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Welfare Implications of the Rebound Effect From More Energy-Efficient Passenger Cars

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Key Points

Improving the energy efficiency of passenger cars makes it cheaper to drive, allowing motorists to take to the roads more frequently. This additional driving, which offsets some of the expected energy savings from energy efficiency, is known as the rebound effect and is perceived negatively. This paper undertakes a cost-benefit analysis of the rebound effect following an energy efficiency improvement in passenger cars for 100 countries. We find that:

The rebound effect in passenger cars is welfare reducing in most cases, especially in countries that had some combination of low gasoline prices, high congestion and high accident costs.

Energy efficiency policies may be less likely to deliver net benefits because of welfare reducing rebound. Furthermore, in countries with the most welfare reducing rebound effects, even a free (that is, zero cost) energy efficiency improvement in passenger cars can become welfare reducing. It is therefore important to model rebound, as it can affect decisions to rollout energy efficiency policies.

Energy efficiency policies such as fuel economy standards may find greater success when fuel prices are higher, and therefore may be more effective when combined with policies that raise energy prices. Additionally, complementary policies that can mitigate congestion and reduce road accidents will also indirectly improve the net benefits of energy efficiency policies for passenger cars.

There may be a need to change the negative perceptions that the rebound effect holds in energy policy discussions. For energy efficiency improvements in other areas such as building lighting or air conditioning, the rebound effect will probably be welfare enhancing due to the absence of externalities such as congestion and accidents.

Summary

Conventional wisdom suggests that improving energy efficiency is a worthwhile investment. Many engineering and economic models have shown that energy-efficient technologies across a number of sectors are welfare enhancing, with higher benefits than costs. However, many of these models fail to account for the rebound effect and its impact on welfare.

Improving the energy efficiency of passenger cars, for example, makes it cheaper to drive, leading consumers to drive more. This additional driving, which offsets some of the expected energy savings from energy efficiency, is known as the rebound effect and is often perceived negatively. This paper is the first to conduct a welfare analysis of the rebound effect from more energy-efficient passenger cars for a large number of countries. The results are then included in a complete welfare analysis of the energy efficiency improvement that accounts for the ensuing rebound effect.

Our findings reveal the rebound effect to be welfare reducing in most cases because of the large externalities associated with increased driving. These externalities include air pollution, greenhouse gas emissions, congestion and accidents, which we find to outweigh the benefits from additional driving. Furthermore, the rebound effect is found to be worse (that is, more welfare reducing) in countries that had some combination of low gasoline prices, high congestion and high accident costs.

Our results carry important implications for energy efficiency policymaking, particularly in the road transport sector, given that many evaluations of energy efficiency do not account for the rebound effect, which can be misleading. We find the rebound effect to have a significant impact on overall welfare. In fact, in countries with the worst rebound effects, we demonstrate that even a 'free' energy efficiency improvement (that is, with zero upfront costs) in passenger cars can become welfare reducing once the negative impact of rebound is taken into account.

Our work has three key messages for policymakers. First, it highlights the importance of accounting for the welfare implications of the rebound effect, which can have a considerable impact on decisions to move forward with energy efficiency policies. In some countries, the welfare reduction created by the rebound effect may be large enough to overturn the welfare enhancement brought about by the energy efficiency improvement. However, in others the welfare enhancement produced by rebound may help increase the net benefits of energy efficiency.

Second, energy efficiency policies such as fuel economy standards are less likely to deliver net benefits when fuel prices are low or congestion and accident costs are high, partly because of the rebound effect. Thus, energy efficiency policies may be more effective when combined with policies that raise fuel prices. Furthermore, complementary policies that can mitigate congestion and reduce road accidents can indirectly improve the net benefits of energy efficiency policies in road transport.

The third key message is that the rebound effect is not always welfare reducing, as some studies have suggested. For some countries, rebound in passenger cars is found to be welfare enhancing. Moreover, when we set the congestion and accident costs to zero to model the potential welfare implications of rebound in other areas, such as building lighting or air conditioning, we find the rebound effect to be welfare enhancing in most cases. It is therefore important to model and understand the welfare implications of the rebound effect before considering any policies to mitigate it. More work in this area could help change the negative perceptions that the rebound effect holds in energy policy discussions. Ultimately, for most energy efficiency policies, the primary goal is to maximize welfare rather than minimize energy consumption, and the rebound effect could help support that goal.

Introduction

Energy is consumed to provide services such as driving, heating or lighting, wherein capital equipment is used to convert the energy into the service. A passenger car, for example, is used to convert gasoline into driving or vehicle kilometers traveled (VKT).

When the energy efficiency of capital equipment improves, economic agents such as households tend to adjust their behavior by consuming more of the energy service. This behavioral response, which reduces the expected energy savings from improved energy efficiency, is known as the rebound effect. Economic agents will normally alter their behavior when energy efficiency improves because the implicit price of the energy service depends on both the price of energy and the efficiency of the capital equipment (in addition to other factors). The implicit price of driving a car, for example, depends on the price of gasoline and its efficiency. Just as a fall in the price of gasoline would result in a fall in the implicit price of driving, a more energy-efficient car will also make it cheaper to drive, which will normally lead to more driving, thus giving rise to the rebound effect. The term ‘driving’ is used throughout this paper to simplify the exposition. We also use the kilometer as the unit of distance. Therefore, the term ‘price of driving’ denotes the price of a VKT.

Although rebound is the economically expected outcome of improved energy efficiency, as noted by Jevons (1865) more than a century ago, many studies have discussed the need to mitigate it (for example, Herring and Roy 2007; Ouyang et al. 2010; Gloger 2011; Maxwell et al. 2011; van den Bergh 2011 and Otto et al. 2014). Rebound is largely perceived as a negative phenomenon that works against the intended objectives of energy efficiency: namely to reduce energy consumption and greenhouse gas (GHG) emissions.

A few studies, however, have noted that the rebound effect may be welfare enhancing (Hobbs 1991; Borenstein 2015 and Chan and Gillingham 2015). Chan and Gillingham (2015) developed a theoretical microeconomic framework for studying the welfare implications of rebound. They showed that in the absence of externalities, the rebound effect is always welfare enhancing. With externalities, however, the welfare implications depend on which is bigger: the benefit from additional consumption of the energy service as a result of rebound or the cost associated with that additional consumption.

Measuring the welfare implications of rebound is critical because it affects the welfare implications of energy efficiency policymaking. An energy efficiency improvement that has larger benefits than costs (in other words, welfare enhancing), for example, may turn out to be welfare reducing after accounting for the welfare implications of the rebound effect. Many economic evaluations of energy efficiency, however, have been done through a narrow lens that focuses only on the upfront capital costs and monetary benefits from reduced energy consumption (Clinch and Healy 2001). Such an incomplete approach to evaluating energy efficiency overlooks the costs and benefits of rebound, which can affect the welfare implications of energy efficiency.

This paper is, to the best of our knowledge, the first to quantify the benefits and costs of the rebound effect for a large number of countries and then use those estimates to consider their impact on the welfare implications of energy efficiency. Our empirical analysis focuses on energy efficiency in passenger cars due to a number of factors. First, passenger cars account for a large share of final energy consumption in most economies around the world (IEA 2016a). Second, many governments have successfully implemented energy efficiency policies in this sector. According to the IEA (2016b), 74 percent of the global road transport sector is now covered by energy efficiency policies, mostly in the form of fuel economy standards. Understanding the potential impact of the rebound effect on such energy efficiency policies is therefore critical. Finally, estimating the rebound effect from more energy-efficient passenger cars is relatively straightforward since many countries rely on a single source of fuel (gasoline or diesel) to power their vehicles. This is described as 'single-energy single-service.' Estimating the rebound effect becomes more complicated when there are multiple sources of energy and multiple services involved, such as the case of electricity, which provides lighting, heating and air conditioning, in addition to many other energy services.

Background

More than a century ago, Jevons (1865) conjectured that an improvement in energy efficiency would not necessarily lead to reduced energy use. The actual reductions in energy use would fall short of the expected reductions because energy efficiency would decrease the relative price of energy, stimulating an increase in consumption. However, little attention was given to the rebound effect until many years later following papers published by Khazzoom (1980) and Brookes (1990, 1992 and 1993).

The rebound effect can occur at different scales and across different economic agents (producers and consumers). A survey of studies conducted by Greening et al. (2000) highlighted the different ‘types' of rebound effects:

- Direct rebound (the focus of analysis in this paper).
- Indirect rebound.
- Economywide rebound.

The different types of rebound effects are best illustrated through an example. Consider a consumer that upgrades to a more energy-efficient passenger car. The relatively lower implicit price of driving due to the higher efficiency will probably spur the owner to drive longer distances, resulting in relatively greater fuel consumption. This is the direct rebound effect. The relatively lower implicit price of driving will also free up some of that consumer's income, which can be spent on other goods and services. Given that other goods and services generally require energy to be produced, an increase in their consumption will stimulate greater energy consumption in other areas of the economy. This is an example of the indirect rebound effect. The direct and indirect rebound effects can alter the prices and consumption patterns of goods and services across the economy, together giving rise to an economywide rebound effect.

The rebound effect is usually expressed as a percentage of the energy savings that were lost due to rebound (Berkhout et al. 2000). If the energy savings from an energy efficiency improvement were expected to be 10 barrels of fuel, for example, but the actual energy savings were only four barrels, then the rebound effect would be 60 percent. A value of zero percent implies no rebound, while a value of 100 percent or greater is known as ‘backfire.'

Surprisingly, the question of how rebound influences the welfare implications of energy efficiency has “not been addressed in the literature,” as noted by Chan and Gillingham (2015). In their paper, they presented a theoretical framework of how the direct rebound effect may influence energy efficiency's welfare implications. In this paper, we empirically estimate the welfare implications of the direct rebound effect following an improvement in the energy efficiency of passenger cars to help answer the question.

Methodology

We use a partial equilibrium analysis to explore the welfare implications of the direct rebound effect and its consequences on energy efficiency. We do not explore the welfare implications of the indirect and economywide rebound effects, which would likely require a calibrated computable general equilibrium model for each country (Allan et al. 2009). Our partial equilibrium analysis rests on calibrated demand curves for gasoline and driving, which are used to estimate the benefits, in addition to external cost data on air pollution, GHG emissions, congestion and accidents. Furthermore, the welfare analysis is conducted for a fixed 10 percent improvement in the energy efficiency of passenger cars on a country-by-country basis for 100 countries.

Welfare analysis of the direct rebound effect requires estimates for the size of the direct rebound effect, the consumer surplus gained from rebound and the external costs associated with rebound. Welfare analysis of energy efficiency, which includes rebound, also requires these estimates, in addition to estimates for the monetary savings from improved efficiency, the upfront cost of the improvement and the reduction in external costs due to energy saved.

Estimating the direct rebound effect using elasticities

As noted previously, the direct rebound effect arises because of the additional driving that occurs due to the energy efficiency improvement. According to Sorrell and Dimitropoulos (2008), the elasticity of the demand for driving with respect to energy efficiency provides a measure of the direct rebound effect. However, very few studies estimate this elasticity. Instead, most studies estimate the elasticity of energy demand with respect to the energy price. Nevertheless, it has been shown that the direct rebound effect can be assumed equal to the negative of the energy price elasticity. For example, if the gasoline price elasticity were estimated to be -0.2 in Saudi Arabia, then the elasticity of the demand for driving with respect to energy efficiency would be 0.2. This implies that a 10 percent improvement in energy efficiency would lead to a 2 percent increase in VKT. In terms of percentages, a gasoline price elasticity of -0.2 implies a direct rebound effect of 20 percent, since a fifth of the expected energy savings are lost due to the increase in VKT (see Appendix A for details).

The energy price elasticity proves to be a reliable proxy for the direct rebound effect when there is a single energy source used to provide a single energy service. However, it becomes biased when multiple energy sources and services are involved. In fact, it has been proven by Hunt and Ryan (2014) and Chan and Gillingham (2015) that the direct rebound effect is equal to the negative of the energy price elasticity only in the single-energy single-service case. For multiple sources of energy and services, different elasticity relationships emerge and the use of gasoline price elasticities will likely lead to overestimated direct rebound effects (Hunt and Ryan, 2014).

In countries such as Saudi Arabia where almost all passenger cars are gasoline-based (IEA 2016a), the price elasticity of gasoline demand provides a reliable estimate of the direct rebound effect. However, in countries such as France where consumers purchase both gasoline and diesel vehicles, estimating the direct rebound effect becomes more difficult. To simplify the analysis, we study the welfare implications of rebound from an improvement in the energy efficiency of gasoline vehicles only, which in most countries account for the majority of energy consumption by passenger cars (ExxonMobil 2016). In summary, the more lopsided the fleet in a country toward gasoline, the more reliably the price elasticity can be used to estimate the direct rebound effect from more efficient gasoline cars.

Estimating the benefits of energy efficiency and rebound

An improvement in energy efficiency can deliver multiple benefits to consumers through gains in consumer surplus and reductions in external costs. When the energy efficiency of a passenger car improves, the implicit price of driving falls. The demand function for driving can then be used to predict the consumer surplus gained from this fall in the implicit price of driving (see Appendix B for details).

In Figure 1, the area underneath the demand curve for driving between the prices before (P_{d0}) and after (P_{d1}) the energy efficiency improvement reflects the total gain in consumer surplus due to that improvement. This area is broken down into two smaller benefits or sections (B_{MS} and B_R). The first (B_{MS}) reflects the expected monetary savings from improved energy efficiency (shaded yellow). In other words, it reflects the fall in spending that consumers get when they invest in an energy efficiency upgrade. Most cost-benefit analyses of energy efficiency only account for this benefit and overlook the benefit due to the direct rebound effect (B_R), which stems from the consumer surplus gained from additional driving (shaded blue).

There is also a third benefit from improved energy efficiency. Since gasoline consumption is associated with external costs such as air pollution and GHG emissions (Parry et al. 2014), any reduction in gasoline consumption because of improved efficiency will lead to a reduction in these energy-related external costs. The benefit from reducing these energy-related external costs can be calculated by multiplying the fall in gasoline consumption (measured in liters) by the externality produced by air pollution and GHG emissions (measured in US$ per liter).

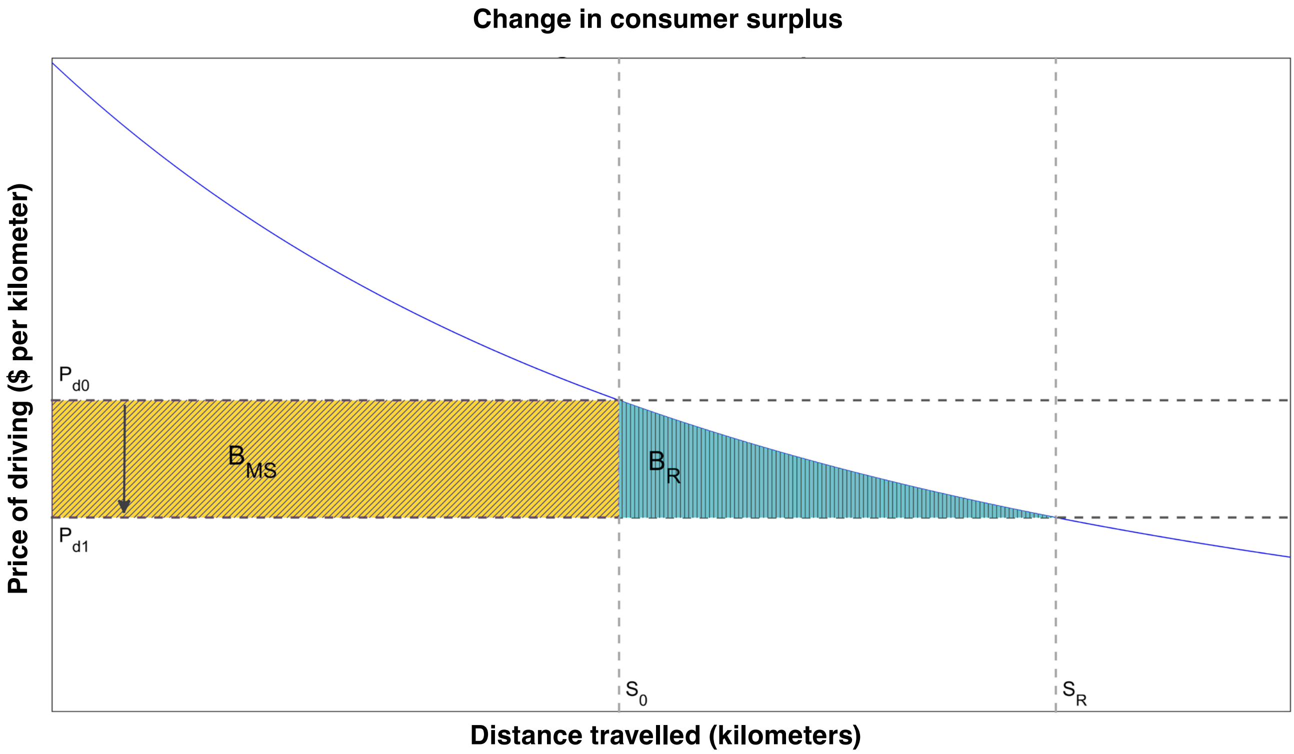

Figure 1. The consumer surplus gained following a fall in the implicit price of driving due to improved energy efficiency.

Source: KAPSARC.

To summarize, the total benefit from improved energy efficiency (B_{EE}) includes the benefit from monetary savings (B_{MS}), the benefit due to the consumer surplus gained from the additional driving that defines the direct rebound effect (B_R) and the benefit due to reduced external costs (B_{EC}), as shown by the following equation:

$$B_{EE}=B_{MS}+B_R+B_{EC} \quad (1)$$

Estimating the costs of energy efficiency and rebound

Although energy efficiency delivers multiple benefits, there are also multiple costs that need to be accounted for. There is first the upfront capital cost of an efficiency improvement. In this paper, we assume that it is zero. (We will subsequently discuss the impact of this assumption on the welfare implications of energy efficiency.) We therefore conduct a cost-benefit analysis of a 'free' energy efficiency improvement, where the term 'free' denotes zero capital costs. However, we do account for a different cost that is often overlooked: the cost of the direct rebound effect.

The cost of the direct rebound effect can be broken down into two segments (see Appendix C for details). The first is due to the external costs that arise from the additional gasoline consumption beyond a scenario in which there was no rebound. This cost can be calculated by multiplying the additional consumption (measured in liters) by the externalities of air pollution and GHG emissions (measured in US$ per liter).

The second segment is due to the external costs that arise from the increase in VKT. By definition, the quantity of driving is assumed to be fixed before and after the energy efficiency improvement when the direct rebound effect is zero. When it is greater than zero, consumers will drive more, leading to greater congestion and accidents. We can account for this cost by multiplying the additional driving (measured in kilometers) by the externalities of congestion and accidents (measured in US$ per kilometer).

Thus, the total cost of the direct rebound effect (C_R) is equal to the fuel-or energy-related external costs (C_E) plus the driving- or service-related external costs (C_S).

$$C_R=C_E+C_S \quad (2)$$

Given that the upfront capital costs are assumed to be zero ($Cc=0$), the total cost of an energy efficiency improvement (C_{EE}) is therefore equal to the total cost of the direct rebound effect (C_R).

$$C_{EE}=C_C+C_R=C_R \quad (3)$$

Estimating the welfare implications of energy efficiency and rebound

The welfare implications of energy efficiency and rebound are governed by the relative sizes of the benefits and costs. For the direct rebound effect, the welfare implications are determined as follows:

$$BCR_R = \frac{B_R}{C_R} \quad (4)$$

The direct rebound effect is therefore welfare enhancing when its benefit-to-cost ratio (BCR_R) is greater than one, that is, when the consumer surplus from additional driving outweighs the associated external costs.

Similarly, the welfare implications of an energy efficiency improvement with zero upfront capital costs are determined as follows:

$$BCR_{EE} = \frac{B_{EE}}{C_{EE}} = \frac{B_{EE}}{C_R} \quad (5)$$

A free energy efficiency improvement (that is, with zero upfront capital costs) is therefore welfare enhancing whenever its benefit-to-cost ratio (BCR_{EE}) is greater than one.

Welfare implications when prices deviate from private cost

The methods presented so far have not accounted for the welfare impacts on the government. If gasoline were sold at private cost, then there would be no need to account for government. However, gasoline is taxed by some governments to correct for externalities, while it is sold at subsidized prices by others. Deviations in the price of gasoline from private cost can affect the welfare results given that the focus has been on consumers only, and that the impact on government spending/revenues has not been accounted for.

As noted by Borenstein (2015), the savings that a consumer gains from improved energy efficiency may be different from the economywide savings because of non-marginal-cost pricing. (We prefer the term non-private-cost pricing given that in countries such as Saudi Arabia gasoline may be sold at low administered prices that lie above marginal cost but below international market prices.) For example, if the private cost of a liter of gasoline was $2, but the consumer only pays $1, then the consumer will only gain $1 in monetary savings for each liter of gasoline saved. However, the economywide monetary savings would be $2 since the government, which was subsidizing the gasoline, would also gain $1 in monetary savings.

We include the government in our welfare analyses by calculating the government's gain or loss and adding the estimates to the benefits or costs of energy efficiency and rebound (see Appendix D for details).

Data

All data used in the analysis are for the year 2010. The gasoline demand data were collected from the IEA's (2016a) World Energy Statistics. Gasoline prices at the pump were from the World Bank's (2016) World Development Indicators, although the dataset lists the prices for super gasoline only, which is usually 95-octane. Given that we are modelling aggregate gasoline demand, the price used to calibrate the demand curves should be a weighted average of the prices of different grades of gasoline in a country. In Saudi Arabia for example, 95-octane gasoline was sold at 16 cents per liter while 91-octane was sold at 12 cents in 2010. A price of 14 cents per liter, for example, would yield a more precisely calibrated demand curve since the demand data captures the consumption of both grades of gasoline. However, the absence of data on prices and consumption by grade restricts us to the use of super gasoline prices for the calibration of the demand curves.

External costs are arguably the most important data input for our welfare analysis, and are obtained from the IMF's (2016) database on transport. The IMF (2016) data originate from a study by Parry et al. (2014) that estimates the external costs of air pollution, GHG emissions, congestion and accidents on a country-by-country basis. We refer to air pollution and GHG emissions as fuel- or energy-related external costs and congestion and accidents as driving- or service-related external costs.

Determining whether a certain cost is internal or external can be tricky. For both congestion and accidents, there are internal and external components to each. An internal cost is one that consumers account for when making decisions regarding driving, while they do not account for the external costs that are ultimately borne by others. In the case of accidents, Parry et al. (2014) view the risk that drivers pose to pedestrians when deciding how much to drive as an external cost. On the other hand, they follow the standard approach of viewing the cost of injury to occupants in single-vehicle collisions as internal, because drivers consider such risks when deciding how much to drive. In the case of congestion, Parry et al. (2014) estimate the external cost by first extrapolating travel delays from a city to a country level. The data is then used to define the total hourly cost of congestion to all passengers per kilometer. Dividing the total cost by the traffic volume produces the average congestion cost per kilometer, which the authors assume is internal. On the other hand, differentiating the total cost with respect to the traffic volume produces the marginal congestion cost to all passengers from an additional kilometer of driving. This marginal cost is made up of the average cost and an additional term, which captures the cost to passengers of other vehicles that is not taken into account by the driver (they only account for the cost to themselves, which is captured by the average cost). The additional term is therefore assumed by Parry et al. (2014) to be equal to the external cost of congestion.

Energy efficiency parameters (for the total stock of passenger cars) were needed to convert gasoline demand curves into demand curves for driving or VKT. These efficiency parameters were obtained from the IMF (2016). It should be noted, however, that the energy efficiency parameters in the IMF (2016) database are not exact, and are estimated on a region-by-region basis due to data limitations. For example, North and South American countries in the database share a fuel economy of 25 miles per gallon, or roughly 8.85 kilometers per liter (KPL). Northern European countries share a fuel economy of 12.4 KPL, while states in the Gulf Cooperation Council such as Saudi Arabia and the United Arab Emirates share a fuel economy of 7.1 KPL.

Results and Discussion

Energy efficiency is often thought to be welfare enhancing so long as the monetary savings from improved energy efficiency are greater than the upfront costs. However, as we have discussed, such a view overlooks other important benefits and costs, mainly the impact of the rebound effect. In this paper, we present the welfare results from an analysis of energy efficiency that accounts for the often-overlooked rebound effect. We begin with the welfare results from the simplest case: a free energy efficiency improvement and zero rebound.

Welfare implications of a free energy efficiency improvement

Given that the upfront cost of a free energy efficiency improvement is, by definition, zero, and that we assume zero rebound, the total cost of the improvement is therefore zero. As a result, such a free energy efficiency improvement will always have larger benefits than costs and be welfare enhancing. The benefits stem from both the cash savings that consumers are rewarded with because of reduced gasoline demand and the associated reduction in energy-related external costs. The demand curve for driving in this simple case is perfectly price inelastic, so that the fall in the implicit price of driving due to improved efficiency does not stimulate any additional demand for driving. In other words, VKT remains fixed.

Welfare implications of the direct rebound effect

The direct rebound effect is found to be welfare reducing in most countries, as shown in Table 1, in which they are sorted in ascending order by total external cost and gasoline price. For most countries, the costs of direct rebound due to the additional air pollution, GHG emissions, congestion and accidents that occur because of the additional driving, are found to outweigh its benefits. Furthermore, the direct rebound effect is found to be welfare reducing across a range of price elasticities (that is, across a range of direct rebound effect sizes). In other words, regardless of the size of the direct rebound effect, its welfare implications remain largely unchanged (minor changes in the second decimal point are not visible in Table 1). A few countries, however, are found to enjoy welfare enhancing direct rebound effects. These countries generally have a combination of high gasoline prices and low external costs.

The size of the direct rebound effect can vary considerably from country to country. Fuel prices and income levels are among the many factors that can affect its size. Dahl (2012) shows in a survey that gasoline price elasticities (and thus direct rebound effects) are smaller in absolute terms in countries with low gasoline prices. Thus, low gasoline prices, which can give rise to welfare reducing rebound, are also likely to lead to smaller rebound effects. However, even for the same country, it is important to note that price elasticity estimates can show considerable variation due to differences in techniques used, time horizons and a number of other factors (Dahl, 1986). Consequently, the results in this paper are presented for a range of price elasticities.

The direct rebound effect is found to be considerably more welfare reducing in countries that had some combination of low gasoline prices and high external costs. Low gasoline prices imply that the consumer surplus gained from the same percentage improvement in energy efficiency is lower than it could have been at higher prices (see Figure 2; area shaded in blue versus yellow). Thus, when energy efficiency improves in a country with low fuel prices (and thus driving costs), the additional fall in the price of driving because of improved efficiency provides little benefit to consumers since driving is already very cheap. High external costs also play an important role. Unlike the external cost of GHG emissions, which is the same for all countries, the external costs of congestion and accidents vary markedly. On the one hand, the cost of congestion estimated by Parry et al. (2014) depends on both how much time is wasted in traffic and the monetary value of that time, which in turn is a function of a country's average income. In general, the higher the income level in a country, the higher the cost of congestion. On the other hand, the cost of accidents depends on both income and road safety levels. In summary, countries with relatively low gasoline prices, high congestion and high accident costs are found to have the worst (smallest benefit-to-cost ratio) direct rebound effects.

There may be benefits associated with the direct rebound effect that have not been captured in our analysis. These benefits may be thought of as external or social benefits, in analogy to the external costs that are considered in this paper. External benefits would reflect welfare gains that are not captured by consumer surplus (Schwartz 2005). For example, the lower cost of driving due to improved efficiency may allow a person to drive greater distances each day, potentially providing access to better job opportunities in farther areas. These opportunities may then contribute to greater productivity in the economy. Such external benefits are difficult to estimate, and would improve rebound's welfare outcomes. Further studies on these external benefits are needed before they could be incorporated into studies such as this one.

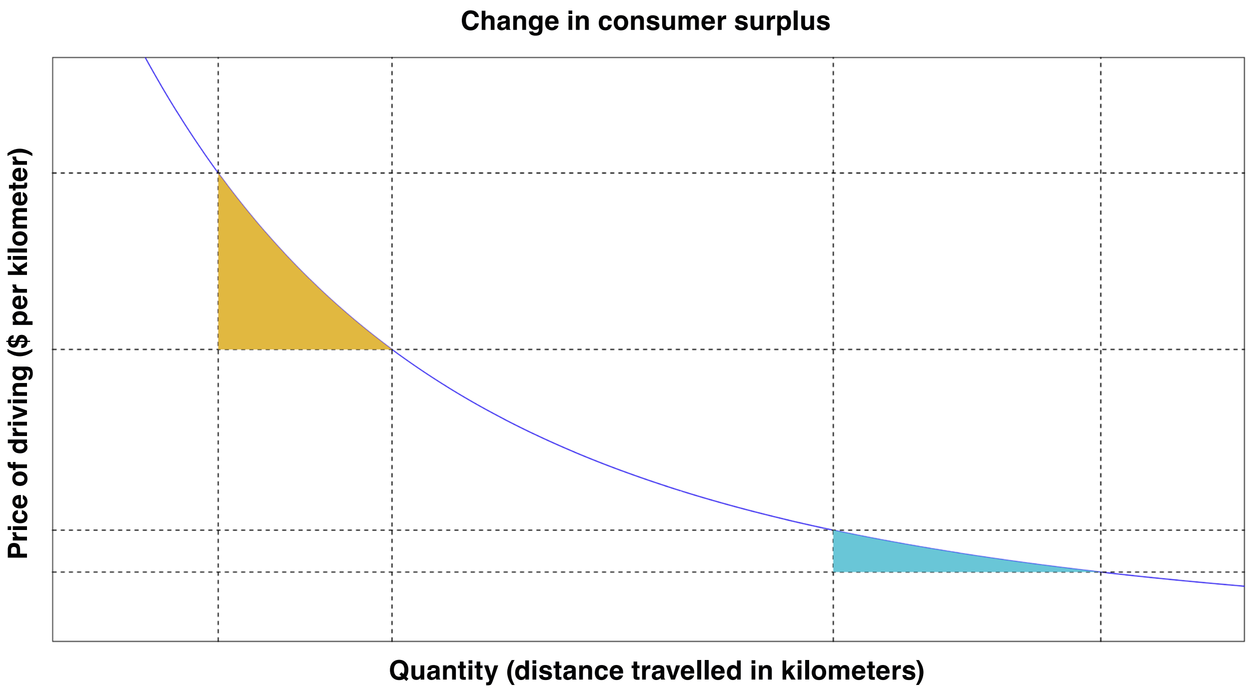

Figure 2. The consumer surplus gained from additional driving (B_R) at high and low prices following the same fixed percentage improvement in energy efficiency.

Source: KAPSARC.

Table 1. The benefit-to-cost ratio of the direct rebound effect following a 10 percent improvement in the energy efficiency of passenger cars for a range of price elasticities.

Country	Total External Cost	Gasoline Price	Gasoline Price Elasticities											
			-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0	-1.1	-1.2
			Implied increase in VKT (following a 10% energy efficiency improvement)											
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%
Bahrain	Low	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Brunei	Low	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Egypt	Low	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nigeria	Low	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bolivia	Low	Medium	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ecuador	Low	Medium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ethiopia	Low	Medium	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ghana	Low	Medium	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Indonesia	Low	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Mexico	Low	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Pakistan	Low	Medium	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Sudan	Low	Medium	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Vietnam	Low	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Bangladesh	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Belarus	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Benin	Low	High	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Bosnia	Low	High	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Brazil	Low	High	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Cameroon	Low	High	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Estonia	Low	High	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Georgia	Low	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Honduras	Low	High	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Ivory Coast	Low	High	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Jordan	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Mozambique	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Nicaragua	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Philippines	Low	High	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Senegal	Low	High	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Slovenia	Low	High	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Thailand	Low	High	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Togo	Low	High	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Ukraine	Low	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Zimbabwe	Low	High	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.1

Iran	Medium	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oman	Medium	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	Medium	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Venezuela	Medium	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Azerbaijan	Medium	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Botswana	Medium	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
El Salvador	Medium	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Kazakhstan	Medium	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Malaysia	Medium	Medium	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Tunisia	Medium	Medium	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
United States	Medium	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Albania	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Bulgaria	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Chile	Medium	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
China	Medium	High	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Costa Rica	Medium	High	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Croatia	Medium	High	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Cyprus	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Czech R.	Medium	High	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hungary	Medium	High	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Kenya	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Latvia	Medium	High	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Lithuania	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Malta	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Mongolia	Medium	High	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
New Zealand	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Paraguay	Medium	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Poland	Medium	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Romania	Medium	High	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Slovakia	Medium	High	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Sri Lanka	Medium	High	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Israel	Medium	Very high	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Portugal	Medium	Very high	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Kuwait	High	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Russia	High	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Syria	High	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Australia	High	High	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Austria	High	High	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Cambodia	High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Canada	High	High	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Colombia	High	High	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Dominican R.	High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Iceland	High	High	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
India	High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Ireland	High	High	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Peru	High	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
South Africa	High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Spain	High	High	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Uruguay	High	High	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Zambia	High	High	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Finland	High	Very high	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
France	High	Very high	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Germany	High	Very high	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Greece	High	Very high	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Italy	High	Very high	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Netherlands	High	Very high	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Sweden	High	Very high	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
UK	High	Very high	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Japan	Very High	High	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
South Korea	Very High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Luxembourg	Very High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Singapore	Very High	High	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Switzerland	Very High	High	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Belgium	Very High	Very high	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Denmark	Very High	Very high	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Norway	Very High	Very high	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Turkey	Very High	Very high	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

Source: KAPSARC.
Note: Light gray areas imply a benefit-to-cost ratio greater than one, while dark gray areas imply the opposite.

The overall welfare implications of a free energy efficiency improvement

With our estimates of the welfare implications of the direct rebound effect in hand, we are now in a position to assess the overall welfare implications of a free energy efficiency improvement, where the term ‘overall’ denotes that the direct rebound effect is accounted for.

As we previously demonstrated, a free energy efficiency improvement will always be welfare enhancing with zero rebound. But what happens when rebound occurs? Table 2 presents the overall welfare implications of a free 10 percent improvement in the energy efficiency of passenger cars, accounting for the direct rebound effect. The countries in Table 2 are once again sorted by total external cost and gasoline price. The results demonstrate that in most cases, a free energy efficiency improvement will continue to be welfare enhancing, even when accounting for the welfare reducing direct rebound effect that is found in most countries. There are however a few countries where a free energy efficiency improvement becomes welfare reducing because of the direct rebound effect. This occurs because these countries had the worst direct rebound effects, which were welfare reducing to a degree that overturns the welfare enhancement originally created by the energy efficiency improvement. As discussed previously, countries that exhibited the worst direct rebound effects shared characteristics such as low gasoline prices, high congestion and large accident costs.

Price elasticity plays an important role in determining the welfare outcomes of energy efficiency. In general, higher elasticities reduce the net benefits of energy efficiency for two reasons: First, they imply larger direct rebound effects and thus larger welfare impacts (the direct rebound effect is welfare reducing in most countries). Second, at higher elasticities, the rebound effect is greater and thus the benefit from reduced external costs (due to energy savings) falls. Table 2 shows that at an elasticity of -0.1 (that is, a direct rebound effect of 10 percent), a free energy efficiency improvement is welfare enhancing in all 100 countries. At this point, the direct rebound effect is too small to have any significant impact. Moving to an elasticity of -0.3, a free energy efficiency improvement becomes welfare reducing in Singapore and Denmark, the two countries with the highest congestion costs among the 100 countries in the IMF (2016) database. With an elasticity of -0.4, Iran and Venezuela join Singapore and Denmark, although different factors play a role. In the case of Iran and Venezuela, both enjoyed the lowest gasoline prices and had medium accident and congestion costs. At an elasticity of -0.6, the group of countries in which a free energy efficiency improvement is found to be welfare reducing grows to 16. Moving to an elasticity of -1.2 (in other words, 120 percent rebound, also known as backfire), we find that a free energy efficiency improvement is welfare reducing in almost half of the countries.

In summary, the more price elastic demand is, the larger the direct rebound effect and the more significant its impact on the welfare implications of energy efficiency. Thus, for large direct rebound effects, countries that have some combination of low gasoline prices, high congestion and high accident costs will probably find a free energy efficiency improvement in passenger cars to be welfare reducing.

How would the results change if the upfront costs of an energy efficiency improvement were accounted for? For countries where a free energy efficiency improvement is found to be welfare reducing, the welfare outcomes would not change. For example, at a direct rebound effect of 30 percent, an energy efficiency improvement in passenger cars would be welfare reducing in Singapore and Denmark (see Table 2). If we then included the upfront costs of the improvement, the welfare reduction would be even greater. However, the assessment that the improvement is welfare reducing in both countries does not change by accounting for the upfront costs (it simply makes the improvement more welfare reducing). On the other hand, for countries where a free energy efficiency improvement is welfare enhancing, accounting for the upfront costs may potentially overturn the result. If the benefit-to-cost ratio is only slightly greater that one, then it is very likely that accounting for the upfront costs, even if small, would overturn the result and produce a welfare reduction (that is, a ratio less than one).

On a final note, when there is an upfront cost to the energy efficiency improvement, the boost to income from improved energy efficiency becomes smaller, as discussed by Borenstein (2015). As a result, the income effect that contributes to rebound becomes weaker, leading to smaller rebound effects.

Table 2. The benefit-to-cost ratio of a free 10 percent improvement in the energy efficiency of passenger cars, accounting for rebound, for a range of price elasticities.

Country	Total External Cost	Gasoline Price	Gasoline Price Elasticities											
			-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0	-1.1	-1.2
			Implied increase in VKT (following a 10% energy efficiency improvement)											
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%
Bahrain	Low	Low	8.6	4.1	2.5	1.8	1.3	1.0	0.8	0.7	0.5	0.4	0.3	0.3
Brunei	Low	Low	10.4	5.0	3.3	2.4	1.8	1.5	1.2	1.0	0.9	0.8	0.7	0.6
Egypt	Low	Low	8.4	4.2	2.8	2.0	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6
Nigeria	Low	Low	16.5	8.1	5.3	3.9	3.1	2.5	2.1	1.8	1.6	1.4	1.3	1.1
Bolivia	Low	Medium	11.6	5.9	4.0	3.1	2.5	2.2	1.9	1.7	1.5	1.4	1.3	1.2
Ecuador	Low	Medium	8.9	4.4	2.9	2.2	1.7	1.5	1.2	1.1	1.0	0.9	0.8	0.7
Ethiopia	Low	Medium	8.7	4.6	3.2	2.5	2.1	1.8	1.7	1.5	1.4	1.3	1.2	1.2
Ghana	Low	Medium	12.9	6.7	4.7	3.6	3.0	2.6	2.3	2.1	1.9	1.8	1.7	1.6
Indonesia	Low	Medium	10.7	5.5	3.8	2.9	2.4	2.1	1.8	1.7	1.5	1.4	1.3	1.2
Mexico	Low	Medium	10.2	5.3	3.7	2.8	2.4	2.0	1.8	1.6	1.5	1.4	1.3	1.2
Pakistan	Low	Medium	12.6	6.6	4.6	3.5	2.9	2.5	2.3	2.0	1.9	1.8	1.6	1.5
Sudan	Low	Medium	39.7	20.1	13.5	10.3	8.3	7.0	6.1	5.4	4.8	4.4	4.0	3.8
Vietnam	Low	Medium	8.4	4.4	3.1	2.4	2.0	1.7	1.5	1.4	1.3	1.2	1.1	1.0
Bangladesh	Low	High	9.7	5.2	3.7	2.9	2.5	2.2	2.0	1.8	1.7	1.6	1.5	1.4
Belarus	Low	High	9.8	5.3	3.7	3.0	2.5	2.2	2.0	1.8	1.7	1.6	1.5	1.4
Benin	Low	High	24.2	13.0	9.3	7.4	6.3	5.5	5.0	4.6	4.3	4.1	3.8	3.7
Bosnia	Low	High	9.5	5.4	4.0	3.3	2.8	2.6	2.4	2.2	2.1	2.0	1.9	1.9
Brazil	Low	High	8.7	4.9	3.7	3.1	2.7	2.4	2.3	2.1	2.0	1.9	1.9	1.8
Cameroon	Low	High	29.8	16.3	11.8	9.5	8.2	7.3	6.6	6.2	5.8	5.5	5.2	5.0
Estonia	Low	High	19.1	10.8	8.1	6.7	5.9	5.3	4.9	4.6	4.4	4.2	4.1	3.9
Georgia	Low	High	11.4	6.1	4.4	3.5	3.0	2.6	2.4	2.2	2.0	1.9	1.8	1.7
Honduras	Low	High	8.4	4.5	3.2	2.5	2.2	1.9	1.7	1.6	1.5	1.4	1.3	1.2
Ivory Coast	Low	High	9.7	5.6	4.2	3.5	3.1	2.8	2.6	2.5	2.4	2.3	2.2	2.2
Jordan	Low	High	9.4	5.1	3.6	2.9	2.4	2.1	1.9	1.8	1.7	1.6	1.5	1.4
Mozambique	Low	High	8.2	4.4	3.2	2.6	2.2	1.9	1.8	1.6	1.5	1.4	1.4	1.3
Nicaragua	Low	High	8.5	4.6	3.3	2.6	2.2	2.0	1.8	1.6	1.5	1.5	1.4	1.3
Philippines	Low	High	13.1	7.0	5.0	4.0	3.3	2.9	2.7	2.4	2.3	2.1	2.0	1.9
Senegal	Low	High	22.5	12.8	9.6	8.0	7.0	6.4	5.9	5.6	5.3	5.1	4.9	4.8
Slovenia	Low	High	9.0	5.2	3.9	3.3	2.9	2.6	2.4	2.3	2.2	2.1	2.1	2.0
Thailand	Low	High	8.5	4.7	3.5	2.9	2.5	2.2	2.1	1.9	1.8	1.7	1.7	1.6
Togo	Low	High	21.3	11.6	8.4	6.8	5.8	5.2	4.7	4.4	4.1	3.9	3.7	3.6
Ukraine	Low	High	10.2	5.4	3.8	3.0	2.6	2.3	2.0	1.9	1.7	1.2	1.2	1.2
Zimbabwe	Low	High	19.3	10.7	7.8	6.4	5.5	4.9	4.5	4.2	4.0	3.8	3.6	3.5

Iran	Medium	Low	4.8	2.2	1.4	0.9	0.7	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Oman	Medium	Low	5.8	2.8	1.8	1.3	1.0	0.8	0.6	0.5	0.5	0.4	0.3	0.3
Saudi Arabia	Medium	Low	5.5	2.6	1.6	1.1	0.8	0.6	0.5	0.4	0.3	0.2	0.2	0.1
Venezuela	Medium	Low	5.4	2.5	1.5	1.0	0.7	0.5	0.4	0.3	0.2	0.1	0.1	0.0
Azerbaijan	Medium	Medium	6.4	3.3	2.2	1.7	1.4	1.2	1.1	0.9	0.9	0.8	0.7	0.7
Botswana	Medium	Medium	6.2	3.3	2.3	1.8	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8
El Salvador	Medium	Medium	6.3	3.3	2.3	1.8	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8
Kazakhstan	Medium	Medium	7.6	3.9	2.6	2.0	1.6	1.4	1.2	1.1	1.0	0.9	0.8	0.8
Malaysia	Medium	Medium	5.7	2.9	1.9	1.5	1.2	1.0	0.8	0.7	0.7	0.6	0.5	0.5
Tunisia	Medium	Medium	6.1	3.2	2.3	1.8	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8
United States	Medium	Medium	6.7	3.4	2.4	1.8	1.5	1.3	1.1	1.0	0.9	0.9	0.8	0.7
Albania	Medium	High	6.5	3.7	2.7	2.2	2.0	1.8	1.6	1.5	1.5	1.4	1.3	1.3
Bulgaria	Medium	High	6.9	3.9	2.9	2.4	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.4
Chile	Medium	High	6.1	3.4	2.5	2.0	1.7	1.6	1.4	1.3	1.3	1.2	1.2	1.1
China	Medium	High	6.0	3.2	2.3	1.8	1.5	1.4	1.2	1.1	1.1	1.0	0.9	0.9
Costa Rica	Medium	High	6.4	3.4	2.5	2.0	1.7	1.5	1.4	1.3	1.2	1.1	1.1	1.0
Croatia	Medium	High	7.6	4.3	3.3	2.7	2.4	2.2	2.0	1.9	1.8	1.7	1.7	1.6
Cyprus	Medium	High	7.0	3.9	2.9	2.4	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.4
Czech R.	Medium	High	5.9	3.4	2.6	2.2	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.4
Hungary	Medium	High	7.3	4.2	3.2	2.7	2.4	2.1	2.0	1.9	1.8	1.7	1.7	1.6
Kenya	Medium	High	7.6	4.2	3.1	2.5	2.2	2.0	1.8	1.7	1.6	1.5	1.5	1.4
Latvia	Medium	High	8.4	4.7	3.5	2.9	2.5	2.3	2.1	2.0	1.9	1.8	1.7	1.7
Lithuania	Medium	High	6.2	3.5	2.6	2.2	1.9	1.7	1.6	1.5	1.4	1.4	1.3	1.3
Malta	Medium	High	6.1	3.5	2.7	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.4	1.3
Mongolia	Medium	High	7.7	4.2	3.0	2.4	2.0	1.8	1.6	1.5	1.4	1.3	1.2	1.2
New Zealand	Medium	High	6.7	3.8	2.8	2.3	2.0	1.8	1.7	1.6	1.5	1.4	1.4	1.3
Paraguay	Medium	High	6.1	3.4	2.5	2.0	1.7	1.5	1.4	1.3	1.2	1.2	1.1	1.1
Poland	Medium	High	6.1	3.5	2.6	2.2	1.9	1.7	1.6	1.5	1.4	1.4	1.3	1.3
Romania	Medium	High	6.0	3.4	2.5	2.1	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.2
Slovakia	Medium	High	7.0	4.0	3.0	2.6	2.3	2.1	1.9	1.8	1.7	1.7	1.6	1.6
Sri Lanka	Medium	High	5.9	3.2	2.3	1.9	1.6	1.4	1.3	1.2	1.1	1.1	1.0	1.0
Israel	Medium	Very high	6.7	3.9	3.0	2.5	2.2	2.0	1.9	1.8	1.7	1.7	1.6	1.6
Portugal	Medium	Very high	6.1	3.6	2.8	2.3	2.1	1.9	1.8	1.7	1.6	1.6	1.5	1.5
Kuwait	High	Low	3.8	1.8	1.1	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.1
Russia	High	Medium	6.6	3.4	2.3	1.8	1.5	1.2	1.1	1.0	0.9	0.8	0.8	0.7
Syria	High	Medium	3.6	1.9	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.6	0.5	0.5
Australia	High	High	5.1	2.8	2.0	1.7	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9
Austria	High	High	5.2	3.0	2.2	1.9	1.6	1.5	1.4	1.3	1.2	1.2	1.2	1.1
Cambodia	High	High	5.1	2.7	2.0	1.6	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8
Canada	High	High	5.0	2.7	2.0	1.6	1.4	1.2	1.1	1.0	1.0	0.9	0.9	0.8
Colombia	High	High	5.3	2.9	2.2	1.8	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0

Dominican R.	High	High	3.7	2.0	1.5	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6
Iceland	High	High	5.3	3.1	2.3	2.0	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.2
India	High	High	4.8	2.6	1.9	1.5	1.3	1.1	1.0	0.9	0.9	0.8	0.8	0.8
Ireland	High	High	4.6	2.7	2.0	1.7	1.5	1.4	1.3	1.2	1.2	1.1	1.1	1.1
Peru	High	High	5.8	3.2	2.4	1.9	1.7	1.5	1.4	1.3	1.2	1.2	1.1	1.1
South Africa	High	High	3.9	2.1	1.5	1.2	1.1	0.9	0.9	0.8	0.7	0.7	0.7	0.7
Spain	High	High	4.4	2.5	1.9	1.6	1.4	1.2	1.1	1.1	1.0	1.0	1.0	0.9
Uruguay	High	High	5.6	3.2	2.3	1.9	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.1
Zambia	High	High	5.4	3.1	2.3	2.0	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.2
Finland	High	Very high	4.6	2.7	2.1	1.8	1.6	1.5	1.4	1.3	1.2	1.2	1.2	1.1
France	High	Very high	4.1	2.4	1.9	1.6	1.4	1.3	1.2	1.2	1.1	1.1	1.1	1.0
Germany	High	Very high	5.2	3.0	2.3	2.0	1.8	1.6	1.5	1.4	1.4	1.3	1.3	1.3
Greece	High	Very high	5.4	3.2	2.5	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.4
Italy	High	Very high	6.0	3.5	2.7	2.3	2.0	1.9	1.7	1.7	1.6	1.5	1.5	1.4
Netherlands	High	Very high	4.2	2.5	2.0	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1
Sweden	High	Very high	4.4	2.6	2.0	1.7	1.5	1.4	1.3	1.2	1.2	1.1	1.1	1.1
U.K.	High	Very high	4.7	2.8	2.1	1.8	1.6	1.5	1.4	1.3	1.3	1.6	1.5	1.5
Japan	Very high	High	2.5	1.4	1.1	0.9	0.8	0.7	0.6	0.6	0.6	0.6	0.5	0.5
South Korea	Very high	High	3.3	1.8	1.4	1.1	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.6
Luxembourg	Very high	High	2.9	1.7	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.6	0.6
Singapore	Very high	High	2.2	1.2	0.9	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4
Switzerland	Very high	High	2.8	1.6	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.6	0.6
Belgium	Very high	Very high	3.6	2.1	1.6	1.4	1.2	1.1	1.0	1.0	0.9	0.9	0.9	0.9
Denmark	Very high	Very high	2.1	1.2	1.0	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5
Norway	Very high	Very high	2.7	1.6	1.3	1.1	1.0	0.9	0.9	0.8	0.8	0.8	0.7	0.7
Turkey	Very high	Very high	2.8	1.7	1.4	1.2	1.1	1.0	1.0	0.9	0.9	0.9	0.9	0.8

Source: KAPSARC.
Note: Light gray areas imply a benefit-to-cost ratio greater than one, while dark gray areas imply the opposite.

Welfare implications of the direct rebound effect in other sectors

Is the direct rebound effect welfare reducing more often than not, even for improvements in the energy efficiency of other energy services? An improvement in the efficiency of building lighting, for example, which normally gives rise to a rebound effect, will not produce any service-related externalities such as congestion and accidents in the case of driving. We can examine the potential welfare implications of such an improvement by setting the external costs of congestion and accidents to zero in our analysis.

In fact, the majority of the cost associated with the direct rebound effect from more energy-efficient passenger cars is due to congestion and accidents. According to Parry et al. (2014), the average external cost of air pollution and GHG emissions together was 10.7 cents per liter, while the average external cost of congestion and accidents amounted to 43.5 cents per liter (both averages were taken across all 100 countries for the year 2010). Service-related externalities thus account for more than 80 percent of the total cost of the direct rebound effect in passenger cars on average. By setting them to zero, however, the costs associated with the direct rebound effect fall significantly given that air pollution and GHG emissions become the only relevant externalities.

Table 3 presents the welfare implications of the direct rebound effect from more energy-efficient passenger cars, assuming zero congestion and accident costs. The results reveal welfare enhancing direct rebound effects for most countries, given that the cost of rebound is considerably lower than before. This suggests that there may be a need to review the conventional wisdom that rebound is a negative phenomenon that always requires mitigation. In fact, such welfare enhancing rebound effects may help improve the welfare implications of energy efficiency when accounted for, thus making energy efficiency more attractive to policymakers.

Table 3. The benefit-to-cost ratio of the direct rebound effect following a 10 percent improvement in the energy efficiency of passenger cars, assuming zero congestion and accident costs, for a range of price elasticities.

		Gasoline Price Elasticities											
Country	**Gasoline Price**	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0	-1.1	-1.2
		Implied increase in VKT (following a 10% energy efficiency improvement)											
		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%
Bahrain	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Brunei	Low	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Egypt	Low	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Iran	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kuwait	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nigeria	Low	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Oman	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Venezuela	Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Azerbaijan	Medium	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Bolivia	Medium	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Botswana	Medium	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Ecuador	Medium	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
El Salvador	Medium	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Ethiopia	Medium	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Ghana	Medium	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Indonesia	Medium	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Kazakhstan	Medium	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Malaysia	Medium	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Mexico	Medium	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7

Pakistan	Medium	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Russia	Medium	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Sudan	Medium	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Syria	Medium	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
Tunisia	Medium	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
United States	Medium	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Vietnam	Medium	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Albania	High	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1
Australia	High	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
Austria	High	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
Bangladesh	High	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Belarus	High	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Benin	High	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Bosnia	High	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Brazil	High	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Bulgaria	High	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1
Cambodia	High	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Cameroon	High	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Canada	High	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Chile	High	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
China	High	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Colombia	High	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
Costa Rica	High	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Croatia	High	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Cyprus	High	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9
Czech R.	High	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
Dominican R.	High	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Estonia	High	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
Georgia	High	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Honduras	High	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Hungary	High	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.8	12.8	12.8	12.8
Iceland	High	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
India	High	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Ireland	High	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Ivory Coast	High	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
Japan	High	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Jordan	High	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Kenya	High	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.9
Latvia	High	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
Lithuania	High	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.6	8.6	8.6	8.6	8.6
Luxembourg	High	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1

Malta	High	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
Mongolia	High	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Mozambique	High	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
New Zealand	High	11.9	11.9	11.9	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
Nicaragua	High	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Paraguay	High	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
Peru	High	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
Philippines	High	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Poland	High	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
Romania	High	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
South Korea	High	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Senegal	High	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
Singapore	High	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Slovakia	High	13.8	13.8	13.8	13.8	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Slovenia	High	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
South Africa	High	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.2
Spain	High	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Sri Lanka	High	7.1	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Switzerland	High	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.4	13.4	13.4
Thailand	High	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Togo	High	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Ukraine	High	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Uruguay	High	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Zambia	High	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
Zimbabwe	High	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Belgium	Very High	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Denmark	Very High	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.8	17.8	17.8	17.8	17.8
Finland	Very High	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
France	Very High	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Germany	Very High	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Greece	Very High	17.8	17.8	17.8	17.8	17.8	17.7	17.7	17.7	17.7	17.7	17.7	17.7
Israel	Very High	10.4	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Italy	Very High	15.5	15.5	15.5	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
Netherlands	Very High	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3
Norway	Very High	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.0	16.0	16.0	16.0	16.0
Portugal	Very High	15.9	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8
Sweden	Very High	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.2	15.2	15.2	15.2	15.2
Turkey	Very High	23.1	23.1	23.1	23.1	23.1	23.1	23.1	23.1	23.1	23.1	23.1	23.1
U.K.	Very High	16.4	16.4	16.4	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3

Source: KAPSARC.
Note: Light gray areas imply a benefit-to-cost ratio greater than one, while dark gray areas imply the opposite.

Conclusion

This paper is, to the best of our knowledge, the first to conduct an empirical welfare analysis of the direct rebound effect from more energy-efficient passenger cars in a large number of countries. It also demonstrates empirically the impact that the direct rebound effect can have on the welfare implications of energy efficiency, which is often overlooked.

Our findings reveal that the direct rebound effect from more energy-efficient passenger cars is welfare reducing in most countries. Because of the high externalities, the costs are often found to exceed the benefits. Furthermore, we find that the direct rebound effect is generally worse (that is, more welfare reducing) in countries with some combination of low gasoline prices, high congestion and large accident costs.

The results carry important implications for energy efficiency policymaking, particularly in the road transport sector, given that most evaluations of energy efficiency do not account for rebound, which can lead to a misleading evaluation. We find the welfare outcomes of the direct rebound effect to have a significant impact on energy efficiency. In fact, in countries with the most welfare reducing direct rebound effects, we demonstrate that even a free energy efficiency improvement in passenger cars can become welfare reducing when accounting for rebound.

Our work has three key messages for policymakers. First, it highlights the importance of accounting for the welfare implications of the rebound effect, which can have a considerable impact on decisions to move forward with energy efficiency policies. For some countries, the welfare reduction produced by the direct rebound effect may be large enough to overturn the welfare enhancement brought about by the energy efficiency improvement. For other countries, the welfare enhancement produced by rebound may help increase the net benefits of energy efficiency.

Second, energy efficiency policies such as fuel economy standards are less likely to be welfare enhancing when fuel prices are low or congestion and accident costs high, partly because of the rebound effect. Thus, energy efficiency policies may be more effective when combined with policies that raise fuel prices. Furthermore, complementary policies that can mitigate congestion and reduce road accidents can indirectly improve the welfare implications of energy efficiency policies in road transport.

The third key message is that the rebound effect is not always welfare reducing, as some studies have suggested. For some countries, rebound in passenger cars is found to be welfare enhancing. Moreover, when we set the congestion and accident costs to zero to model the potential welfare implications of rebound in other energy services, such as lighting, we find the rebound effect to be welfare enhancing in most cases. It is therefore important to model and understand the welfare implications of the rebound effect before considering any policies to mitigate it. More work in this area could help change the negative perceptions that the rebound effect holds in energy policy discussions. Ultimately, for most energy efficiency policies, the primary goal is to maximize welfare rather than minimize energy consumption, and the rebound effect could help support that goal.

The analysis presented in this paper considered the welfare implications of more energy-efficient passenger cars and the ensuing direct rebound effect, focusing only on consumers and the government. We effectively assumed a market structure of perfect competition such that producer surplus falls to zero. Furthermore, the welfare implications of the indirect rebound effect were not considered in our analysis. Future work could account for both of these factors, providing a more complete picture of the welfare implications of energy efficiency and rebound. Future research could also examine whether the welfare results presented here hold for other energy services.

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Appendix A: Estimating the Direct Rebound Effect from Elasticities

Our treatment begins with a general framework that links energy demand to energy service demand. As shown by Sorrell and Dimitropoulos (2008),

$$S = \eta E \tag{A1}$$

where S is the demand for the energy service, η the energy efficiency and E the demand for energy. In the case of gasoline vehicles, S would be the demand for driving (measured in kilometers), η the average efficiency of gasoline vehicles (measured in kilometers per liter) and E the demand for gasoline (measured in liters).

Sorrell and Dimitropoulos (2008) also show that the implicit price of driving (P_d) depends on both the price of gasoline (P_g) and the level of energy efficiency.

$$P_d = P_g / \eta \tag{A2}$$

It is worth noting that one limitation of this widely used definition is that it overlooks the time cost of driving, an important consideration for motorists (Small and Van Dender 2007).

Given the empirical nature of this study, we follow the approach used by Davis (2017) by assuming that gasoline demand takes the form of a constant elasticity function. As he shows, this functional form is not only conducive to welfare analysis but is also consistent with many empirical studies that model gasoline demand (for example, the studies surveyed by Dahl 2010). We define the following demand curve for gasoline:

$$E = AP_g^{\alpha} \tag{A3}$$

where A is the 'scale parameter' and α the long-run price elasticity of gasoline demand. The scale parameter captures all factors other than the price of gasoline that can affect demand such as income, demographics, driving behavior and energy efficiency. Using data on gasoline demand and prices, the scale parameter can be estimated easily.

The elasticity of gasoline demand with respect to the price of gasoline is denoted by:

$$\varepsilon_{E,Pg} = \alpha \tag{A4}$$

The constant elasticity gasoline demand function implies the following demand curve for driving:

$$S = \eta A P_g^{\alpha} \tag{A5}$$

Depending on the functional form of the scale parameter A, the demand for driving may or may not be a constant elasticity function. To resolve this issue, we choose the following form for the scale parameter A:

$$A = \frac{K}{\eta^{\alpha+1}} \tag{A6}$$

where K is the 'reduced scale parameter'. Unlike the scale parameter, which is a function of factors such as income, demographics, driving behavior and energy efficiency, the reduced scale parameter is defined to be a function of all of those factors except for energy efficiency. The reduced scale parameter can be estimated using the estimated scale parameter in addition to data on energy efficiency and the price elasticity.

The reduced scale parameter allows us to express the demand for driving as a constant elasticity function with the same elasticity as the gasoline price elasticity:

$$S = KP_d^{\alpha} \tag{A7}$$

Given that the reduced scale parameter does not depend on energy efficiency, any improvement in energy efficiency will only affect the demand for driving through a fall in the implicit price of driving. In other words, the reduced scale parameter allows us to model an improvement in energy efficiency as a 'slide' or movement along the demand curve for driving, which is commonly referred to as a pure price effect (Greening et al. 2000).

The functional form used for the scale parameter A, shown in Equation (A6), achieves a number of objectives. First, it allows the demand for the energy service, in this case driving, to be expressed as a constant elasticity function. Second, it allows an improvement in the energy efficiency of passenger cars to manifest as a pure price effect. In contrast, many other functional forms would cause the improvement in energy efficiency to manifest simultaneously as a slide along the demand curve and a shift in demand. Finally, the elasticity relationships derived using this functional form are consistent with a single-energy single-service case.

The elasticity of driving with respect to energy efficiency ($\varepsilon_{S,\eta}$) is often used as a measure of the direct rebound effect (Sorrell and Dimitropoulos 2008). However, very few studies estimate this elasticity. Instead, most studies focus on estimating the elasticity of energy demand with respect to the price of energy ($\varepsilon_{E,Pg}$). Nevertheless, Sorrel and Dimitropoulos (2008), Hunt and Ryan (2014) and Chan and Gillingham (2015) have shown using a general theoretical framework how the former elasticity can be estimated from the latter.

These elasticity relationships can also be shown to hold true using the constant elasticity functions introduced in this paper. Taking the derivative of the demand function for driving with respect to energy efficiency, we find that:

$$\frac{\partial S}{\partial \eta} = \frac{\partial S}{\partial P_d}\frac{\partial P_d}{\partial \eta} = \left(\alpha \frac{S}{P_d}\right)\left(-\frac{P_E}{\eta^2}\right) = -\alpha\frac{S}{\eta} \tag{A8}$$

Therefore,

$$\varepsilon_{S,\eta} = \frac{\partial S}{\partial \eta}\frac{\eta}{S} = -\alpha = -\varepsilon_{E,P_g} \tag{A9}$$

Appendix B: Estimating the Benefits of Energy Efficiency and Rebound

When the energy efficiency of passenger cars improves, the implicit price of driving falls from P_{d0} to P_{d1}. The demand function for driving can then be used to predict the consumer surplus gained from this price decrease, as follows:

$$B_{CS} = \int_{P_{d1}}^{P_{d0}} K\, P_d{}^{\alpha}\, dP_d = \frac{K}{\alpha+1}\left[P_{d0}{}^{\alpha+1} - P_{d1}{}^{\alpha+1}\right] = B_{MS} + B_R$$

(B1)

where B_{CS} denotes the benefit due to the consumer surplus gained from improved energy efficiency, and is broken down into two smaller areas (B_{MS} and B_R). The first (B_{MS}) reflects the expected monetary savings from improved energy efficiency. In other words, it reflects the fall in spending that consumers are rewarded with when they invest in an energy efficiency upgrade, and can be easily calculated:

$$B_{MS}=(P_{d0}-P_{d1})*S_0$$

(B2)

where S_0 is the demand for driving before the energy efficiency improvement; S_R denotes the demand for driving after the improvement, which increases because of the rebound effect.

As noted by Clinch and Healy (2001), most cost-benefit analyses of energy efficiency only account for the monetary savings (B_{MS}) when computing the benefits of an energy efficiency improvement. Such analyses overlook the benefit due to the direct rebound effect (B_R), which stems from the consumer surplus gained from additional driving, which can be computed as follows:

$$B_R = B_{CS} - B_{MS} = \frac{K}{\alpha+1}\left[P_{d0}{}^{\alpha+1} - P_{d1}{}^{\alpha+1}\right] - (P_{d0} - P_{d1}) * S_0$$

(B3)

There is a third benefit from improved energy efficiency. Since gasoline consumption is associated with external costs such as air pollution and GHG emissions (Parry et al. 2014), any reduction in gasoline consumption will lead to a reduction in these externalities. The benefit from reducing these external costs can be calculated by multiplying the fall in gasoline consumption (measured in liters) by the externalities of air pollution and GHG emissions (measured in US$ per liter), which are denoted by δ_E.

$$B_{EC}=(E_0 - E_{NR})\, \delta_E$$

(B4)

B_{EC} denotes the benefit from lower external costs, E_0 the gasoline consumption before the energy efficiency improvement and E_{NR} the gasoline consumption after the improvement, assuming no rebound. The following formula can be used to estimate E_{NR} following an x percent improvement:

$$E_{NR} = \frac{S_0}{\eta_0(1+x)} = \frac{S_0}{\eta_1} = E_0\left(1 - \frac{x}{1+x}\right)$$

(B5)

In this paper, we consider a 10 percent improvement in the energy efficiency of passenger cars. However, it is worth noting that the size of the improvement does not alter the welfare outcomes in any significant way.

Appendix C: Estimating the Costs of Energy Efficiency and Rebound

The cost of the direct rebound effect can be broken down into two segments. The first is due to the external costs that arise from the additional gasoline consumption above a scenario in which there was no rebound. This cost can be calculated by multiplying the additional consumption (measured in liters) by the marginal damages due to air pollution and GHG emissions (measured in US$ per liter).

$$C_E=(E_R - E_{NR})\, \delta_E \qquad \text{(C1)}$$

C_E denotes the total energy-related cost of the direct rebound effect. E_R denotes the gasoline consumption following rebound, which can be estimated by inserting the improved energy efficiency value (η_1) into the gasoline demand function.

The second segment is due to the external costs that arise from the additional driving that defines the direct rebound effect. By definition, the quantity of driving is assumed to be fixed before and after the energy efficiency improvement when the direct rebound effect is zero. When it is greater than zero, consumers will drive more, leading to greater congestion and accidents. We can account for this cost by multiplying the additional driving by the externalities of congestion and accidents (measured in US$ per kilometer), which are denoted by δ_S.

$$C_S=(S_R - S_0)\, \delta_S \qquad \text{(C2)}$$

C_S denotes the total driving-related cost of the direct rebound effect and S_R the demand for driving following rebound, which can be estimated by inserting the lower price of driving (P_{d1}) into the demand function for driving.

Appendix D: The Welfare Implications When Prices Deviate From Private Cost

We can account for the impact of improved energy efficiency on the government by calculating the government gain or loss following the energy efficiency improvement, assuming no rebound initially. This gain or loss to the government, which we denote by G_{NR}, can be estimated through the following equation:

$$G_{NR} = \left(P_g{}^* - P_g\right) * (E_0 - E_{NR}) \quad \text{(D1)}$$

where $P_g{}^*$ is the private cost of a liter of gasoline, P_g the domestic price for gasoline in a country, E_0 the level of gasoline consumption before the energy efficiency improvement and E_{NR} the level of energy consumption after the improvement, assuming no rebound.

We account for the impact of the direct rebound effect on the government by calculating the government gain or loss because of rebound. This gain or loss, denoted by G_R, can be estimated through the following equation:

$$G_R = \left(P_g{}^* - P_g\right) * (E_{NR} - E_R) \quad \text{(D2)}$$

where E_R is the level of gasoline consumption following rebound.

We account for the net impact of the energy efficiency improvement on the government as follows:

$$G = G_{NR} + G_R = \left(P_g{}^* - P_g\right) * (E_0 - E_R) \quad \text{(D3)}$$

Equation (D3) demonstrates that for direct rebound effects smaller than 100 percent, governments that tax gasoline will see a negative impact on their revenues when energy efficiency improves, while governments that subsidize gasoline will see a positive impact.

Following the approach used by Davis (2017), we use the opportunity cost of gasoline to measure private cost. Given that gasoline is traded internationally, we use global spot prices as measures of opportunity cost. Four different spot prices were used in the calculations. For Middle Eastern countries, the average 2010 'free on board' (FOB) spot price of 95-octane gasoline at Jebel Ali port was used (Platts 2016); for Asian countries, the 2010 spot price at Singapore port (Platts 2016); for European and African countries, the 2010 Eurobob gasoline spot price at Rotterdam port (Platts 2016); for North and South American countries, an average of the 2010 New York Harbor and U.S. Gulf Coast Conventional Gasoline spot prices (Reuters 2016).

To include the government in the welfare analysis of the direct rebound effect, the variable G_R is added to either the benefits (when positive) or costs (when negative) of rebound in Equation (4). To include the government in the overall welfare analysis of an energy efficiency improvement, the variable G is added to either the benefits or costs of energy efficiency in Equation (5), depending on its sign.

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About the Project

KAPSARC's work on energy demand and efficiency looks at how economic growth, population, energy prices and energy efficiency influence energy demand in different countries, with a focus on Saudi Arabia and the Gulf Cooperation Council. Our objective is to understand and quantify the influence of each of these factors, which also allows us to estimate underlying energy efficiency in different countries. Our work also looks at the welfare implications of policies, from price reform to energy efficiency, and their impact on energy demand.