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ABSTRACT

The global rise of greenhouse gas (GHG) emissions and its potentially devastating consequences require a comprehensive regulatory framework for reducing emissions, including those from the transport sector. Alternative fuels and technologies have been promoted as means for reducing the carbon intensity of the transport sector. However, the overall transport policy framework in major world economies is geared towards the use of conventional fossil fuels. This paper evaluates the effectiveness and efficiency of current climate policies for road transport that (1) target fuel producers and/or car manufacturers, and (2) influence use of alternative fuels and technologies. With diversifying fuel supply chains, carbon intensity of fuels and energy efficiency of vehicles cannot be regulated by a single instrument. We demonstrate that vehicles are best regulated across all fuels in terms of energy per distance. We conclude that price-based policies and a cap on total emissions are essential for alleviating rebound effects and perverse incentives of fuel efficiency

standards and low carbon fuel standards. In tandem with existing policy tools, cap and price signal policies incentivize all emissions reduction options. Design and effects of cap and trade in the transport sector are investigated in the companion article (Flachsland et al., 2010).

Keywords: Fuel efficiency standards, low carbon fuel standards, climate change

1. Introduction

The transport sector accounts for more than half of the oil used worldwide and roughly a quarter of energy-related CO₂ emissions (IEA, 2008). If emissions from feedstock and fuel production are included, the transport sector is responsible for close to 27% of global greenhouse gas (GHG) emissions. The sector's global growth rate of energy consumption during 1990-2002 was highest among all the end-use sectors. In the USA, for instance, between 1990 and 2006, growth in transport emissions represented almost half of the increase in total US GHG emissions (EPA, 2009).

To prevent dangerous climate change, global emissions in 2050 will need to be at least halved compared to 2005 levels. Transport is supposed to play a vital role in abatement efforts. Yet world transport energy use and emissions are projected to increase by more than 50% by 2030 and will more than double by 2050 in a business-as-usual scenario. Around 75% of the projected total increase in world oil demand will come from the transport sector by then. While oil extraction is expected to peak and begin to decline in the near future, the shortfall is partially compensated with non-conventional oil (such as tar sands) and other fossil resources such as gas-to-liquids and coal-to-liquids. On average, these fuels are more carbon intensive than oil, caused by upstream emissions in the supply chain. While international shipping and aviation contribute significantly to the projected rise in emissions, the highest share will still come from road transport, i.e. motorized vehicles. Shifting towards a sustainable, low-carbon transport system is, hence, imperative for successful climate stabilization, and also for dealing with ever more problematic congestion challenges in a rapidly urbanizing world.

A variety of measures have been suggested to counter rising GHG emissions in the road transport sector, including land-use policies, transport demand management, infrastructure investments and (alternative) fuel technologies (Kahn Ribeiro et al., 2007; Creutzig and He, 2009; Cervero and Murakami, 2010; Creutzig and Edenhofer, 2010). Fuel technologies are required to reduce the relative impact of road transport: More efficient cars and alternative propulsion systems, such as battery electric vehicles (BEVs), fuel cell hybrid electric vehicles, and electric bicycles can improve the energy efficiency and reduce the carbon intensity of transport. In fact, the global market share of electric vehicles, such as battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) is unanimously projected to grow. However, the extent and pace of growth is uncertain and dependent on a number of factors. Projected market shares in the total of the vehicle fleet in 2020 range between 1% and 13%, with 7% as the median estimate (BCG, 2009). In the long term, the IEA (2009b, see also Fulton, 2010) forecasts a 50% market share in 2050. The near-term economic potential of electric vehicles is dependent on various uncertain factors including energy prices (oil, electricity), battery technology and cost, economies of scale, recharging infrastructure, regulatory requirements and fiscal incentives. Depending on future oil price and regulation, electric vehicles (including fuel cell hybrid electric vehicles) will have between 40% and 95% market shares in 2030 in Germany (Mock et al., 2009). Electric vehicles have zero tail pipe emissions, but can have significant upstream emissions, e.g. when electricity is produced in coal powerplants. Hence, their carbon footprint – the total set of greenhouse gases (GHG) emissions caused by fuel production, supply and consumption - is less related to the vehicle technology but hinges on regional power supply.

Irrespective of the detailed trajectory of their future market gains, alternative vehicles will imply a long-term shift in the energy used for vehicle propulsion. The fuel market for vehicles will

become more diverse, and supply chains will become more complicated: Whereas conventional fossil fuels - gasoline and diesel - powered nearly all of road transport over the last century and still completely dominate the fuel market, electricity and potentially hydrogen, but also non-conventional fossil fuels, such as the Canadian tar sands, will provide a small but significant proportion of energy for vehicles within the next decade. As the carbon footprint of fuels diversifies, emissions partially decouple from the energy content of fuels. Instead, the varying carbon intensity of fuels - a function of both feedstock and production process – determines the overall carbon footprint. From a climate perspective, only the global warming effect of these fuels matters. However, in the current EU and Californian policy framework, cars are regulated with respect to GHG emissions per distance (CO_{2e}/km) – in the case of electric cars irrespective of the precise global warming potential of fuels used. Furthermore, sometimes the more environmentally-benign fuels are more tightly regulated with respect to greenhouse gas emissions than the more harmful fuel: For example, in the European ETS, GHG emissions of electric rail are part of a cap-and-trade scheme whereas conventional transport fuels are not covered by climate policies. Hence, providing a level playing field for all fuels becomes increasingly important to achieve efficient and effective abatement in the transport sector.

In this paper, we review policy instruments that regulate the GHG emissions of fuels and vehicles. We recommend to modify and rearrange regulation in light of alternative fuels, and to close up the policy space by a quantity instrument, such as cap and trade. A detailed fuel pathway inventory reveals that alternative vehicles and fuels foster a shift in focus from tail pipe emissions to upstream emissions. Also, due to a number of different possible fuel pathways, life cycle emissions of vehicle usage partially decouple from fuel efficiency (section 2). A decomposition of transport's

GHG emissions into three factors allows for conceptualizing the match between policy instruments, actors, and level of regulation (section 3). Fuel efficiency standards are the most effective transport policy instrument currently but are not specifically designed to flexibly regulate vehicles across all propulsion technologies. Also, the increased efficiency of the car fleet is partially offset by increased driving due to rebound effects (section 4). Renewable fuel standards seek to increase the market share of biofuels. However, GHG mitigation effectiveness is severely compromised by ignoring life cycle emissions. In contrast, low carbon fuel standards (LCFS) incentivize the production of fuels with respect to their life cycle emissions. However, leakage, perverse incentives, and complex fuel supply chains of biofuels limit the absolute effectiveness of LCFSs and render proper evaluation difficult (section 5). A cap on total GHG emissions and associated price signal can remedy rebound effects and perverse incentives (section 6).

2. Fuel pathways inventory

To evaluate climate policy instruments in the transport sector, accurate and precise accounting of GHG emissions throughout fuel pathways is required for two reasons:

1. Accounting and emission inventories of fuels are preconditions for any instrument that regulates fuels according to their lifecycle GHG emissions.
2. Understanding where emissions occur enables appropriate matching of instruments, emission process and actor.

Fuel pathways in road transport can be characterized by two main factors: the *global warming potential* (GWP) of its primary energy source, such as coal or wind energy, and the efficiency loss at different lifecycle stages. In the following, we provide a brief overview on the lifecycle emissions of alternative feedstocks and describe the issues associated with the different pathways:

- Conventional fuels (gasoline and diesel) have a high and relatively constant GWP per unit of primary energy. Some GHG emissions are produced at production (e.g. 7% for diesel) and by processing at refineries (e.g., 12% for diesel) (CARB, 2009a). Conventional fuels are consumed in internal combustion engines (ICE). The majority of emissions occur at end use (70-90%). Therefore, the decisive emissions factor is fuel efficiency of vehicles. Diesel engines are more efficient than gasoline engines and produce 16-24% less emissions (Kahn Ribeiro et al., 2007).
- Unconventional fuels (e.g. Canadian tar sands) can have, at the stage of fuel production, about 4.5 times larger upstream GHG emissions than U.S domestic crude oil (US DOE, 2009). However, they still constitute only about one fifth of overall lifecycle emissions. Hence, while fuel efficiency remains the dominant issue, carbon intensity of fuels becomes more important.
- Biofuels can follow a myriad of specific pathways, and produce GHG emissions at biorefineries and in agricultural feedstock production further upstream in the supply chain. The latter requires dealing with complex issues such as nitrous oxide emissions from fertilizer use (Crutzen et al., 2008), emissions from direct and indirect land use change (Farrell et al., 2006; Creutzig and Kammen, 2010) as well as emissions from alternative agricultural management practices (Kim et al. (2009)). As a result, the GWP of biofuels

varies dramatically with pathway. Uncertainty over life-cycle emissions can be substantial and make proper assessment challenging. The most market-dominant biofuel, US corn ethanol, is estimated to have higher life-cycle emissions than gasoline (Hertel et al., 2010).

- Compressed natural gas has a lower GWP than conventional fuels. Similar to conventional fuels, most emission occur at end use. Total life-cycle emissions are 15-25% lower than for gasoline engines (Kahn Ribeiro et al., 2007).
- Electricity can have very high GWP when produced in a coal power plant, and close to zero emissions when generated by renewable sources. Electric motors are significantly more efficient than ICEs, and total well-to-wheel efficiency of BEVs ranges between 75-85%. Electricity can be deployed for plug-in hybrids, full battery electric cars, or fuel cell hybrid electric vehicles. Alternative storage mediums such as compressed-air have well-to-wheel efficiency of < 30% (Creutzig et al., 2009).
- About 96% of hydrogen produced globally comes from fossil fuel feedstock. More specifically, 48% is produced via steam methane reformation (SMR) with natural gas as the feedstock, 30% comes from steam reforming or partial oxidation of petroleum and 18% from coal gasification. Electrolysis of water provides the remaining 4% (Balat & Balat, 2009). GHG emissions can vary considerably across these different pathways. Hydrogen can be deployed for fuel cell cars, hydrogen ICE vehicles, or fuel cell hybrid electric vehicles.

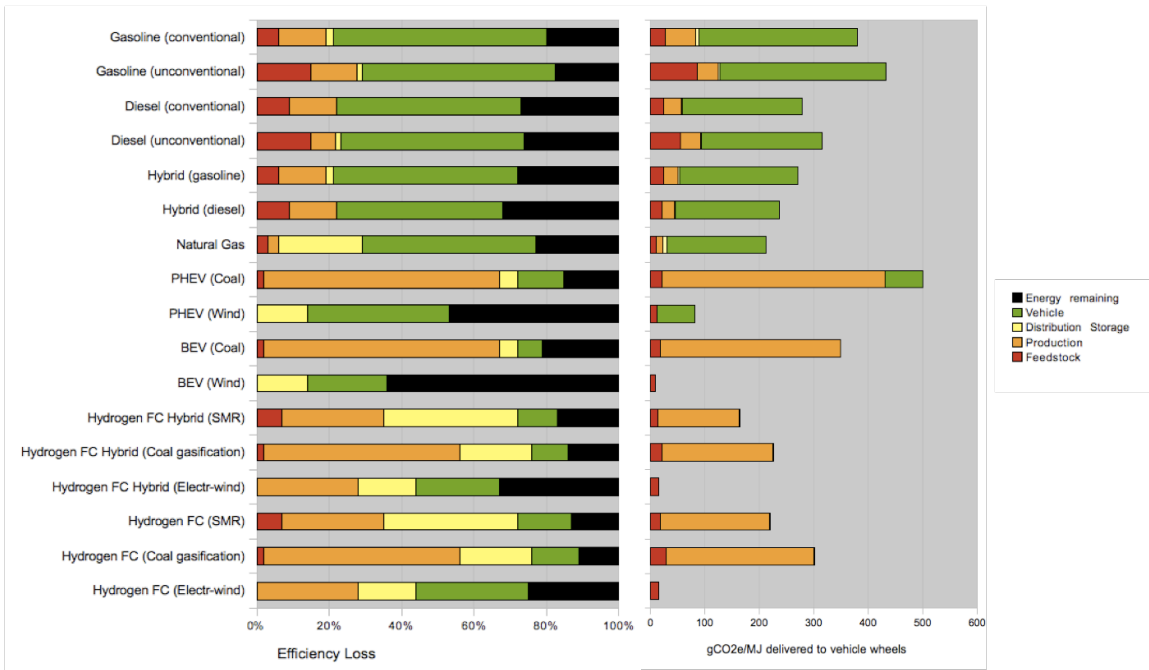


Figure 1. Overview on efficiency losses and life-cycle emissions of fuel supply chains. Numbers and references are given in (Creutzig et al., 2010).

Figure 1 provides an overview over the life-cycle emissions of different fuels (see the appendix for details). Figure 2 displays lifecycle emissions of different biofuels and natural gas. The following facts can be observed:

- Emissions of fossil fuels mostly occur downstream at the vehicle stage.
- Unconventional fossil fuels, such as those produced from Canadian tar sands, have significant additional emission at the stage of feedstock recovery.
- Emissions of alternative fuels mostly occur upstream at production stage.
- Emissions of BEVs or PHEVs vary considerably with upstream feedstock.
- Emissions of vehicles powered by hydrogen vary with vehicle technology, distribution system and feedstock.

- Emissions from biofuels crucially depend on specific feedstock. Uncertainties render accurate accounting difficult (not shown in the figure).

Crucially, fossil fuel emissions mostly occur with end use, while alternative fuel emissions occur upstream. For all of these fuels, proportionality between emissions and energy intensity is given for specific supply chains. Due to downstream mixing of upstream supply sources, however, carbon content cannot be determined from vehicle technology alone. Comprehensive policy instruments need to be adaptive to varying fuel supply chains in order to provide a level playing field across all fuels.

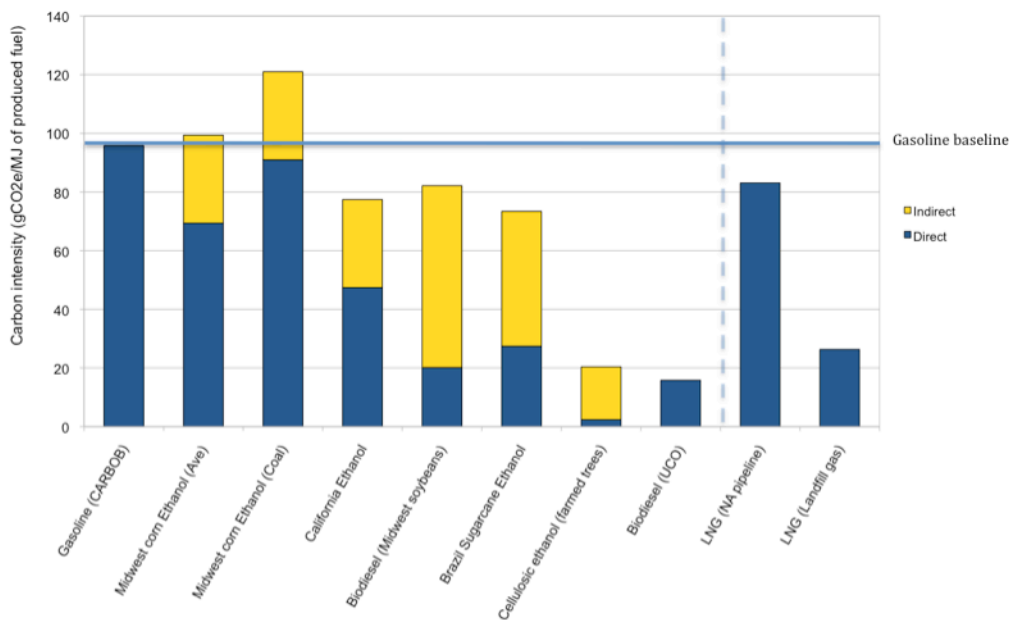


Figure 2. Overview on life cycle emissions of different biofuels and natural gas, as estimated by CARB (2009b).

3. Decomposition of GHG emissions

Generally, total GHG emissions can be decomposed into carbon intensity of fuels, energy intensity of GDP, GDP per head and population (Nakicenovic et al., 2000). For transport, Figure 1 makes clear that both carbon intensity of fuels and fuel efficiency of cars matter. More comprehensively, we decompose GHG emissions from the transport sector into carbon intensity (gCO₂e/MJ), energy intensity (MJ/km), and total transport demand (km) (compare with Schipper et al., 2007; Kamaketa & Schipper, 2009; Creutzig & Edenhofer, 2010), such that each factor of GHG emissions in road transport can be predominantly attributed to a distinct actor.

- a. Fuel producers: carbon intensity
- b. Car manufacturers: energy intensity
- c. Consumers: travel demand (and realized mileage)

Hence, policy instruments should target actors by focusing on their respective decomposed emissions factor. *Fuel producers* are responsible for the specific global warming potential of fuels. For example, refineries can change the mix of fuels, e.g. from tar sand oils and crudes to low carbon biofuels, and utilities can switch to renewable energies. The relevant measure here is the carbon intensity measured in gCO₂e/MJ (for the absolute amount of GHG emitted, see section 6). Low carbon fuel standards, renewable fuel standards and emissions trading are possible policy instruments that regulate GHG emissions of fuel producers. *Car manufacturers* are responsible for the energy intensity of their cars measured in MJ/km. For example, they can increase the efficiency of ICE vehicles, or switch to more efficient technologies, such as BEVs. Fuel efficiency standards and vehicle taxes are possible policy instruments to regulate energy intensity of cars. Finally, *consumers* are responsible for overall transport demand. Total transport demand can be influenced by spatial planning, infrastructure investments and (local) pricing tools. Transport demand

management can contribute significantly to reduced GHG emissions from the transport sector. However, these policies are mostly locally focused and their analysis is beyond the scope of this study. The overall correspondence between decomposition factors, actors and possible policies is outlined in Figure 3.

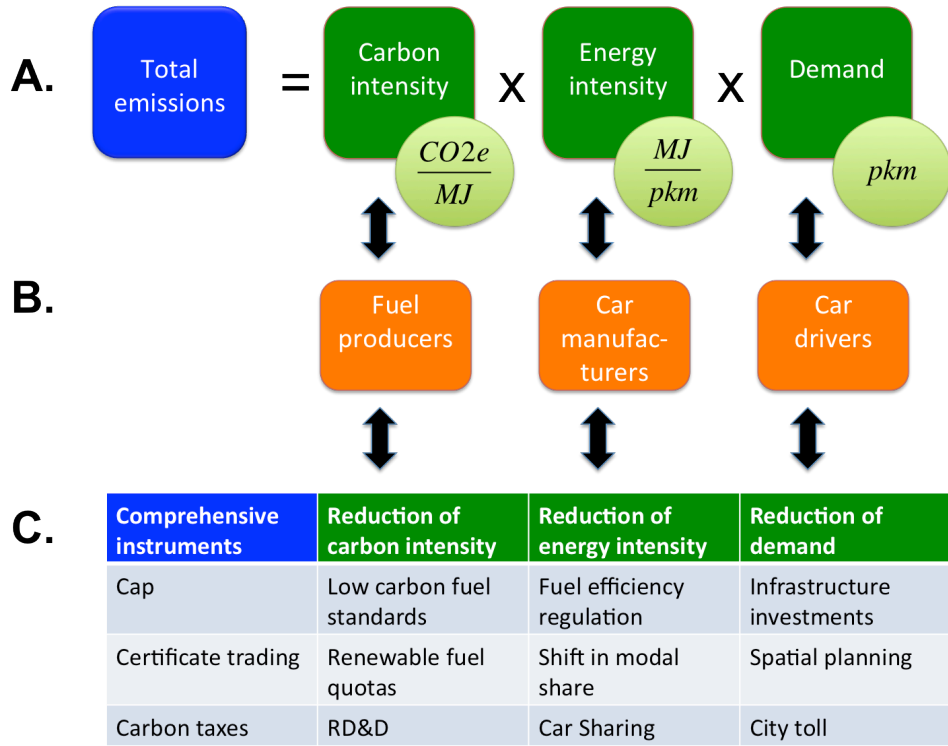


Figure 3: Decomposition of greenhouse gas emission in transportation and related policy instruments.

4. Tackling energy intensity

4.1 Existing Standards

Fuel efficiency standards are mandated world-wide in the most important automobile markets in order to foster climate change mitigation and reduce oil dependency. Fuel efficiency standards can also effectively complement price instruments that are not fully effective due to

dynamic market failures (see also Flachsland et al., 2010; Plotkin, 2008). In the following, an overview on fuel efficiency standards in different world regions is given.

European Union. The European Union started with a voluntary agreement, setting an industry-wide target of 140gCO₂/km to be reached collectively by members of each of the European, Japanese and Korean car manufacturers associations. In 2009, as not all individual members could fulfill their corresponding 25% reduction target, the EU mandated a industry fleet target of 130 g CO₂/km until 2015 with additional 10gCO₂/km to be achieved with complimentary measures, such as efficient tires, air conditioning, tire pressure monitoring, and gear shift indicators (EC, 2009c). As a weight-based average fleet standard, the manufacturer's individual target depends on its fleet characteristics and has to be fulfilled as a fleet average. Hence, a manufacturer offering smaller cars has to comply with a target below 130 g/km, and a manufacturer of heavier cars has to comply with a target above 130 g/km. Beyond this, intermediate steps for the years 2012-2015 are also mandatory, e.g. 65% of the fleets must comply with the 130gCO₂/km target in 2012. A long-term target of 95 g/km is set for 2020. The latter will be reviewed in 2013. In order to foster demand for fuel efficient vehicles, 16 of 27 EU member states have CO₂- or fuel efficiency based registration and/or annual taxation.

Japan. Japan established mandatory fuel efficiency standards for 2010 and 2015 for gasoline and diesel vehicles under its Top Runner program (An et al., 2007). As in the EU, the fuel economy targets are specified by weight class. The targets were derived from the best performance of current models. Additional acquisition taxes and annual taxes are in place. In 2009, the Japanese government implemented a limited tax incentive program fostering the purchase of low emitting and fuel efficient vehicles.

China. China implemented weight-based fuel economy standards to reduce oil dependency. Standards are specific for the weight of each car. Currently an updated fuel economy standard for 2012/13 is being discussed which would set fleet averages for each car manufacturer. In addition, excise and sales taxes incentivize the purchase of smaller-engine vehicles (Bradsher, 2009). Current standards are relatively ambitious. The average new car will be required to achieve >42mpg.

United States and California. In a joint rule making initiated by the Obama administration, the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA), the US set an industry average target of 250 gCO₂/mile (35.5 mpg) for vehicles in 2016, corresponding to the Corporate Average Fuel Economy (CAFE) target. As law makers allow EPA more flexibility in instrument design, the EPA regulation will be a little bit more stringent than the anticipated CAFE standard, i.e. by incentivizing direct and indirect efficiency improvements in air conditioning. The fuel efficiency standard is differentiated across two vehicle classes, with 39 mpg for passenger cars and 30 mpg for trucks in 2016. California has already imposed rules on automakers that started in 2009 (Pavley I). These regulations will be harmonized with federal CAFE and GHG standards from 2012 onwards (CARB, 2010).

General observations. The historic development of fuel efficiency standards in different world regions is displayed in Figure 4. This figure is an update from An et al. with new significant EU, US, and Chinese regulation (2007). The data is displayed in MJ/km – a possible measure of energy efficiency.

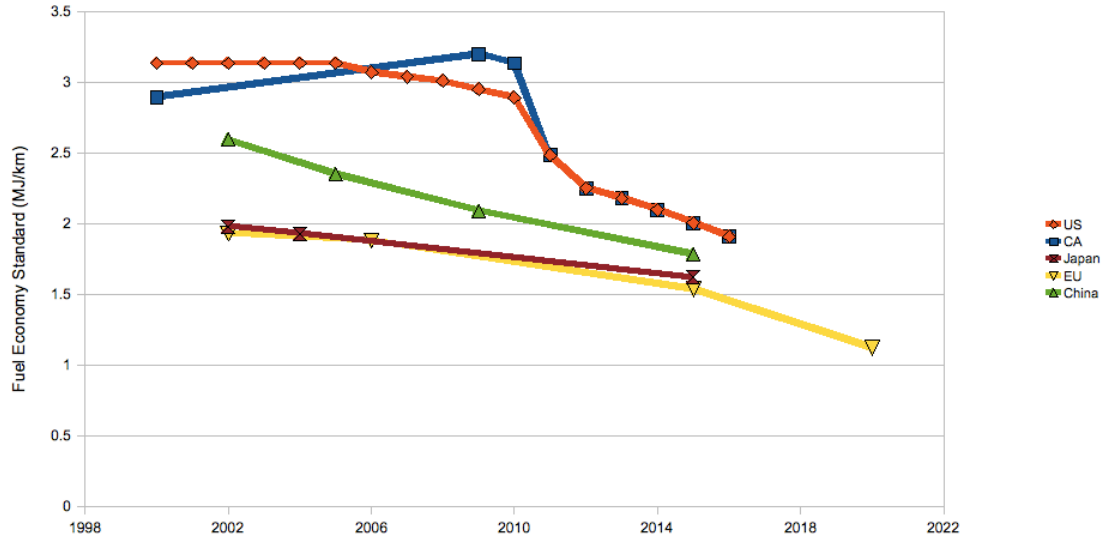


Figure 4. Energy intensity standards extrapolated from current volume and GHG fuel efficiency standards. 1 liter gasoline = 32 MJ. Data adapted from An et al. (2007) with updated fuel efficiency regulations.

The following observations emerge:

- Europe and Japan lead the world in terms of fuel efficiency.
- The US is still a laggard, but making huge progress with recent Californian and federal regulation, achieving the greatest absolute emission reduction from any global policy (An et al., 2007).
- For an emerging economy China sets impressive fuel efficiency standards, which are motivated by energy security concerns and strategic world-market positioning.

4.2 Evaluation

Fuel efficiency standards are here evaluated according to their effectiveness and their efficiency.

Effectiveness. Fuel efficiency can be effective a) with respect to reducing energy intensity and GHG emissions per car and b) with respect to absolute reduction of GHG emissions. The first goal is generally fulfilled, or will be fulfilled, if fuel efficiency standards are controlled and enforceable, and penalties for non-compliances are higher than the corresponding compliance costs. This is the case for OECD countries, where non-compliance costs outweigh abatement costs. In general, fuel efficiency standards are effective in increasing fuel efficiency and reducing GHG per car.

An intensity reduction in terms of lower CO₂e/MJ is not necessarily equivalent to an absolute reduction in GHG emissions. Two different so-called rebound effects could compromise the desired outcome. First, car drivers could use the reduction in marginal cost from lower fuel use to increase total travel distance. Based on a review of 22 studies Greening et al. (2000) suggest a potential size of the rebound effect in the transport sector between 10%-30%, but highlight the existence of unmeasured components such as changes in automotive attributes related to shifts towards increases in weight, horsepower and acceleration of cars purchased. The rebound effect generally decreases with income and increases with fuel costs and level of congestion (Small & Van Dender, 2007; Hymel et al. 2010). The sharp rise in oil prices in 2008 might therefore have led to stronger rebound effects than previously observed, but empirical evidence is currently still missing. Hence, this kind of rebound effect is low to moderate in magnitude and becomes less significant with rising real income.

Second, market forces could induce a higher additional production of fuel efficient cars without inducing a simultaneous reduction in gas guzzlers. To our best knowledge, there is no quantitative study on this effect. In fact, for quantitative evaluation, one would need to have access to pricing strategies of car manufacturers.

In spite of moderate rebound effects, total expected GHG abatement by fuel efficiency standards is significant and may be the single most effective climate policy in the transport sector (for quantitative evaluation see Creutzig et al., 2010).

Efficiency. For evaluating the efficiency of fuel efficiency standards two questions can be posed: 1) Is the level of total induced abatement too low, more or less appropriate, or too much with regard to overall welfare? 2) Is this the most cost effective strategy to mitigate GHG emissions?

In the climate change economics literature an overall reduction of global GHG emissions of about 80% by 2050 has been suggested to be cost efficient by some leading scholars (e.g. Stern et al., 2007, Edenhofer et al., 2010). For the EU, this implies a 30-40% reduction by 2020, i.e. more than the currently envisaged 20% reduction. According to current EU regulation, the transport sector will reduce its GHG emissions by 7% by 2020 – and fuel efficiency standards are expected to contribute most of this reduction. Hence, fuel efficiency standards certainly do not induce GHG emission reduction that are beyond the societal optimum. The question remains whether there are more cost efficient options. According to published abatement cost curves, 65-80% of abatement options in the road transport sector below 100€/tCO₂e are automobile technologies and, hence, can be addressed with fuel efficiency standards (e.g., Blom et al. 2007). The remaining options are mainly related to different kinds of biofuels. Hence, from this cost curve perspective fuel efficiency standards are cost-effective if the use of low-carbon biofuels is simultaneously incentivized by policies – which is the case in most world regions. The details of policies that address the carbon content of fuels is given in section 5. A comprehensive perspective on marginal abatement cost curves is given in the companion paper (Flachsland et al., 2010).

Furthermore, one can ask what specific design of fuel efficiency standards is most efficient. For example, some world regions have fleet average requirements (e.g., EU) whereas other world

regions have targets for each car of a specific weight class (e.g., China). Given the same level of overall ambition, the first rule is more cost-efficient, as it gives flexibility to car manufacturers in determining where to invest in fuel efficiency. Effectiveness is not impacted if the fleet average target remains the same.

Fuel efficiency standards are mostly attribute based, e.g. weight based in the EU and footprint based (wheelbase times track width = the area between the wheels) in the US. If the overall ambition of the fuel efficiency standard is binding, attribute-based standards do not compromise the effectiveness of the standard. However, they have distributional impact, as the burden of efficiency gain is shifted from manufacturers of heavy or big cars to those of smaller cars (compared to an attribute-neutral standard). Hence, from a climate-pricing perspective, gas guzzlers are underpriced whereas small fuel efficient cars can be overpriced. Attribute-based standards can have a regressive impact. In fact, attribute-based standards – to some degree - reflect industrial but not environmental objectives: the US standard favors pick-up trucks, the EU standard compact but heavy sports vehicles, and the Chinese standard smaller domestic vehicles. Attribute-based standards are not necessarily efficient. Efficiency (and distributional fairness) could be guaranteed by setting an economy wide fleet average target, and by allowing trading of efficiency gains between car manufacturers.

In summary, fuel efficiency standards are an effective and efficient policy instrument to reduce GHG emissions in the road transport sector – if accompanied with policy instruments that also address other actors. In particular, fuel efficiency standards sufficiently address the responsibility of car manufacturers. Emissions that are outside of the control of car manufacturers, such as those related to the CO₂ intensity of fuels, must be addressed at the appropriate level and directed towards other actors such as fuel producers or suppliers.

Region	Target	Unit	Structure	Test
EU	CO ₂ emissions	gCO ₂ /km	weight-based fleet standard	NEDC
California	GHG emissions	gCO ₂ e/mile	Absolute fleet standard for LDT1/LDT2	FTP 75
US	Fuel economy and GHG	mpg and gCO ₂ e/mile	Footprint-based fleet standards for cars/ light trucks	FTP 75
Japan	Fuel economy	km/l	Weight-based fleet standard	Japan 10-15
China	Fuel economy	l/100km	Weight-based fleet standard	NEDC

Table 1: Overview on fuel efficiency standards in some world regions.

4.3 Regulate vehicles by energy intensity

In the light of the discussion in section 2 and of the overview on existing standards, what is the appropriate unit to evaluate the environmental (climate change) performance of automobiles? Vehicle fuel economy standards mandate a certain fuel use for some fixed distance traveled (e.g. litres/100km), or its inverse (e.g. miles per gallon). The EU explicitly sets CO₂ emissions standards in gCO₂/km. The Californian standard goes beyond CO₂ and regulates all GHG, including for example, nitrous oxides, measuring gCO₂e/mile. Here gCO₂e is a shorthand for all GHG converted

to CO₂ equivalent units. An overview of fuel efficiency standards in different world regions is given in Table 1. When the GHG content of fuel is known and constant – as is the case for the current fuel mix (gasoline and diesel) – then vehicle economy standards can easily be translated into CO₂ emission standards, since fuel use directly corresponds to emissions. However, as pointed out in section 2, this is not true for alternative fuels, such as biofuels or electricity, where the GHG content is highly dependent on the fuel production process. How reasonable are each of the units? Relevant criteria are a) scope; b) adequacy; and c) perception.

Scope. Measures based on liter or gallons of fuel required are limited in scope because they do not explicitly take alternative fuels such as electric vehicles or fuel cell vehicles into account. Currently, this is arguably irrelevant. However, with governments world-wide pushing for significant market penetration of electric cars and biofuels, volume based measures become clearly outdated. In contrast, GHG measures fulfill the requirement of scope in so far as they in principle cover all cars on an equal accounting base. The Californian measure goes beyond the EU measure by including non-CO₂ GHG emissions, such as nitrous oxides, in vehicles emissions accounting. Finally, energy-intensity based fuel efficiency standards, such as measures in MJ/km, would have sufficient scope. A conversion of MJ electricity into a equivalent volume based measures is also possible and under discussion. This would allow a smooth continuation of existing standards – that were implicitly based on energy-intensity.

Adequacy. Adequacy in this context refers to the question how appropriate the measure is with respect to incentivizing fuel efficiency measures of car manufacturers and simultaneously being accurate. From this perspective gCO₂e/km measures are in the medium-to-long run inadequate, because car manufacturers cannot influence the electricity mix which powers electric cars. Also, gCO₂e/km changes with consumer decisions. For example, in some countries consumers

can choose providers that exclusively sell electricity from renewable sources, whereas the average mix can be heavily dependent on coal.

Perception. Can consumers intuitively understand fuel efficiency gains by looking at each of these measures? In fact, the perception aspect is not relevant for regulating car manufacturers, but applies to the consumer. A recent study pointed out that measures in distance per amount of fuel, particularly miles per gallon lead to systematic misunderstanding of consumers. People falsely believe that the amount of gas consumed by an automobile decreases as a linear function of the car's mpg, when in fact, the relationship is curvilinear (Larrick & Soll, 2008). As a result, people underestimate fuel savings starting from a low baseline and overestimate fuel savings starting from a high baseline. For example, fuel savings of a switch from 12 mpg to 14 mpg (120 gallons per 10000 miles) outweigh fuel savings of a switch from 28 mpg to 40 mpg (107 gallons per 10000 miles). Hence, for the purpose of purchase decisions, the US mpg values and the Japanese km/l values should be substituted by some measure of fuel per distance, for example gallons per 10,000 miles or MJ/km, roughly corresponding to annual distance traveled.

Along with our argument in sections 2 and 3, a car manufacturer's performance should be measured in units of energy intensity, or volume-based equivalent measures. In the latter case, the performance of BEVs or PHEVs as measured in kWh/km would be translated in l/km or mpg (or gallons per mile) based on the kWh content of one liter or gallon of gasoline. Such measures would correctly address the car manufacturer's performance.

In summary, a number of considerations favor an evaluation of fuel efficiency in terms of energy intensity, e.g. MJ/km, providing a level-playing field across different kinds of cars. This is, however, only truly effective if GHG emissions are regulated across all fuels upstream – to also provide a playing level field for the carbon content. As long as this is not the case, the current EU

and Californian GHG measures should stay in place, as they provide a level-playing field for the currently dominating gasoline and diesel fuels and vehicles. In the medium run, and in the light of ever-more diversifying fuel supply chains for all kind of vehicles, car manufacturers are best evaluated in terms of energy intensity – the factor they can control – and cease to be evaluated in terms of carbon intensity, better addressed at the level of fuel suppliers.

5. Regulating carbon intensity

This section analyzes regulation and market-based instruments that target the carbon content of transport fuels. We look at renewable fuel policies and mandates, describe low carbon fuels standards (LCFS), highlight current implementation of LCFSs, and evaluate these implementations.

5.1.1 Renewable fuel policies

Biofuels have been discussed as low or zero carbon sources of energy for transportation, and as a suitable strategy for reducing oil dependency (e.g. von Blottnitz and Curran, 2007). Hence, the development of biofuels has been supported by a range of policy instruments, including volumetric targets or blending mandates, tax incentives or penalties, preferential government purchasing, government funded RD&D (research, development, & deployment), and local business incentives for biofuel companies. For example, biodiesel production in Germany jumped with the introduction of a tax break, and slumped again with introduction of a new tax rate (Hogan, 2009). Another powerful tool that has been introduced into the policy arena over the past decade are renewable fuel mandates..

Renewable fuel mandates require fuel producers to produce a pre-defined amount (or share) of biofuels and blend them with gasoline. They aim to reduce the carbon intensity of transportation fuels by entering larger amounts of low carbon fuels into the market without setting particular intensity targets. Some renewable fuel mandates are non-discriminatory in that they do not differentiate between different types of biofuels. From an environmental perspective this assumes that any renewable fuel source is less carbon intensive than conventional gasoline. However, recent evidence shows that this might not be generally the case (see Crutzen et al. 2007; Searchinger et al., 2008). Discriminatory renewable fuel mandates are only applicable to a selection of biofuels or introduce quotas for the least carbon intensive biofuels.

5.1.2 Implementation

Europe. In its directive on the promotion of the use of energy from renewable sources (DIRECTIVE 2009/28/EC), the EU mandates 10% renewable fuels used in transportation by 2020. This renewable fuel quota is expected to be met mostly by biofuels. The directive generally does not discriminate between biofuels. However, it incentivizes the production of biofuels on degraded land through a generic carbon credit, prohibits the production of biofuels on biodiverse or carbon rich land and rewards the production of secondary biofuels. It further requires reporting on compliance with sustainability criteria of major biofuel exporting countries and sets a roadmap for incorporating the issue of indirect land use change.

U.S.. In the US, the Renewable Fuel Standard (RFS) program was originally created under the Energy Policy Act (EPAAct) of 2005. As required under EPAAct, the RFS increases the volume of renewable fuel required to be blended into gasoline to 7.5 billion gallons by 2012 (RFS1). Under the Energy Independence and Security Act (EISA) of 2007, the Renewable Fuel Standard program will increase the volume of renewable fuel required to be blended into transportation fuel from 9

billion gallons in 2008 to 36 billion gallons by 2022 (RFS2) (EPA, 2010a). The RFS1 did not discriminate among biofuels and the quota was met mostly by domestic corn ethanol. The RFS2 sets explicit quota for cellulosic and other advanced biofuels, and biodiesel.

5.1.3 - Evaluation

Renewable fuel standards address the quantity of renewable fuels, but not their carbon intensity. This is particularly problematic as life-cycle emissions vary considerably according to feedstock. The carbon implications of such a policy can therefore also vary greatly. Non-discriminatory standards are more problematic in this context than discriminatory ones.

The merits of the current E.U. and U.S. legislations in terms of greenhouse gas emission remains unclear. This is related to major sources of uncertainties in the life cycle of biofuels including indirect land-use emissions (e.g., induced deforestation by higher world-market prices for ethanol) and nitrous oxide emissions, but also land management practices (Searchinger et al., 2008; Crutzen et al., 2007; Kim et al., 2009). Conventional corn ethanol – currently dominating the U.S. biofuel market - under some calculations has higher GHG life cycle emissions than conventional gasoline (Searchinger et al., 2008; Hertel et al., 2010). Furthermore, given the current scientific evidence it remains doubtful whether fulfilling the 10% renewable fuels target in transportation will be associated with any carbon savings (Edwards et al., 2008) .

The Renewable Fuel Standard 2 (RFS2) requires that 36 billion gallons of biofuels be sold annually by 2022, of which 21 billion gallons must be advanced biofuels and the other 15 billion gallons can be corn ethanol. The advanced biofuels need to achieve certain life-cycle emission threshold (EPA, 2010b). However, this regulation is clearly insufficient for four reasons:

1. Only biofuels but no other alternative fuels can contribute to achieve this goal. Hence, this is a technology-specific regulation.
2. Only some but not all biofuels are subject to meeting threshold values.
3. Life cycle accounting is implemented as a step function. However, regulation needs to address fuels proportional to their GHG emissions to be both effective and efficient.
4. In the current regulation, life cycle accounting is not accurate. performed by relying on hypothetical technologies. In fact, the regulation has been criticized for relying on hypothetical 2022 CCS technology for capturing the emissions released in the refinement process as benchmark, for underestimating indirect land-use emissions, and for ignoring epistemic and highly relevant uncertainties related to land-use change (Plevin, 2010; Plevin et al., forthcoming).

Altogether renewable fuel standards and quota are not functional as a GHG mitigation policy. Standards incentivize production of the most economic biofuels – often in contradiction with GHG emission reduction or sustainability concerns.

5.2.1 Low carbon fuel standards

A low carbon fuel standard (LCFS) is different from renewable fuel standards in that a) it mandates a specific overall decrease in the average carbon intensity of all fuels and b) it accounts for the carbon emissions of each individual fuel, including non-conventional fossil fuels. The primary purpose of a LCFS is to reduce the carbon intensity of fuels for light-duty vehicles. As such, a LCFS provides a level playing field across all fuels, rather than mandating specific fuels of the RFS. It targets fuel suppliers – refiners, importers, and blenders of passenger vehicle fuels – and requires that the average GHG intensity of their fuel mix be reduced by a specified percentage from

a set baseline carbon intensity. This gives a supplier the flexibility to reduce emissions by switching fossil fuel feedstock, providing low carbon biofuels, electricity, and hydrogen, or by improving the efficiency of their fossil fuel supply chain. Lifecycle GHG intensity is defined as grams of carbon dioxide equivalent per megajoule of fuel energy (gCO₂e/MJ). Non CO₂-GHG, such as methane and nitrous oxide, are converted into CO₂ equivalent emissions (CO₂e). Emissions for each fuel are based on complete lifecycle analysis, including resource extraction, cultivation, pipeline transport, processing, conversion, production, distribution and consumption. The maximum average GHG intensity level is reduced over time. Suppliers that reduce the average carbon content of their fuels below the target receive credits that can be sold to other suppliers.

5.2.2 Implementation

California. Executive Order S-01-07 from January 2007, issued by Californian Governor Schwarzenegger, mandates an emission reduction of 10% from the entire fuel mix by 2020 (Schwarzenegger, 2007; CARB, 2009b). The final rules were adopted by the Californian Air Resources Board (CARB) in April 2009; implementation started in January 2010. Gasoline and diesel and their substitutes have been assigned carbon intensities in gCO₂e/MJ based on lifecycle GHG intensity, adjusted for corresponding vehicle drive-train efficiency. The so-called default and opt-in rule has two components: First, CARB provides a conservative estimate of GHG intensity for each fuel (default). Second, suppliers can obtain credits by providing evidence that the fuel they produce has lower GHG intensity than the value calculated by CARB (opt in). The two regulated fuels, gasoline and diesel, and their substitutes need to decrease their GHG intensity by 10% from 2010 until 2020 (CARB, 2009b). The LCFS utilizes market-based mechanisms to extend choices to suppliers for reducing emissions while responding to consumers; fuel providers may a) reduce emissions from processing or b) buy and blend low-carbon biofuels, such as ethanol, into gasoline

or diesel products or c) purchase credits from power utilities, based on their average carbon intensity, or hydrogen owner at the point of delivery, supplying low-carbon certificates for electric or hydrogen vehicles. Eleven U.S. states in the Northeast and Mid-Atlantic Regions, and British Columbia and Ontario have signed letters of intent, and partial legislation, to introduce LCFS in coordination with California (Massachusetts Government, 2008; Taylor et al., 2008).

European Union. In the EU, the Fuel Quality Directive COM-2007-18 requires 6% reduction in CO₂e of transportation fuels from 2010 to 2020 (EC, 2009c). Subject to further regulation, an additional 2% reduction should be obtained through the introduction of electric cars and capture and storage technologies. An additional 2% reduction is to be obtained through the purchase of credits under the Clean Development Mechanism. The Fuel Quality Directive allows reduction of CO₂e in the fossil fuel lifecycle, e.g. by improving the efficiency of exploration and processing, and also via the introduction of renewable fuels that have lower lifecycle emissions than conventional fuels. Indirect life cycle emissions are not (yet) part of EU life cycle accounting, though the Fuel Quality Directive does include certain sustainability criteria that biofuels must meet in order to qualify towards meeting the 6% objective. Electricity is not part of the 6% target; hydrogen could be included in future regulation.

5.2.3 Evaluation

The LCFS will be effective in creating incentives to increase efficiency in exploration and processing of conventional fuels, and switching to low-carbon fuels. In the EU, most reduction in carbon content is expected via introduction of renewable fuels (EC, 2009c). However, due to low penetration of flex-fuel vehicles in Europe, a high percentage (above 10%) of ethanol in the overall

fuel mix is challenging. Moreover, Edwards et al. (2008) warn about the detrimental effects policies could have which incentivise the use of biofuels. Hence, as a result a lower percentage of renewable fuels with high GHG reduction could be used, rather than a high percentage of renewable fuels with relatively low GHG reduction, such as CNG and biomethane (Arnold, 2009). In California, savings of the LCFS are estimated to be \$11 billion from 2010-2020, probably realized as profits by biofuel producers; 25 new biorefineries could be built (CARB, 2009b). The LCFS is the first policy implemented that successfully addresses the carbon content of all fuels in transportation, treating gasoline, unconventional fuels, renewable sources and electricity on equal footing. For the first time, a full lifecycle analysis for all fuels is required.

However, four key shortcomings can be identified:

1. **Leakage/Shuffling.** Companies will seek to comply at lowest costs, for example by shifting the consumption of renewable fuels from other states to California while gasoline made from tar sands will be exclusively sent to non-LCFS states (Sperling & Yeh, 2009). The global rebound effect (additional consumption in other world regions caused by lower fuel prices) could be 25% percent or more in which case the LCFS is less effective than anticipated (Stoft, 2009). Broad or even international coverage of LCFS could reduce the shuffling and rebound effects (Farrell & Sperling, 2007).
2. **Perverse incentives.** From an economic perspective, the LCFS creates perverse incentives: The LCFS acts as a tax on high carbon fuels but as a subsidy on low carbon fuels. If demand and/or supply of high carbon fuels is relatively inelastic, additional production of low-carbon fuels is incentivized which can increase total GHG emissions (Holland et al., 2009).
3. **Uncertainty in lifecycle emissions.** Lifecycle analyses of LCFSs are more comprehensive than those of the RFS2 in (1) including all fuels, not only biofuels, and (2) requiring precise

accounting, not only thresholding crossing of emission values, and (3) not relying on uncertain future technologies (such as CCS) for accounting. However, major uncertainties with respect to indirect land-use emissions and to a lesser degree nitrous oxide emissions from biofuels remain, and a comprehensive policy strategy for this issue is lacking. Further research is needed to continuously increase the data accuracy on ILUC and update lifecycle emissions assumptions for all varieties of biofuels.

4. **Inconsistency in setting incentives.** Electric utilities generate credits by fueling electric cars. As accounting is based on the average fuel mix, no significant incentive is given to reduce the carbon intensity of its electricity mix. A more encompassing instrument would also incentivize the electricity sector to reduce emissions.

5.3 – Wider sustainability considerations

The current discussions on the sustainability of biofuels very much focus on carbon aspects. However, there is a much wider range of issues, which needs to be considered (Yeh and Sperling, 2010). A fundamental problem of biofuels, for example, is food insecurity induced by land competition between biomass for fuels and food (Creutzig and Kammen, 2009). Other scholars have recently highlighted sustainability challenges associated with water use in the life cycle of biofuels (Gernes-Leenes et al., 2009) or the potentially high health costs of air emissions from first generation biofuels (Hill et al., 2009). Von Blottnitz and Curran (2007) find in that even though many biofuels showed a better performance in terms of global warming and resource use, impacts on acidification, human and ecological toxicity were often assessed unfavourably. The strong focus in the political debate on climate change related issues often diverge researchers attention

away from these aspects leaving a considerable evidence gap. However, there is considerable agreement that most of these problems can be largely overcome with the emergence of second and third generation biofuels. These technologies are suggested to bring the required quantum leap in the improvement of the sustainability performance of these fuels to make them a viable policy option (Tilman et al. 2006; Tilman et al., 2009; von Blottnitz and Curran, 2007; Hill et al., 2009).

6. Towards GHG pricing instruments

Policy instruments to regulate GHG emissions in the transport sector have only limited coverage. While fuel efficiency standards and low carbon fuel standards can be effective and efficient policy instruments in their particular context, they lack comprehensive scope and fail in setting optimal incentives due to both generic inconsistencies and specific design.

Fuel efficiency standards are subject to two rebound effects. First, increased market shares of more efficient cars is partially offset by greater demand for road transport. Second, car manufacturers can react to standards through technology and innovation, shifting their automobile portfolio, but also by pushing additional fuel efficient cars into the market (e.g. by offering discounts). As such, fuel efficiency standards set perverse incentives. Additionally, fuel efficiency standards – targeting car manufacturers - are set in CO₂e/km in the EU and California, capturing emissions from well-to-wheel. However, car manufacturers can only influence tank-to-wheel efficiency and/or emissions.

Low carbon fuel standards favor low-carbon fuels but can incentivize increased production of low carbon fuels without lowering the production of high carbon fuels. In its current implementation, the Californian LCFS disproportionately favors electricity (counting only a third of GHG emissions). The upstream GHG emissions of electric cars are not strictly accounted for. Also,

transport demand remains mostly unregulated, and may even increase in addition to business-as-usual due to rebound effects.

Some failures can be alleviated by better design, e.g. switching to energy-based efficiency measures for fuel efficiency standards. However, for rebound effects, perverse incentives, and overall regulation of GHG emissions in the road transport sector, other instruments are required. Here we argue for quantity instruments, regulating absolute emissions, and an associated price signal. This can be either cap and trade, or a cap and dividend scheme. The effects of such an instrument would be as follows:

- A transport-sector or economy-wide cap and a price on GHG emissions ensures efficiency and environmental effectiveness, and provides a level playing field across all fuels.
- Low carbon fuels are systematically incentivized. As such, a cap with corresponding price signal perfectly complements fuel efficiency standards measured in tank-to-wheel efficiency.
- A cap eliminates the perverse incentive effects of LCFS.
- An economy-wide cap makes specific and inefficient cross-sectoral regulation (e.g. the LCFS regulation of electricity) unnecessary.
- Possible rebound effects of fuel efficiency standards (higher transport demand) are avoided.
- Transport demand is subject to an economy-wide efficient price signal and becomes part of the overall mitigation effort.

The main effects are summarized in Figure 5. Existing instruments, such as fuel efficiency standards and LCFSSs, may still have an important role in a cap and price signal world. For example,

efficiency standards are needed to achieve economy-wide dynamic efficiency and counter loss aversion bias of consumers. LCFSs can be phased out as a stringent cap and credible enforcement is implemented. However, the accounting framework of LCFS is a crucial precondition for region-wide cap and trade that unsufficiently covers world-wide emissions (arising from agricultural production). As such, the Californian LCFS and the European FQD can be understood as ancillary steps to an economy-wide cap in these world regions. Finally, a price signal of cap-and-trade is unlikely to spur large-scale investments in new fuels technology if price signal is relatively low and cross-sector only incentivizes reductions from stationary sources in the near term. This is only a problem if relevant learning curve effects are expected for low-carbon biofuels, i.e. if current high costs of biofuel infrastructure are justified by future gains. As long as an economy-wide cap and price instrument is not in place, a low carbon fuel standard is a reasonable second-best policy for local regulators. However, both fuel efficiency standards and LCFS need to be adapted to achieve their primary objectives.

Altogether, cap and price instruments would disincentivize the increased production of low-carbon fuels that would be optimal under LCFS alone and counteract the rebound effect of fuel efficiency standards. An associated price signal will reduce transport demand to welfare enhancing levels. We conclude, therefore, that quantity instruments and a price signal can help to remedy some weaknesses of current standards. The companion paper (Flachsland et al., 2010) analyzes the design and effects of possible policy options.

Similar to our conclusions, DeCicco (2010) asks for aligning incentives and actors when regulating GHG emissions in the transport sector, specifically emphasizing the need for a energy-based metric for new vehicles. Yeh and Sperling (2010) review existing LCFS schemes and point out the need to properly align LCFSs with existing or envisaged cap and trade schemes.

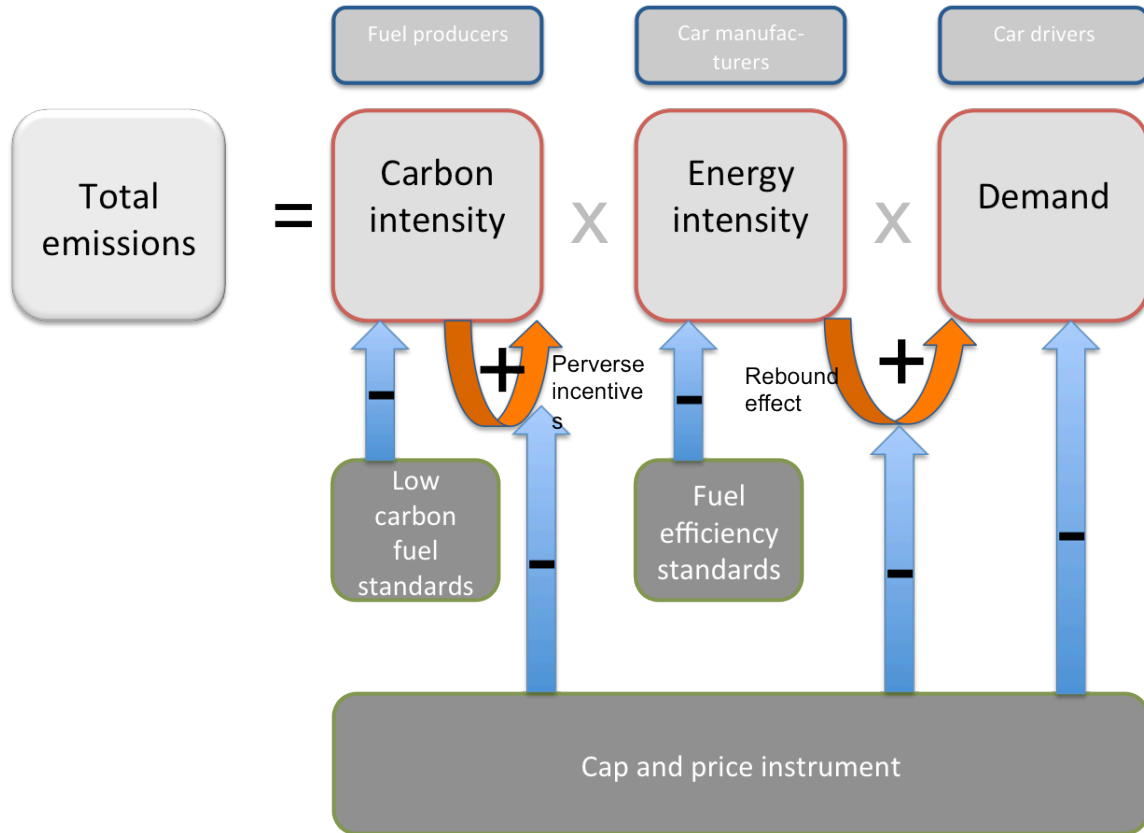


Figure 5. Closing up the policy space through a cap and price instrument. A quantity target and pricing alleviates rebound effects and perverse incentives of fuel efficiency standards and LCFSS.

7. Conclusion

Climate change regulation in the transport sector is still in its infancy. Qualified instruments have been put forward, notably in California and the EU, that are effective in reducing the climate impact of the transport sector. However, with diversified fuel supply chains and rising alternatives to the internal combustion engine, existing policy instruments need to further evolve to ensure efficiency in terms of setting harmonized incentives across different technologies and fuel chains, and effectiveness in achieving emission reduction objectives. In this article, we elucidate that most

GHG emissions of ICE vehicles and fuels occur at tank-to-wheel (downstream), but emissions of alternative fuels tend to occur at well-to-tank (upstream). Emissions in the transport sector can be decomposed into carbon intensity, energy intensity and travel demand. Regulation aimed at curing market failures needs to address each decomposition factor to appropriately target and incentivize the corresponding actors to reduce their emissions factor. Hence, volume and GHG-based fuel standards need to evolve towards energy intensity based fuel standards and complementary regulation of upstream GHG emission to coherently address alternative fuel vehicles, such as electric cars. Distance should also always be in the denominator to align perception with fuel savings.

Renewable fuel standards suffer from ignoring or insufficiently addressing the GHG content of biofuels. Low carbon fuel standards are more comprehensive than renewable fuel standards in regulating the GHG content of transport fuels. Lifecycle issues, however, are not completely resolved. As an intensity-based standard, perverse incentives may partially counteract carbon intensity reduction by volume augmentation.

Finally, a cap and price signal can address the drawbacks of existing regulation. In principle, both emissions trading and GHG taxes can be used to achieve effectiveness and efficiency as both instruments directly tackle greenhouse gas emissions. Thus, both simultaneously address all driving factors for road transport emissions with one harmonized instrument. A comprehensive analysis of quantity-based instruments is given in the companion paper (Flachsland et al., 2010).

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