 percent in industrialized countries, close to Sorrell's (2007) estimate of 10 to 30 percent. In contrast, results from studies using household survey data have been less consistent. For instance, the estimate from three different studies using the same data ranged from 0 to 87 percent. Household survey data do allow for greater insight into behavior at the individual level, although their scope is limited and fraught with other uncertainties (Sorrell 2007). In particular, household survey data do not enable long-term comparisons.

Table 1: Selected Estimates of the Direct Rebound Effect in Transportation

Study	***Effect Estimate***	***Data and Methodology***
Sorrell (2007)	10 to 30% (long-run)	Survey of 17 studies using aggregate or household survey data.
Industrialized Countries – Aggregate Data		
Gillingham (2011)	7% (short-run)	Careful analysis of price elasticities
Greening, Greene and Difiglio (2000)	10% (short-run) 20 to 30% (long-run)	Survey of aggregate studies in 1990s
Small and Van Dender (2007)	4.1% (short-run) 21% (long-run)	Pooled cross-sectional time-series data of US states from 1966-2004
	1.1% (short-run) 5.7% (long-run)	As above, with data from 2000-2004
Barla, Lamonde, Miranda-Moreno and Boucher (2009)	8% (short-run) 20% (long-run)	Panel data of Canadian provinces from 1990-2004
Wang, Zhou, Zhou and Zha (2012)	45%	Time-series data from Hong Kong from 1993-2009
	35%	As above, with data from 2002-2009
Industrialized Countries – Household Survey Data		
Frondel, Peters and Vance (2008)	57 to 67%	Household travel diary data collected in Germany from 1997-2005
Goldberg (1996)	0% (short-run)	US Consumer Expenditure Survey data from 1984-1990
Puller and Greening (1999)	35 to 80%	US Consumer Expenditure Survey data from 1980-1981 and 1984-1990
West (2004)	87%	US Consumer Expenditure Survey data from 1997
Developing Countries		

Roy (2000, citing Ganguly and Roy 1995)	24% (short-run) 50% (long-run)	Aggregate time-series data from 1973-1974 and 1989-1990.
Wang, Zhou and Zhou (2011)	96%	Aggregate time-series data of 28 Chinese provinces from 1994-2009 (includes only urban populations and does not differentiate between private and public transport modes)

Several key factors influence the magnitude of the rebound effect. Small and Van Dender (2007) show that the rebound effect declines with rising real income in the United States. They estimated that the rebound averaged 22% over the period 1966-2001, but that it decreased to 11% for 1997-2001, and declined further to 6% for 2000-2004. (In contrast to these results, a study using travel diary data of German households by Frondel, Ritter and Vance (2010) finds no evidence that income level causes variation in the rebound effect.)

Other factors that appear to correspond to reduced rebound are increased urbanization (Small and Van Dender 2007) and increased driving intensity (Frondel, Ritter and Vance 2011). The view that rebound could be greater in developing countries, where there is greater unmet demand for energy services, is somewhat substantiated by the limited empirical evidence available (Roy 2000, Sorrell 2007, Wang, Zhou and Zhou 2011). By extension, this view could plausibly imply a greater rebound in subpopulations within the United States whose demand for energy services is far from being met. This reinforces the impact of the factors mentioned previously, since it is likely that such subpopulations experience lower income, less urbanization, and lower driving intensity.

Increased fuel cost is found to be associated with increased rebound (Small and Van Dender 2007). An explanation could be that drivers are more sensitive to fuel price changes when prices are high.

The interaction of fuel economy regulation with other environmental and transport policies adds further complexity to the debate. Since rebound is determined by the cost of driving, policies that change fuel price can directly affect the rebound effect. Environmental policies such as a cap-and-trade emissions reduction system or a fuel tax cause fuel cost to rise, thus increasing the marginal cost of driving. If fuel economy standards were coupled with such emission measures, the higher fuel price would dampen the rebound effect (Frondel and Vance 2011). Congestion, on the other hand, has a dampening effect on the rebound. It creates a non-pecuniary incentive to car owners to drive less (Hymel, Small, and Van Dender 2008).

Research that estimates indirect and economy-wide effects is limited. An often cited source of economy-wide rebound analysis is the National Energy Modeling System (NEMS) designed and implemented by the Energy Information Administration (EIA). Using NEMS, a scenario of accelerated technology whereby the national energy intensity is 6.5 percent lower than in the base case, produces a total energy demand that is 5 percent less (Greening 2000, citing Kydes 1997). This suggests that improved energy efficiency (part of the accelerated technology assumption) leads to an economy-wide rebound in the order of 25 percent.

4 Rebound in Fuel Efficiency Policy

The federal government takes the rebound effect seriously. In preparing its final rule for the new standards for light-duty vehicles, the National Highway Traffic Safety Administration investigated the existing literature on the rebound effect extensively, before using 10 percent as the primary point estimate of the rebound effect.[3]

The rebound effect is pertinent to determining how high the fuel efficiency bar should be set. If the main policy goal is to protect the environment or to increase energy security, standards will have to be raised above the actual desired level of efficiency improvement in anticipation of the offsetting effect of the rebound. If economic development were also a concern, a rebound would help to achieve this goal, by encouraging diffusion of energy services and stimulating consumption in other sectors of the economy. While it is hard to imagine a scenario in which economic development was the sole reason for raising fuel economy standards, it could be a concurrent goal strong enough not to warrant anxiety over a rebound from tightening fuel efficiency standards.

One clear message emerging from the research is that policymakers should pay attention to the factors driving the heterogeneity of the rebound effect. If rebound were homogeneous throughout the country, the remedy for a federal transport efficiency policy like CAFE would be straightforward. For example, if the target is to reduce fuel consumption by 9 percent, and we expect the rebound to be in the range of 10 percent, the new standard should be pitched at a level that increases fuel efficiency by 10 percent. However, as some empirical research has demonstrated, several household characteristics—income and driving intensity—as well as population characteristics—level of urbanization and congestion, and stage of development—cause rebound heterogeneity.

What complicates matters further is that these factors are not static. These changes may make it necessary for policy to take into account anticipated demographic changes and other

[3] National Highway Traffic Safety Administration, "Final Regulatory Impact Analysis - Corporate Average Fuel Economy for MY 2012-MY 2016 Passenger Cars and Light Trucks", March 2010, 369.

factors driving the rebound effect, possibly justifying regular reviews of fuel economy standards and their relative effectiveness.

5 *Further Research and Policy Evaluation*

The evidence pointing to heterogeneous rebound warrants significant further study on the distributional impacts of fuel standards. On the one hand, rebound could assist to increase the welfare and economic productivity of the lower-income, more energy service deprived population segment. On the other hand, these communities might have to bear a greater environmental and health impact from increased traffic, particularly since they are likely to live in areas where road infrastructure is less well-maintained.

The research community interested in empirics could make use of the imminent increases of the CAFE fuel standards as an opportunity to gather more evidence on the rebound effect in the United States. There is ample time to plan and collect data for comprehensive policy evaluation studies. Since medium- and heavy-duty trucks will be regulated for the first time in 2014, research on this category of vehicles can offer insight into the impact of the rebound effect on the production side of the economy.

Most empirical research on the rebound effect studies the change in consumption of an energy service that undergoes an efficiency improvement in isolation. Since the various modes of transport are substitutable for each other to a certain degree, understanding how fuel standards for cars affects the demand for alternate transport modes like bicycles, subways, trains, and also rental vehicles, will provide a more complete picture. For instance, the reason to worry about a large rebound effect could be lessened if we know that consumers are substituting away from other even more fuel-intensive modes of transport. Once again, such substitution effects are likely to be heterogeneous.

Our current understanding of how the rebound effect could interact with transport or environmental policies that do not directly affect fuel price is limited. More theoretical and empirical work could be carried out to increase knowledge in this area, particularly that covering politically feasible policies, such as those that promote vehicles running on electricity or alternative fuels for cars, and that improve public transport infrastructure.

Lastly, we could benefit from greater investigation into the behavioral pathways that could influence the rebound effect. Research on the rebound effect has centered on narrowing down the range of its magnitude using quantifiable measures like fuel consumption and driving intensity. Less is known about how behavioral factors like social influence and cognitive dissonance could play a part. For example, a driver who is willing to purchase a more fuel-efficient car that costs more upfront might conscientiously drive less to keep up his self-image as an environmentalist. By gaining a better understanding of the behavioral reasons underlying the rebound effect, researchers could provide policymakers with additional levers to implement efficient fuel economy standards.

6 Conclusion

The bottom line is clear: The rebound effect provides an important caveat, but it does not negate efforts at improving fuel efficiency, whether in the transport or other sectors. Instead, we should design policy with the rebound in mind, to account for it so that fuel standards can be set at the desired or efficient level. Understanding the extent of rebound will help us to fine-tune our policies, but should not result in a policy overhaul.

Empirical research using US data shows that the rebound effect exists, and that it is small to moderate, ranging about 1 to 10 percent in the short run, and about 5 to 30 percent in the long run. In the short run and on an individual level, the rebound effect is unlikely to be large. Unless fuel efficiency can significantly reduce transport costs within a short period of time, human behavior is more likely to remain at *status quo*. Policymakers, however, are still rightly concerned about the rebound effect even in the short term, since it could potentially have an immediate impact on fuel demand, vehicle emissions, road congestion, as well as the effectiveness of fuel economy regulation.

In the long run and on an aggregate level, the rebound effect will likely boost economic development much like other technological improvements lead to greater capital investments and, thus, growth. Greater energy efficiency lowers the marginal cost of using energy and thus increases its consumption. At least part of the rebound effect in this case is contributed by those for whom owning and using energy-consuming appliances was previously cost-prohibitive. Another part of the rebound effect would be accounted for by increased productive activity. These two portions of the rebound effect—lowering the bar for the energy-poor and increasing production even when resources are the same—translate into clear welfare improvements. Knowing this does not solve the Jevons Paradox, but it assuages our worry of the rebound implications in the long-run.

In the end, the rebound effect itself is welfare-enhancing. As improved efficiency reduces the cost of travel, resources can be put to better uses. Those that previously could not afford to travel more, now can. By choosing to travel more, consumers reveal their preference. The rebound effect makes hitting a particular emissions target through efficiency standards alone more challenging, but the rebound effect itself should not be considered a negative. The opposite of energy efficiency is energy waste, and that, clearly, is negative.

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