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# Climate policies for road transport revisited (I): Evaluation of the current framework

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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 a 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., in this issue).



## 1. Introduction

The transport sector accounts for more than half of the oil used world-wide and roughly a quarter of energy-related $CO_2$ 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 have been projected to increase by more than 50% by 2030 and to at least double by 2050 in the IEA business-as-usual scenario. Around 75% of the projected total increase in world oil demand could come from the transport sector by then, according to these calculations (IEA, 2008). While oil extraction is expected to peak and decline within this decade (IEA, 2010), the shortfall will likely to be 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 energy and carbon intensive than oil, caused by upstream emissions in the supply chain (Charpentier et al., 2009). While international shipping and aviation contribute significantly to the projected rise in emissions, the highest share will still come from road transport. Hence, shifting towards a sustainable, low-carbon road transport system is imperative for successful climate stabilization.

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, including biofuels (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

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total global vehicle fleet by 2020 range between 1% and 13%, with 7% as the median estimate (BCG, 2009). According to IEA (2009, see also Fulton, 2010) projections, a 50% market share by 2050 is possible.[1] Geographic variations in penetration are likely to be a result of different domestic policies and consumer preferences: for example, electric vehicles (including fuel cell hybrid electric vehicles) may have between 40% and 95% market shares in 2030 in Germany (Mock et al., 2009).[2] The near-term economic potential of electric vehicles is ultimately dependent on various uncertain and political factors including energy prices (oil, electricity), battery technology and cost, economies of scale, recharging infrastructure, regulatory requirements and fiscal incentives.

Electric vehicles have zero tail pipe emissions, but can have significant upstream emissions, e.g. when the electricity is produced in coal power plants. 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 may become more diverse, and supply chains of some of these new fuel technologies will be more complicated: whereas conventional fossil fuels – gasoline and diesel – powered nearly all road transport over the last century and still dominate the fuel market, electricity, and potentially hydrogen, but also non-conventional fossil fuels, such as Canadian tar sands, and biofuels will provide a small but significant proportion of energy for vehicles within the next decade. As the resource base of transportation fuels diversifies, GHG emissions partially decouple from the end-of-pipe energy content of fuels. In fact, both varying feedstock and varying production process will increasingly determine the overall carbon footprint of road transportation. From a climate perspective, only the lifecycle emissions of these fuels matter. However, in the current EU and Californian policy framework, cars are regulated with respect to GHG emissions per distance ($CO_2$e/km)—in the case of electric, hydrogen, and biofuel-powered cars, this emissions metric may not accurately reflect the global warming impact of fuels used, if the regulatory emissions accounting generalizes across feedstocks and production processes for each final fuel. Furthermore, sometimes the more environmentally benign fuels are more tightly regulated with respect to GHG 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. As the paper will discuss below, providing a level playing field for all fuels is important for achieving 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 modifying and rearranging existing regulation in light of alternative fuels, and to close up the policy space with 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, lifecycle 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 currently the most effective (and politically popular) transport policy instrument 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 and low carbon fuel standards (LCFS) seek to increase the market share of biofuels and aim to incentivize the production of fuels with low lifecycle emissions. However, insufficient accounting standards, uncertainty in accounting of upstream emissions, leakage, perverse incentives, and complex fuel supply chains of biofuels seriously limit the effectiveness of these instruments to reduce the carbon intensity of fuels (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 to effectively regulate the GHG emissions associated with fuels.
2. Understanding where emissions occur enables appropriate matching of policy instruments, emission sources, and actors.

Each step in a transport fuel pathway can be characterized by two factors: the GHG emissions emitted and the efficiency loss. In the following, we provide a brief overview on the lifecycle emissions of alternative fuels and describe the issues associated with the different pathways:

- When produced from conventional fossil resources, gasoline and diesel result in high GHG emissions compared to some alternative fuels (see Fig. 1). Some GHG emissions are produced at the feedstock (crude oil) recovery stage (e.g. 7% for diesel) and at the production stage (e.g., 12% for diesel, at the crude oil refinery) (CARB, 2009a). The majority (70–90%) of conventional fuel emissions occur at end use, usually combusted in an internal combustion engine (ICE). Therefore, the decisive factor in determining differences in the lifecycle GHG performance of conventional fuel vehicles is their fuel efficiency. Diesel engines are more efficient than gasoline engines and produce 16–24% less emissions (Kahn Ribeiro et al., 2007). Gasoline or diesel may be produced from algae, carbon capture and storage (CCS)-production technologies, thus the lifecycle GHG emissions of these fuels may also vary.
- Unconventional fuels (e.g. Canadian tar sands) can have at the stage of feedstock recovery about 4.5 times larger GHG emissions than US domestic crude oil (US DOE, 2009). However, this stage still constitutes only about one fifth of overall lifecycle emissions. Hence, while fuel efficiency remains the dominant factor in determining the GHG performance of the vehicle, upstream emissions can become more prominent.
- Biofuels can follow a myriad of specific pathways, and produce GHG emissions at biorefineries and in agricultural feedstock production. The latter requires dealing with complex GHG accounting 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

[1] This is a rather optimistic scenario. Scenarios crucially depend on sets of assumption and can vary significantly with different assumptions. More fundamentally, "The problem, in short, is this: scientists and other analysts have an unfortunate tendency to reduce projections of future energy use to deterministic relationships that are poorly founded in empiricism, or sometimes never supported by data at all." (Cullenward et al., 2011). Scenarios, however, remain useful in visualizing possible futures.

[2] See footnote 1.

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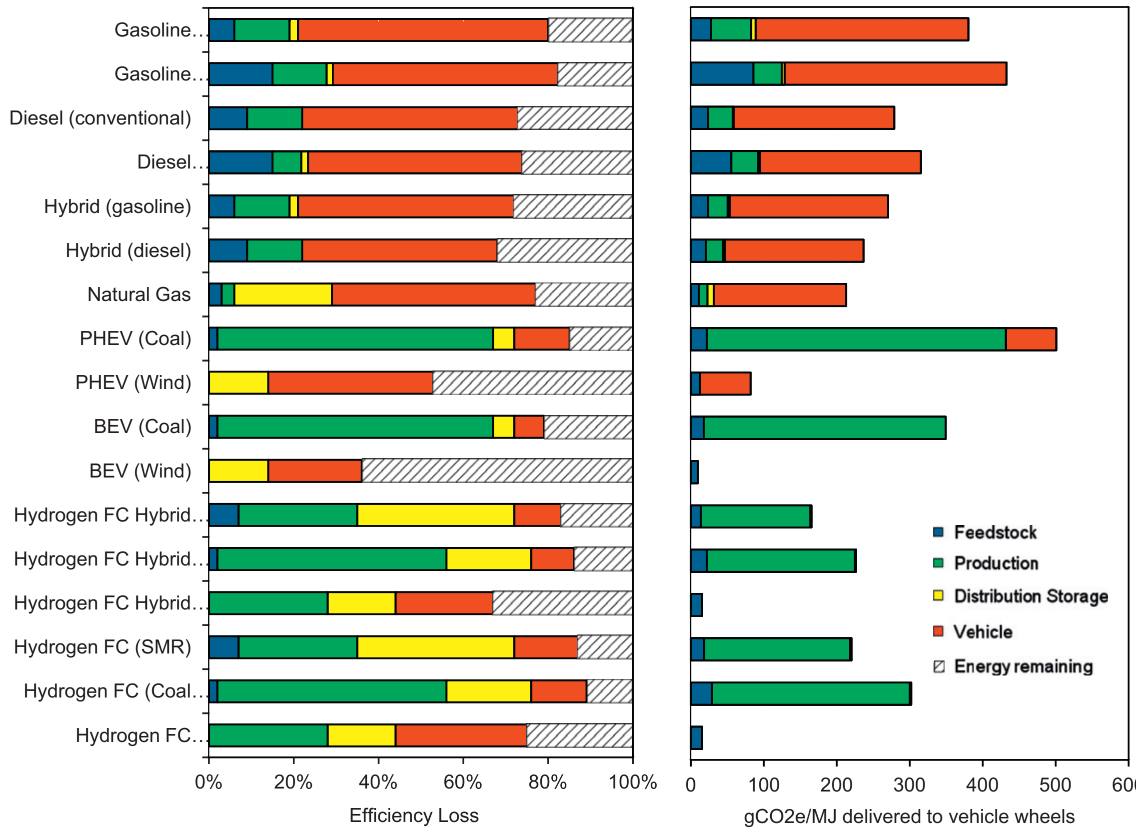


**Fig. 1.** Overview on efficiency losses and lifecycle emissions of fuel supply chains. Numbers and references are given in Creutzig et al. (2010).

Kammen, 2010) as well as emissions from alternative agricultural management practices (Kim et al., 2009). As a result, the lifecycle GHG emissions of biofuels vary dramatically across production pathways. For example, one of the most market-dominant biofuels, US corn ethanol, is estimated by some authors to have higher lifecycle emissions than gasoline (Hertel et al., 2010). In such a case, the lifecycle GHG performance of the fuel is increasingly dominated by its supply chain components. Uncertainty over lifecycle emissions of biofuels can be substantial and can make proper assessment challenging (Plevin et al., 2010).

- Compressed natural gas (CNG) generally has lower lifecycle GHG emissions than conventional fuels. Similar to conventional fuels, most emissions occur during the end use phase. Total lifecycle emissions are 15–25% lower than for gasoline engines (Kahn Ribeiro et al., 2007).
- Electricity can have very high lifecycle GHG emissions when produced in a coal power plant, and close to zero emissions when generated by alternative energy sources such as wind or solar. Note that the majority of GHG emissions in electricity pathways is generated at the fuel production stage, as opposed to the end use stage as is the case for conventional fuels. Electric motors are significantly more efficient than ICEs, and total well-to-wheel efficiency of battery electric vehicles (BEVs) running on electricity produced from renewables ranges between 75 and 85%.[3] Electricity can be deployed for plug-in hybrids (PHEVs), BEVs, or fuel cell hybrid electric vehicles. Alternative storage media such as compressed-air have well-to-wheel efficiencies of less than 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 and Balat, 2009). Similar to electricity pathways, the largest proportion of lifecycle emissions occurs at the production stage, as opposed to zero emissions at the end use stage. GHG emissions can vary considerably across these different production pathways. Hydrogen can be deployed for fuel cell cars, hydrogen ICE vehicles, or fuel cell hybrid electric vehicles.

Fig. 1 provides an overview over the lifecycle emissions of different fuels (see Creutzig et al., 2010). Fig. 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, or use phase.
- Unconventional fossil fuels, such as those produced from Canadian tar sands, have comparable emissions during the use phase (combustion process), but have significantly higher emissions at the stage of feedstock recovery in their supply chain.
- Emissions of certain alternative fuels (e.g. hydrogen and electricity) can occur mostly upstream at the 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 and production process and can exceed or undermatch emissions from gasoline (Fig. 2). Fundamental uncertainty issues

[3] This includes grid loss, but not efficiency loss in a power plant. It represents the well-to-wheel efficiency from wind sources. The well-to-wheel efficiency from coal sources is around 25%.

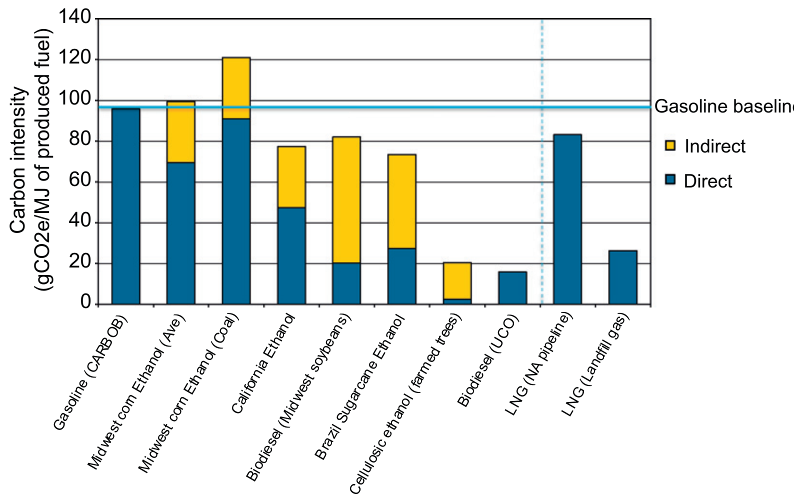


**Fig. 2.** Overview on lifecycle emissions of different biofuels and natural gas, as estimated by CARB (2009b). Modeling and epistemic uncertainties render the displayed estimates of indirect land use emissions irrelevant for policy purposes (Plevin et al., 2010).

are also the question of system boundaries render accurate accounting difficult (not shown in the figure).

Crucially, fossil fuel emissions mostly occur with end use, while alternative fuel emissions tend to occur upstream. Like fossil fuels, biofuel emissions take place at end use, while their lifecycle GHG emissions vary dramatically with production process, largely due to changes in soil and biosphere carbon stocks.[4] 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.

## 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, Fig. 1 makes clear that both carbon intensity of fuels and fuel efficiency of cars matter. We decompose GHG emissions from the transport sector into carbon intensity ($gCO_2e$/MJ), energy intensity (MJ/km), and total transport demand (km) (compare with Schipper et al., 1997; Kamaketa and Schipper, 2009; Creutzig and 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* can influence the specific carbon content of fuels. For example, refineries can change the mix of fuels, e.g. from tar sand oils and crudes to biofuels with lower lifecycle emissions, and utilities can switch to renewable energies. The relevant measure here is the carbon intensity measured in $gCO_2e$/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* can influence 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, *drivers* of vehicles can (at least partially) decide how often and far they travel—the last factor of the decomposition. Crucially, decisions of planning officials and policy makers on infrastructure investments, land-use planning, and pricing shape transport demand for the medium- and long-term. 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 Fig. 3.

## 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 Plotkin, 2008; Flachsland et al., in this issue). 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 140 $gCO_2$/km to be reached collectively by members of each of the European, Japanese, and Korean car manufacturer associations. In 2009, not all individual members could fulfill their corresponding 25% reduction target, which resulted in the revised EU mandate of a 130 $gCO_2$/km industry fleet target by 2015 with additional 10 $gCO_2$/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 must comply with a target

[4] "Traditional" accounting of biofuels – offsetting end-use emissions with photosynthetic absorption – is problematic, as land-use change effects are often not appropriately accounted for (Searchinger et al., 2009; DeCicco, 2010).

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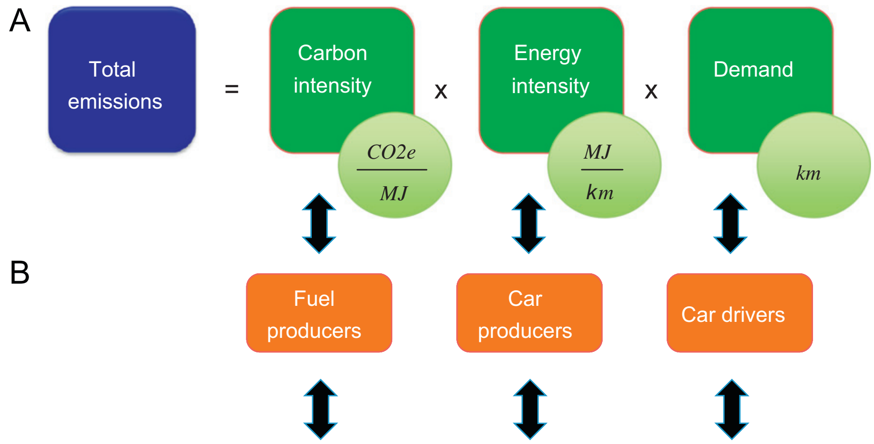


C

| Comprehensive instruments | Reduction of carbon intensity | Reduction of energy intensity | Reduction of demand |
|---|---|---|---|
| Cap | Low carbon fuel standards | Fuel efficiency regulation | Infrastructure investments |
| Certificate trading | Renewable fuel quotas | Shift in modal share | Spatial planning |
| Carbon taxes | RD&D | Car Sharing | City toll |

**Fig. 3.** Decomposition of greenhouse gas emission in transportation (A), relevant actors (B), and corresponding policy instruments (C).

below 130 g/km, and a manufacturer of heavier cars must comply with a target above 130 g/km. A long-term target of 95 g/km is set for 2020.

**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 efficiency standards to reduce oil dependency. Standards are specific for the weight of each car. Currently an updated fuel efficiency 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 $>42$ mpg.

**North America**: In 2009 rule-making pushed 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 $gCO_2$/mile (35.5 mpg) for vehicles in 2016, coordinated with the Corporate Average Fuel Economy (CAFE) target. The fuel efficiency standard is differentiated across two vehicle classes, with 39 mpg for passenger cars and 30 mpg for trucks in 2016. Since 2009, California has also imposed rules on automakers (Pavley I), which will be harmonized with federal CAFE and GHG standards from 2012 onwards (CARB, 2010). Canada's fuel efficiency standards are linked to the US system, but are specified in l/100 km—a fuel intensity metric.

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

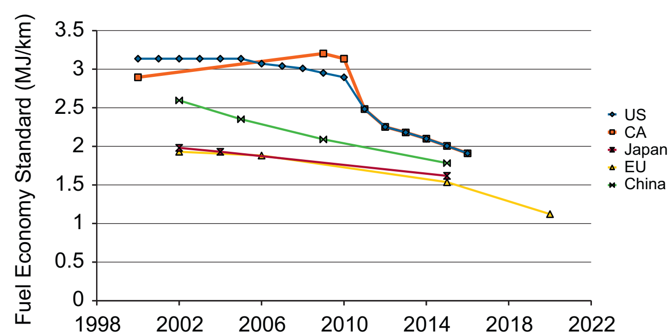


**Fig. 4.** Fuel economy standards in units of energy intensity extrapolated from current volume and GHG standards. 1 l gasoline = 32 MJ. Data adapted from An et al. (2007) with updated fuel efficiency regulations.

The following observations are illustrated in Fig. 4:

- Europe and Japan have achieved the highest average fuel efficiency across their fleets.
- US is still a laggard, but making swift progress with recent California and federal regulation, achieving the greatest absolute emission reduction of all fuel efficiency regulations (An et al., 2007).
- For an emerging economy, China sets comparatively ambitious fuel efficiency standards, which are motivated by energy security concerns and strategic world-market positioning.

### 4.2. Evaluation

Fuel efficiency standards are evaluated according to their effectiveness and their economic efficiency. For this analysis, carbon intensity is assumed to be regulated by complementary instruments (Sections 5 and 6).

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#### 4.2.1. Effectiveness

Fuel efficiency can be effective (a) with respect to reducing energy consumption and GHG emissions per km driven and (b) with respect to absolute reductions in GHG emissions (within and beyond the transport sector). The first goal is generally fulfilled, or will be fulfilled, if fuel efficiency standards are enforceable and controlled, 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 km driven.

Fuel efficiency improvements in sold vehicles is not necessarily equivalent to an absolute reduction in economy-wide 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% and 30%. More recent studies suggest that the magnitude of the rebound effect decreased with rising income and urbanization to below 10% (Small and Van Dender, 2007a, 2007b; Hymel et al., 2010). The sharp rise in oil prices in 2008 might have led to stronger rebound effects than previously observed, but empirical evidence is currently still missing. Hence, this kind of rebound effect becomes less significant with rising real income, and is low to moderate in magnitude in affluent societies.

Second, market forces could induce a higher additional production of fuel efficient cars without inducing a simultaneous reduction in gas guzzlers. The optimal response of a car manufacturer to fleet average fuel efficiency standards is an internal trading scheme where fuel efficient cars earn credits, and gas guzzlers have to submit allowances. As a result of this internal market, efficient cars become cheaper, and gas guzzlers become more expensive. If the additional consumption of fuel efficient cars overcompensates the reduced consumption of gas guzzlers, a positive rebound effect is observed. To the best of our knowledge, there is no study, which has quantified this effect.

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.

#### 4.2.2. Economic efficiency

For evaluating the economic 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 high with regard to overall welfare? (2) Is this the most cost efficient 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% $CO_2$ emission reduction by 2020, i.e. more than the currently envisaged 20% reduction. According to current EU regulation, the transport sector is supposed to reduce its GHG emissions by 7% by 2020—and fuel efficiency standards are expected to contribute a large share but not 100% to this reduction. Hence, fuel efficiency standards do not induce GHG emission reductions 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 €/t$CO_2$e are automobile technologies and, hence, can be addressed with fuel efficiency standards (e.g., Blom et al., 2007). Alternative fuels offer additional abatement options. However, some of these fuels, such as electricity and hydrogen, are generally considered comparatively expensive abatement options due to the need for infrastructural changes. The highly uncertain GHG emission contribution of biofuels and a lack of updated studies make it difficult to reliably estimate biofuel abatement costs (see Section 5). A comprehensive perspective on marginal abatement cost curves is given in the companion paper (Flachsland et al., in this issue).

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 the fuel 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 can be underpriced whereas small fuel efficient cars can be overpriced. Moreover, attribute-based standards can have a regressive impact. In fact, they – 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. However, attribute-based standards are not necessarily economically efficient. Economic 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 can be an effective and economically efficient policy instrument to reduce GHG emissions in the road transport sector—if accompanied with policy instruments that also address other actors.

### 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. l/100 km), or its inverse (e.g. miles per gallon). The EU explicitly sets $CO_2$ emissions standards in g$CO_2$/km. The Californian standard goes beyond $CO_2$ and regulates all GHG, including for example, nitrous oxides, measuring g$CO_2$e/mile.[5] 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 conventional fossil-based transport fuels (gasoline and diesel) – then vehicle economy standards can easily be translated into $CO_2$ 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, hydrogen, or electricity, where the GHG content is highly dependent on the feedstock and fuel production process. Given this variability, how appropriate are different fuel efficiency metrics? Relevant criteria are (a) scope, (b) adequacy, and (c) perception.

**Scope**: The scope of a measure is characterized by the degree to which varying fuels or propellants are explicitly included. 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. With governments world-wide pushing for swift market penetration of electric cars and biofuels, volume based measures become clearly outdated. In contrast, GHG measures fulfill the scope requirement in so far as they, in principle, cover all cars on an equal accounting base. The Californian measure goes beyond the

[5] g$CO_2$e is a shorthand for all GHG converted to $CO_2$ equivalent units.

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

| Region | Target | Unit | Structure | Test |
|---|---|---|---|---|
| EU | $CO_2$ emissions | $gCO_2$/km | Weight-based fleet standard | New European Driving Cycle |
| California | GHG emissions | $gCO_2$e/mile | Absolute fleet standard for LDT1/LDT2 | Federal Test Procedure 75 |
| US | Fuel economy and GHG | mpg and $gCO_2$e/mile | Footprint-based fleet standards for cars/light trucks | Federal Test Procedure 75 |
| Japan | Fuel economy | km/l | Weight-based fleet standard | Japan 10–15 mode |
| China | Fuel economy | l/100 km | Weight-based fleet standard | New European Driving Cycle |

EU measure by including non-$CO_2$ GHG emissions, such as nitrous oxides, in vehicles emissions accounting. Energy-intensity based fuel efficiency standards, such as measures in MJ/km, would have sufficient scope.

**Adequacy**: Adequacy in this context refers to the question how appropriate the measure is with respect to incentivizing fuel efficiency improvements by car manufacturers and simultaneously accurately reflecting vehicle performance. From this perspective $gCO_2$e/km measures are in the medium-to-long run inadequate, because car manufacturers can neither influence the electricity mix, which powers electric cars nor upstream emissions of liquid fuels (see also DeCicco, 2010). Also, $gCO_2$e/km changes with consumer behavior. For example, in some countries consumers can chose 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? The perception aspect is not relevant for regulating car manufacturers, but applies to the consumer (car drivers). A recent study highlights that fuel efficiency measures in terms of distance per unit of fuel consumed, particularly miles per gallon (mpg), are widely misunderstood by consumers. People falsely believe that the amount of fuel consumed by an automobile decreases as a linear function of the car's mpg, when in fact, the relationship is curvilinear (Larrick and Soll, 2008). People therefore 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 to 14 mpg (120 gallons per 10,000 miles) outweigh fuel savings of a switch from 28 to 40 mpg (107 gallons per 10,000 miles). Hence, for the purpose of purchasing decisions, the US mpg values and the Japanese km/l values should be substituted by some measure of fuel per distance, for example gallons or MJ per 10,000 miles (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 level playing field for the carbon content. As long as this is not the case, the current EU and Californian fuel efficiency standards measured in GHG intensity 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 kinds 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. Renewable fuel policies*

Renewable fuel policies were historically motivated by energy security concerns, and to promote agricultural industries (Duffield and Collins, 2006). In the last decade, biofuels have also been discussed as low or net-zero carbon sources of energy for transportation (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 research, development, and deployment (RD&D), and local business incentives for biofuel companies.

As one of the most powerful instruments, 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 GHG intensity targets. While most major world economies have put fuel mandates in place, the EU and US mandates are quantitatively most important. The EU mandates 10% renewable fuels used in transportation by 2020 (DIRECTIVE 2009/28/EC) and 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. In the US, the Energy Independence and Security Act (EISA) of 2007 specifies the Renewable Fuel Standard program that requires 36 billion gallons to be blended in by 2022 (RFS2) (EPA, 2010a). The RFS2 sets an explicit subquota of 21 billion gallons for cellulosic and other advanced biofuels, and biodiesel.

The merits of the current EU and US legislation in terms of GHG emissions remain unclear. This is related to major sources of data uncertainties in the lifecycle 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), fundamental modeling uncertainty (e.g. the choice of system boundaries), and epistemic uncertainty (e.g., Plevin, 2010a). Conventional corn ethanol – currently dominating the US biofuel market – under some calculations has higher GHG lifecycle emissions than conventional gasoline (Searchinger et al., 2008; Hertel et al., 2010). For these reasons it remains doubtful whether fulfilling renewable fuels target in transportation will be associated with any carbon savings (e.g., Edwards et al., 2008; Plevin, 2010a).

According to the Renewable Fuel Standard 2 in the US, advanced biofuels need to achieve certain lifecycle emission threshold (EPA, 2010b). However, this regulation is clearly insufficient for four reasons:

1. Only biofuels, and no other alternative fuels, can contribute to achieving this goal. Hence, this is a technology-specific regulation.
2. Only some but not all biofuels are subject to meeting threshold values.
3. Lifecycle accounting is implemented as a threshold function of GHG emissions. However, regulation needs to address fuels proportional to their total lifecycle GHG emissions to be both effective and efficient.
4. In the current regulation, the lifecycle emissions accounting is not adequate due to its reliance on new or unproven technologies. The regulation has been criticized for considering hypothetical 2022 CCS technology for capturing the emissions released in the refinement process as a benchmark, for underestimating indirect land-use emissions, and for ignoring epistemic and highly relevant uncertainties related to land-use change (Plevin, 2010b; Plevin et al., 2010).

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. Moreover, the high uncertainties on lifecycle emissions of biofuels suggest to backscale current biofuel mandates in the EU and the US.

### 5.2. *Low carbon fuel standards*

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 threshold crossing of emission values, and (3) not relying on uncertain future technologies (such as CCS) for accounting. The primary purpose of a LCFS is to reduce the carbon intensity of vehicle fuels. As such, a LCFS provides a level playing field across all fuels, rather than mandating the use of specific fuels like an 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 biofuels with (verifiably) lower lifecycle GHG emissions than conventional fossil transport fuels, 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 to per megajoule of fuel energy ($gCO_2e/MJ$). Non-$CO_2$-GHG, such as methane and nitrous oxide, are converted into $CO_2$ equivalent emissions ($CO_2e$). Emissions of each fuel are based on complete lifecycle analysis, including resource extraction, cultivation, pipeline transport, processing, conversion, production, distribution, and consumption. Suppliers that reduce the average carbon content of their fuels below the target receive credits that can be sold to other suppliers.

#### 5.2.1. *Implementation*

**California**: Executive Order S-01-07 of January 2007, issued by California Governor Schwarzenegger, mandates an emission reduction of 10% from the entire transport 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.[6] Eleven US 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 $CO_2e/MJ$ of transportation fuels from 2010 to 2020 (EC, 2009c; Arnold, 2009).[7] The Fuel Quality Directive requires reduction of $CO_2e$ in the fossil fuel lifecycle by improving the efficiency of exploration and processing, and via the introduction of renewable fuels that have lower lifecycle emissions than conventional fuels. While the Fuel Quality Directive includes sustainability criteria, indirect lifecycle emissions are not (yet) part of EU lifecycle accounting. Electricity is not part of the 6% target; hydrogen could be included in future regulation.

#### 5.2.2. *Evaluation*

The Californian LCFS, and to some degree the European FQD, are the first policies that are implemented to try to address the carbon content of all fuels in transportation, treating gasoline, unconventional fuels, renewable sources, and electricity on equal footing, requiring a full lifecycle analysis for all fuels.

However, four key essential 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 and Yeh, 2009). The global rebound effect (additional consumption in other world regions caused by lower fuel prices) could be 25% 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 and 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, low carbon fuels may complement rather than supplement high carbon fuels (Holland et al., 2009).
3. **Inconsistency in setting incentives for electricity provision**: In California, 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.
4. **Uncertainty in lifecycle emissions**: Epistemic uncertainty and modeling uncertainties on system boundaries and discounting rates will make verifiable and reproducible ILUC estimation

[6] Gasoline and diesel and their substitutes have been assigned carbon intensities in $gCO_2e/MJ$ 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). Fuel providers have flexible options to comply. They 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 owners at the point of delivery, who receive low-carbon certificates for fueling electric or hydrogen vehicles.

[7] Subjected 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.

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impossible (Plevin et al., 2010),thus challenging the overall concept of the LCFS (DeCicco, 2009).

### 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 lifecycle of biofuels (Gerbens-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 that even though many biofuels showed a better performance in terms of global warming and resource use, impacts on acidification, human and ecological toxicity where often assessed unfavorably. 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, some fuel supply chains (with second or third generation biofuels as end products) may overcome these problems if land use change can be avoided (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 particular contexts lack comprehensive scope and fail in setting optimal incentives due to both generic inconsistencies and specific design.

Fuel efficiency standards are subjected to two rebound effects, affecting transport demand and, possibly, vehicle manufacturing. While fuel efficiency standards can effectively improve fuel economy, they are unsuitable to regulate varying carbon intensity of fuels. 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, to address rebound effects, perverse incentives, and uncertainties in upstream emissions and to comprehensively regulate all GHG emissions in the road transport sector, other instruments are required. Here we argue for quantity instruments to regulate 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. End-of-pipe GHG emissions of biofuels (biogenic carbon) can be included in the cap. By proving low life cycle emissions based on facility-based accounting, biofuel producers and providers could generate credits (see DeCicco, 2009). Such a scheme can reduce some but not all of the generic uncertainties in lifecycle analysis of biofuels.
- 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 subjected to an economy-wide efficient price signal and becomes part of the overall mitigation effort.

The main effects are summarized in Fig. 5. Existing instruments, such as fuel efficiency standards and LCFSs, may still have

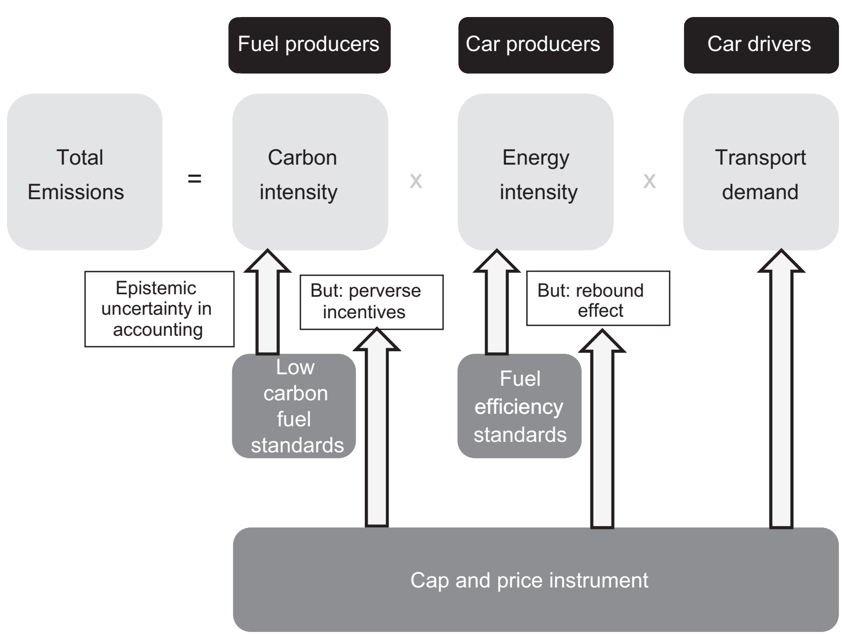


**Fig. 5.** Closing up the policy space through a cap and price instrument. A quantity target and pricing alleviates rebound effects and perverse incentives of fuel efficiency standards and LCFSs. Epistemic uncertainty in ILUC accounting may require a precautionary treatment of biofuel emissions.

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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 has been a crucial precondition for region-wide cap and trade that insufficiently 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 is unlikely to spur large-scale investments in new fuel technology if the price signal is relatively low and cross-sector regulation 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.

Altogether, quantity 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. Including biogenic carbon into a cap, and introducing facility-based accounting, can remedy some of the weaknesses of LCFS (DeCicco, 2009). 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., in this issue) analyzes the design and effects of possible policy options.

## 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 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 emissions to coherently regulate alternative fuel vehicles, such as electric cars. Furthermore, distance should always be in the denominator to reduce misconceptions over 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, severely compromise the efficiency of LCFS. As an intensity-based standard, perverse incentives may partially counteract carbon intensity reduction by resulting in an increased transport fuel consumption.

Similar to our conclusions, DeCicco (2010) calls for aligning incentives and actors when regulating GHG emissions in the transport sector, specifically emphasizing the need for an 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. DeCicco (2009) criticizes lifecycle accounting in LCFSs and suggests an inclusion of biogenic carbon of biofuels and other transport fuels into a cap-and-trade scheme.

Altogether, a quantity and price instrument 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., in this issue).

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