HOW TO REGULATE CO_2-EMISSIONS OF PASSENGER CARS IN EUROPE? AN APPLIED GENERAL EQUILIBRIUM ANALYSIS

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Abstract

Regulation of the fuel use per kilometre travelled is an inefficient means of regulating the overall CO_2 emissions of passenger cars as part of a general climate protection policy in the EU. We measure the excess costs of fuel standards as compared to carbon taxes using an intertemporal computable general equilibrium model. We find that welfare losses can be reduced to about one third by using fuel taxes instead of relative standards as the policy instrument for carbon abatement.

Keywords: Passenger transport; Relative fuel standards; Efficient regulation; Climate protection policy
Topic area: B7 Input-Output System and Transportation

1 Introduction

In the last decade, there have been considerable attempts to bring about climate protection policies through international agreements. The process of bargaining over and fixing agreements has gained prominence under the name of "Kyoto". EU-Europe has always played a leading role in climate change policy and has accepted a large part of the reduction burden. Though not the only cause of the greenhouse effect, CO_2 has been the main focus of climate change policy. Given that a country (or a group of countries like the EU) has accepted a certain reduction commitment, economic theory suggests that the disaggregation of this reduction target to different sectors in the economy takes place in a way that marginal abatement costs are equalised across sectors. This is required by the minimisation of total abatement costs, thus by the strategy that minimises total losses for the respective country. However, in most countries, we do not observe uniform abatement policies – sectors are normally treated differently according to their special characteristics and the political power of special interest groups. In EU-Europe, a trading system for CO_2 emission certificates has been established to start in 2005 (EU 2001a), but it only encompasses certain production sectors. Of the main sources of CO_2 emissions, it is mainly the transport sector that is not included in the trading system. However, it is generally agreed upon that this sector must also participate in the emission reduction strategies (EU 2001b). The regulation in the transport sector is complicated by the fact that a regulation scheme must be found that is applicable to the different transport modes (air, railway, water, and street transport) and to passenger transport as well as commodity transport. There has been no general agreement about a uniform mode of regulation yet. However, with respect to passenger cars, European automobile producers favour – and have advanced – the form of a voluntary agreement (ACEA, the European Automobile Manufactures Association, committed to an average emission of new cars of 140g CO_2 per km starting in 2008, see ACEA/EU, 1998). This form of regulation is of interest in two respects: (1) as a voluntary agreement as such (see, e.g., Grepperud 2002), (2) as an agreement about a relative emission standard[1], as opposed to the absolute overall emissions. Our focus in this paper is on the second point.

The traditional economic approach to emission reduction would favour either a Pigouvian tax or an encompassing certificate system as a means of equalising abatement costs across sectors – or at least within a sector. However, taxes on fuel (and emission certificates) are difficult to implement from a political economy perspective. Producer associations are strongly opposed to such regulation schemes and see a main purpose of voluntary commitments in preventing other forms of regulation. The reasons usually given in official documents are rather vague (speaking of "considerable administrative costs" as in VDA, 2002). A plausible reasoning would be that the opposition against standard economic tools of environmental regulation (environmental taxes and emission certificates) arises because of their redistributive effects: Both taxes on fuel and certificates (if they are auctioned) make transport services more expensive by generating a revenue for the government. In contrast, a relative fuel standard (either strictly administered or as a voluntary agreement) is in its economic effects equivalent to combining an emission tax with an output subsidy to recycle revenue. It is thus clearly preferable from the standpoint of the automobile producers to the pure other forms of regulation. Besides automobile producers there is another powerful lobbying against (higher) taxes on fuels.[2] However, under usual assumptions about the economy, we must consider a relative fuel standard an inefficient policy instrument.

Since the carbon coefficient of fossil fuels is fixed and there are no end-of-the-pipe technologies, CO_2-reduction in automobile transport essentially means reduction of fuel use. The fuel use of cars is determined (1) by the fuel economy of given car classes: their fuel use under certain standardised conditions (and by technologies devised to increase this fuel economy), (2) by the type of fuel (cars with a Diesel engine use less fuel, so that even with a higher carbon coefficient, they produce less CO_2 per km), (3) by the weight of the car (usually highly correlated with perceived comfort), (4) by the vehicle miles travelled per time period, (5) by the way of driving and traffic conditions (the elimination of traffic congestions would reduce fuel use per km), and finally, of course, (6) by the overall level of traffic. An optimal strategy of emission reduction in passenger transport would potentially exploit all of these margins of passenger car use. Fuel taxes indeed affect all these dimensions and are hence preferable on efficiency grounds (Thorpe 1999). By contrast, a regulation of the average fuel efficiency primarily works on margins (1), (2) and (3). And even on these margins it is difficult to reach the efficient point by regulation of relative fuel standards. The information requirements are highly restrictive if one wants to calculate an efficient specific target for each individual producer and car type. In extreme cases, regulation of relative emission targets might not at all be able to meet absolute overall abatement targets for CO_2. When we impose stricter fuel efficiency standards, emissions per vehicle mile will go down. On the other hand, stricter fuel efficiency standards make it cheaper to drive an additional mile. Individual travelling adjustment, therefore, compensates – or even overcompensates – the reduction in overall emissions. For the US Corporate Average Fuel Economy (CAFE) Standards Jones (1993) and Greene et al. (1999) estimate that this rebound effect offsets at least 10 - 20 per cent of the emission reduction. In addition, stricter fuel efficiency standards drive up the costs of new cars and delay the retirement of older, less efficient vehicles (Portney et al. 2003).

While, under the usual assumptions of general equilibrium models, it is clear that relative emission standards are an inefficient means of emission reduction, we can not know from

[1] This kind of standard, emissions per unit produced or used, is sometimes misleadingly referred to as "specific standard". In accordance with the theoretical literature (Ebert 1998), we stick to relative standard

[2] See, e.g. Goel and Nelson (1999) which analyze the determination of fuel taxes in a vote-maximization framework.

analytical models alone how large the welfare loss of this inefficient means (as compared to efficient regulation) are. Given that technological standards (all the more when implemented as voluntary agreements) are relatively simple and have low administrative costs, their inefficiency might be tolerated if it is small. This is where numerical analysis comes in. In this paper, we present a Computable General Equilibrium (CGE) Model that has been constructed to capture the adjustment of automobile fuel efficiency to different sorts of regulation in the context of full macroeconomic adjustment. In our numerical exercise we simulate the economic and environmental effects of the voluntary agreement between the European automobile producers association (ACEA) and the EU from 1998. Special features that depart from standard CGE-models are the introduction of a sector that produces transport services for final demand, and the introduction of a separate stock of automobile capital. Automobiles are thus viewed as a capital stock in a dynamic investment context. Transport services for final consumption are produced using the capital services of this automobile capital stock and further inputs, mainly fuel. The elasticity of substitution between automobile capital services and fuel thus plays a central role in this model.

Our paper is structured in the following way: In section (2), we describe the numerical model. First, there is a short summary of the general model features that are standard in current CGE modelling. Second, we present in more detail the special treatment that the transport sector receives in our model. Third, we describe the data sources used for calibration. Chapter (3) contains our simulations of two different policy variants aimed at reducing CO_2 emissions in passenger transport to the extent foreseen in the ACEA agreement. Here we answer the question what the efficiency losses of relative emission standards are as compared to fuel taxes. Chapter (4) concludes. A detailed description of all model parts can be found in the appendix.

2 Model description

For our simulations, we use a dynamic general equilibrium model of the world economy, which is based on the fundamental GTAPinGAMS structure (Rutherford 1998). In the following section, we describe briefly the general features of the model that are standard in contemporary CGE modelling. In Section 2.2, we take a closer look at the specific modelling of the transport sector, which is the distinctive feature of the model presented in this paper.

2.1 General features of the model

As our focus is on EU climate protection policy, we use a CGE model of the world economy where countries are aggregated into ten regions (six European regions, USA, Japan, oil-exporting countries, rest of the world). The sectoral disaggregation is like the one often found in models that focus on energy policy analysis. The full input-output decomposition of national accounts has been re-aggregated into nine sectors (macro good, energy intensive production, transport, five differentiated energy sectors and an aggregated savings good; as in Rutherford and Paltsev 2000). The model is set up as a full dynamic model with optimal savings and investment decisions. Period length is chosen to be five years with the model horizon extending from 2005 to 2035. (The properties of the last period are chosen according to Rutherford et al. 1998, in order to induce a smooth intertemporal behaviour of the model despite its finite number of periods.) Details about the structure of the production functions and the utility function of the representative consumer are presented in the appendix. International trade is modelled in the Armington fashion, i.e. goods produced in different countries are treated as imperfect substitutes and their import shares depend on their relative prices (Armington 1969). (The only exception is the international crude oil market, which has been homogenised so that every country either imports or exports crude oil.) The basic equilibrium conditions in this model are (i) zero profit conditions for all production sectors (under the assumption of perfect competition), (ii) market clearance on all markets (perfectly adjusting prices) and (iii) exhaustion of the representative consumer's budget through consumption purchases.

As benchmark for the policy simulations, we chose a steady-state growth path of the world economy starting in 2005. Sensitivity analysis shows that it does hardly matter at all for comparative static effects (expressed in per cent changes against the benchmark) whether we use this steady-state path or a (considerably more complicated) calibrated business-as-usual path with different growth rates for different world regions and actual forecasts for fossil fuel production and use.

2.2 Modelling passenger car transport services

The crucial idea of our way of transport services modelling is that households do not consume cars as such, but transport services that must be produced with various inputs. The value of these services has been calculated from data sources that are independent from GTAP (see next Section). It is mainly composed of capital services of the automobile stock present in the respective economy, fuel and expenditures for repair and maintenance. To preserve macroeconomic consistency, the consumption of passenger car transportation services has been subtracted from the aggregated consumption value of the national accounts.

The second special feature in the modelling of the production of transport services is the introduction of an automobile capital stock besides the standard stock of productive capital. This automobile capital stock captures the fact that adjustment of the average automobile characteristics is not instantaneous. Cars from earlier vintages contribute to a certain extent to the production of current transport services. The approach to automobile capital is partial putty-clay: The cars that already exist in the initial period of the model exhibit a constant fuel coefficient. Cars that are built and introduced later on are malleable and exhibit a variable fuel coefficient. On the one hand, this is a convenient way of accommodating announcement effects. Policies that will be introduced later but are announced today will have an impact on the economy even before they come into force. But this will only affect the new vintages of cars, old cars remain unchanged. On the other hand, the approach of partial putty-clay implicitly assumes that the fuel efficiency of existing cars that have been introduced after the initial period can be adjusted ex post according to changing fuel prices. This is not fully realistic. However, a more realistic view on this issue can only be gained with a model that traces each vintage of cars and determines its respective fuel coefficient endogenously. This is beyond the scope of the present paper.

The size of the automobile stock and the investment in new cars is again calculated from independent data sources (see next Section). Investment in new cars is calculated in a way that warrants steady state growth of the automobile capital stock. As vehicle production is not a part of the initial sectoral disaggregation of the model, the value of automobile production is subtracted from the aggregated value of the macro-good production, and it is assumed that automobile production uses the same structure of inputs as this macro good.

2.3 Calibration

The main data source for the calibration of national and international commodity flows is the GTAP5 database (GTAP 2002). International car stocks are from UN and World Road statistics. The shares of home production and imports for automobile investment are again calculated from the GTAP5 database. Additionally, we use data from the German Automobilist Association (ADAC) to calculate the average properties (price, fuel use, repair and maintenance costs) of a car put into use in Germany. As we lack such detailed data for most other countries, we assumed that the parameter values are identical throughout the world.

3 Simulations

3.1 Main policy variants: Relative standard vs. fuel taxes

Our main policy focus in this paper is to compare fuel efficiency standards and fuel taxes as alternative means of reducing the CO_2 emissions of passenger cars. Our first policy simulation implements a fuel efficiency standard for new cars in Europe that is 30% above the benchmark value and takes effect in 2005. This approximately matches the reduction target formulated in the voluntary agreement of ACEA (ACEA/EU 1998) of lowering CO_2 emissions from about 185 g/km to 140 g/km. Tables 1 and 2 present the time paths of important endogenous variables of the model that describe the transport sector from 2005 to 2035.[3] We chose one representative European region (Germany & Austria, Table 1) and one representative non-European region (USA, Table 2). All European and all non-European regions behave quite similar as long as we consider a uniform European policy. The entries in the tables are in general per cent changes. Share changes are given in percentage points. Tax and subsidy levels are in absolute ad valorem terms.

The regulatory policy is again stated in row 1 of Table 1: We fix the average fuel efficiency of new cars at 30 per cent above its benchmark value starting in 2005.

Table 1: Relative standard of 1.3 of benchmark value

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	30.00	30.00	30.00	30.00
average fuel efficiency (all cars)	11.37	23.01	27.54	29.15
total stock of cars	-2.96	-3.07	-3.08	-3.09
total number of cars added to stock	-3.18	-3.09	-3.09	-3.09
real capital content of new cars	11.95	11.95	11.95	11.95
average price of new cars	11.43	11.50	11.52	11.55
total expenditure for transport services	1.19	1.10	1.10	1.10
share of fuel expenditures	-4.78	-4.81	-4.82	-4.83
total emissions of CO_2	-12.87	-21.21	-24.01	-24.97
implicit tax on fuel use	7.37	7.40	7.40	7.41
implicit subsidy on cars	-0.46	-0.46	-0.46	-0.46
welfare of representative consumer	-0.62			

In row 2, we see that the average fuel efficiency of the whole automobile fleet gradually adjusts to this value over time as the old capital stock with its fixed fuel coefficient depreciates. In rows 3 to 8, we can trace important indicators of the automobile market. The total stock of cars (which is calculated under the assumption that vehicle miles travelled are constant) decreases by about 3 per cent, and so does the number of new cars added to the stock. The capital content of new cars with a higher fuel efficiency increases by 12 per cent, which, given slight changes in the capital price, translates into a price increase for new cars of 11.5 per cent. The elasticity of the technology cost curve implied by the parameterization of the model in this scenario is thus about 0.38 (relative car price changes with respect to relative fuel efficiency changes), which is broadly in the range of empirical estimates (Greene/DeCicco 2000). The total expenditures for transport services, which are mainly composed of the services of automobile capital and fuel costs, are only slightly increased. Given the higher fuel efficiency of cars, the share of fuel purchases in overall expenditure for transport services decreases considerably. From an environmental point of view, the central

[3] Period length in the model is five years. So we report only every second period in the tables.

result of Table 1 is total CO_2 emissions from passenger cars, as given in row 9. The reduction in overall emissions is even higher as the one we would expect from the higher fuel efficiency per car, because the number of cars is reduced, too.

Table 2: Relative standard of 1.3 of benchmark value

USA	2005	2015	2025	2035
average fuel efficiency (new cars)	-0.10	-0.16	-0.19	-0.19
average fuel efficiency (all cars)	-0.04	-0.13	-0.17	-0.19
total stock of cars	0.06	0.05	0.05	0.05
average price of new cars	-0.03	-0.01	0.00	0.00
share of fuel expenditures	-0.04	-0.06	-0.07	-0.07
total emissions of CO_2	0.11	0.19	0.22	0.24
welfare of representative consumer	0.01			

Rows 10 and 11 show the implicit taxes and subsidies that are equivalent to directly imposing the technological standard. We see that both the implicit tax rate and the implicit subsidy are very high. An implicit tax rate of more than 700 per cent means that, with an initial tax rate of about 100 per cent, the implicit fuel price now is four times its initial value; on the other hand, a subsidy of nearly 50 per cent means that consumer car prices are effectively reduced to one half. Finally, we see that the welfare of the representative consumer goes down by about two thirds of one per cent. A welfare loss was to be expected qualitatively with a regulation of this kind. Its quantitative impact can only be assessed in the context of the CGE analysis we perform.

Table 2 shows, by way of comparison, the effects of a European carbon abatement policy to the USA (and to other non-European countries, which are very similarly affected). These effects are in general very small. All changes remain far below one per cent. Interestingly, however, the CO_2 emissions from passenger cars in the USA go slightly up. These small leakage effects are due to a decrease in the international crude oil price (because of lower European fuel consumption). Lower international oil prices also explain the small welfare gain for the USA.

Table 3: Fuel taxes with the same absolute emissions as standards

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	14.53	17.39	18.11	18.33
average fuel efficiency (all cars)	5.51	13.34	16.63	17.81
total stock of cars	-8.07	-10.69	-11.38	-11.60
total number of cars added to stock	-12.35	-11.75	-11.71	-11.72
real capital content of new cars	5.58	5.90	5.93	5.93
average price of new cars	3.90	3.98	3.95	3.97
total expenditure for transport services	6.12	7.04	7.31	7.39
share of fuel expenditures	9.31	11.49	12.05	12.22
total emissions of CO_2	-12.87	-21.21	-24.01	-24.97
endogenous tax on fuel use	2.20	2.87	3.05	3.11
welfare of representative consumer	-0.22			

Now we turn to our second policy simulation. Instead of directly imposing a technological fuel efficiency constraint on the model, we calculate the fuel tax rates that are necessary to bring about the same reductions in overall CO_2 emissions as in the first scenario. This is reflected in Table 3, which again shows the case of Germany and Austria, by entries in the "total emissions" row that are identical to those in Table 1.

The results in Table 3 are qualitatively as to be expected. The fuel tax rate that achieves the same emission reduction as the fuel efficiency standard is between 200 and 300 per cent. This is considerably less than the implicit tax in the first scenario, but it still far exceeds fuel tax values that seem politically feasible. Driven by the fuel tax, the fuel efficiency of new cars increases in this scenario, too, but only roughly half as much as with the efficiency standard policy. Again, average fuel efficiency of the total car fleet adjusts over time to the fuel efficiency of new cars. Now the number of new cars is considerably reduced (about 10 per cent), which is what we expect with drastically increasing fuel prices. However, note that total expenditure for cars decreases considerably less, because the price of new cars increases (although not as much as the number of cars goes down). Total expenditure for transport services increases because of the higher fuel prices. This means, we have an implicit demand elasticity for transport services of less than one in the model. The share of fuel expenditures in total expenditures is largely increased. The overall reduction of CO_2 emissions reported again in row 9 of Table 3 is thus brought about by a combination of higher fuel efficiency per car and fewer cars.

In terms of welfare, the tax regime compares favourably with the fuel efficiency regime. The welfare of the representative consumer is reduced, as it is in the first scenario, but the reduction is considerably smaller than with fuel efficiency standards (only about one third). That means, our initial guess that fuel taxes are a more efficient way of controlling carbon emissions than relative emission standards holds. The main difference between the two scenarios is that in the fuel tax regime, we have a larger reduction in the car stock, and thus a larger part of the CO_2 emissions reduction is effected through output reduction instead of higher fuel efficiency. This points to the importance of the elasticity of substitution between transport services and other consumption goods in the representative consumer’s utility function (see Section 4.2). The lower this elasticity, the lower we would expect the welfare difference between the two regulation regimes to be.

We do not report again the results for a representative non-European country. In this scenario, too, the spillover effects are very small and countries like the USA are hardly affected at all by a European policy of CO_2 reduction in passenger car transport.

When we computed the tax rates that are equivalent to fuel efficiency standards, we assumed that the reductions brought about by the efficiency standards must be exactly matched in each period. From an environmental point of view, it is unimportant, at which time an additional unit of CO_2 is emitted. We therefore also consider the case where overall emissions are restricted to the value attained in the scenario with fuel efficiency standards, but the allocation of emissions to the single periods of the model is left to the discretion of a welfare-maximising tax planner. The results of this scenario are displayed in Table (4).

We can see from Table (4) that with additional freedom of choice with respect to the individual tax rates, emission reductions are initially lower and later higher than in Table (3), where emissions are exogenously restricted in each period. There are three reasons for this deviating time pattern: (1) In the initial periods, there is still a considerable fraction of old cars whose fuel consumption cannot been adjusted, so the welfare losses of a given tax increase are higher than in later periods. (2) Future utility is discounted, so that later CO_2 reductions are less welfare decreasing than earlier ones. (3) The economy in the benchmark is on a steady-state growth path. A given relative reduction in emissions therefore corresponds to higher absolute reductions in the future. And the emission target is in absolute terms.

Table 4: Optimal fuel taxes with intertemporal reduction target for emissions

Germany & Austria	2000	2010	2020	2030
average fuel efficiency (new cars)	8.49	12.67	18.16	25.19
average fuel efficiency (all cars)	3.53	9.91	16.67	24.40
total stock of cars	-4.14	-7.24	-11.50	-16.72
total number of cars added to stock	-7.63	-11.93	-17.96	-20.25
real capital content of new cars	3.32	5.77	9.23	11.89
average price of new cars	2.51	4.59	7.30	6.73
total expenditure for transport services	3.57	4.99	7.33	10.37
share of fuel expenditures	5.11	7.97	12.10	17.99
total emissions of CO_2	-7.41	-15.61	-24.15	-33.06
endogenous tax on fuel use	1.10	1.84	3.07	5.15
welfare of representative consumer	-0.12			

The optimal choice of tax rates over time means that the welfare loss can be reduced to about one half as compared to the case with reduction targets for each period separately. However, it would not be appropriate to compare Table (4) directly with the case of efficiency standards for each period in Table (1). When one considers the consequences of a second-best time path of tax rates, this should be compared with an optimal time path of fuel efficiency standards, and not with standards that are uniform over time. [However, the calculation of optimal fuel efficiency standards would require different modelling and solution techniques. This is why we do not approach this case.]

3.2 Sensitivity analysis

In the appendix, we report results from a sensitivity analysis with respect to two key parameters of the model: (1) the elasticity of substitution in consumption between transport services and other consumption, $\sigma_{TRN,C}$, (2) the elasticity of substitution in the production of transport services between automobile capital and fuel, $\sigma_{TC,F}$. The main findings in this sensitivity analysis are, as qualitatively predicted in the theoretical model:

1. The higher $\sigma_{TRN,C}$, the lower are welfare losses through CO_2 regulation.
2. The higher $\sigma_{TRN,C}$, the higher the relative benefits from using a tax instead of a relative real standard as policy instrument.
3. The lower $\sigma_{TC,F}$, the higher are the welfare losses from fuel efficiency standards of a given value.
4. The lower $\sigma_{TC,F}$, the more can the welfare loss be reduced by using a tax instead of a fuel efficiency standard.

4 Conclusions

With the help of a CGE model of the world economy with special focus on the passenger car transport sector, we are able to compare the quantitative impacts of different policy approaches to regulating CO_2 emissions from passenger cars. We simulate two alternative policies in the EU: first, a regulation of fuel efficiency standards as it is contained in the voluntary agreement between the European automobile producers association (ACEA) and the EU from 1998. This means an increase in fuel efficiency of about 30 per cent of the benchmark value. The CO_2 reduction of passenger cars that can be achieved with this standard is between 12 per cent in 2005 and 25 per cent in 2035.

The second scenario takes the CO_2 reductions that are the consequence of the fuel efficiency standard as an explicit reduction target. Then the level of the fuel tax is determined that achieves exactly this absolute reduction target. The numerical simulation shows that in this case fuel efficiency also goes up, but only about one half of the amount of the explicit regulation. The rest of the required CO_2 reduction is brought about by a general decrease in the car stock. In terms of welfare, the fuel tax outperforms the fuel efficiency standard as a means of CO_2 emission regulation. Welfare losses are about 0.2 per cent as compared to 0.6 per cent in the fuel efficiency standard scenario. Welfare losses can thus be reduced to approximately one third by choosing another regulatory regime.

What we observe here, is a confirmation of the general economic presumption that a regulatory regime is the more efficient the more margins of substitution it affects (which of course does not necessarily hold under second-best conditions). In our numerical model, one tries to reduce CO_2 emissions with fuel efficiency standards by effecting only one margin, the fuel use per kilometre travelled. The overall stock of cars, which is the additional margin captured in our model remain unaffected. A fuel tax, in contrast, works in both dimensions. A policy that affects only this one additional margin achieves a reduction of welfare losses to one third in our model. When we also consider the additional ways of adjustment enumerated in the introduction of this paper, e.g. variations in the vehicle kilometres travelled in one time period or variations in fuel use that depend on the driving style or traffic conditions, we can presume (although this remains to be shown in a more detailed model) that the reductions in welfare losses are even higher.

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I Appendix: Model Description

This section provides a summary of the essential features of our intertemporal multi-region, multi-sector general equilibrium model.

- Output and factor prices are fully flexible and markets are perfectly competitive.
- Labour force productivity increases at an exogenous growth rate (Harrod-neutral technological progress).
- In equilibrium there is a period-by-period balance between exports from each region and global demand for those goods. The model adopts the Armington assumption for export and import markets of a non-energy macro good to differentiate between commodities produced for the domestic market, the export market and the import market. Fossil fuels are treated as perfect substitutes on international markets.
- In each region, a representative consumer maximizes the present value of life-time utility subject to (i) an intertemporal balance of payments constraint, (ii) the constraint that the output per period is either consumed (incl. inter-mediate demand and exports) or invested, and (iii) the equation of motion for the capital stock, i.e. capital stocks evolve through depreciation and new investment. This gives the optimal level of consumption and investment over time.
- The agents have an infinite horizon, and their expectations are forward looking and rational. To approximate an infinite horizon model with a finite horizon model we assume that the representative consumer purchases capital in the model's post-horizon period at a price that is consistent with steady-state equilibrium growth (terminal condition).

The model is formulated as a system of nonlinear inequalities using GAMS/MPSGE (Rutherford 1999) and solved using PATH (Dirkse and Ferris 1995). The inequalities correspond to the three classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero-profit) conditions for constant returns to scale producers, (ii) market clearance for all goods and factors, and (iii) income balance for the representative consumers in each region. The fundamental unknowns of the system are three vectors: activity levels (production indices), non-negative prices, and consumer incomes. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition, and a consumer income variable to an income definition equation. An equilibrium allocation determines production, prices and incomes.

Most of the functions used in the model are of the nested CES type (with extreme cases Cobb-Douglas (CD) and Leontief (L)). The derivation of cost and demand functions from these functions is standard, so that we can use the simplified notation Output = CES(Input):

The production function has the following structure:

Y = L(intermediate inputs, crude oil,CES(energy,CES(primary inputs)))

energy = CES(electricity,CES(coal,CES(gas, refined oil)))

On the output side, total domestic production splits up into domestic use and exports. With regard to imports, the Armington assumption is applied which assures that two-way trade is possible (except for the crude oil market, where we consolidate trade flows such that each country either exports or imports oil). According to the Armington approach the commodity varieties from different countries are incomplete substitutes for domestic consumption. Formally, there is a hypothetical Armington commodity, A, which satisfies domestic demand, and which is composed of domestic and foreign goods varieties in the following fashion:

A = CES(domestic production, CES(foreign production from other countries))

Domestic demand is composed of final demand of private and public consumers (These values are separately given in the GTAP dataset. However, our model does not contain an explicit public sector, tax revenue from all sources goes directly to the representative consumer.) and intermediate demand from other sectors. All demand fractions are of the same structure as the Armington commodity.

Final demand of the representative consumer is on the highest level the composite

C = CES(passenger transport services, other consumption commodities aggregate)

The consumption commodities aggregate, CC, can be decomposed further:

CC = CES(CES(non energy commodities), energy)

and finally, the energy aggregate, E, in final demand is composed of

E = CES(refined oil products, coal, gas).

Conventional productive capital and automobile capital are treated analogously. Capital in each period is composed of the capital from the previous period (less depreciation) plus new investment. Depreciation and capital maturation rates have been adjusted to match the requirements of the 5-year periods in the model. The capital stock produces proportional capital services each year that enter the production functions (the production function of consumer transport services in the case of automobile capital). The proportionality factor has been calibrated according to the benchmark interest rate. Investment into conventional productive capital is a Leontief-composite of output of all productive sectors with the share parameters determined through benchmark investment. By contrast, investment into automobile capital is assumed to have the same input structure as the macro good in the economy. Domestic investment into automobile capital is composed of domestic and imported automobile varieties in proportion to the benchmark GTAP shares in the sector "motor vehicles and parts" (which, as such, is not part of our model).

Consumer transport services, TRN, are produced in the following way:

TRN = CES(maintenance and repair, CES(capital services, fuel))

For old automobile capital, there are the same inputs, but production coefficients are fixed.

Finally, the policy instruments are implemented as follows: The relative fuel standard is conceived as a combination of a tax on fuel input in the production of transport capital services with new cars, and a subsidy on transport capital services output. These two endogenous implicit tax rates are complementary to two constraints: the emission standard (output of transport services over fuel input) and a tax revenue recycling constraint that says that the combination of the tax and the subsidy must generate zero revenue. In the case of an absolute emission standard, there is an endogenous tax on fuel used in both new and old transport capital services. (We assume that it is not politically feasible to discriminate between new and old automobile capital in this respect.)

II Appendix: Sensitivity Analysis

In this appendix, we report detailed results of our sensitivity analysis. We focus on two key elasticities of the model: (1) the elasticity of substitution in consumption between transport services and other consumption, (2) the elasticity of substitution in the production of transport services between automobile capital and fuel.

First, we vary the elasticity of substitution in consumption between transport services and other consumption, $\sigma_{TRN,C}$. The benchmark value of $\sigma_{TRN,C}$ is 0.6; we report alternative scenario results for $\sigma_{TRN,C} = 0.4$ (Tables 5 and 6) and $\sigma_{TRN,C} = 0.8$ (Tables 7 and 8). In welfare terms this makes only a minor difference. However, the pattern of adjustment to relative real standards varies with $\sigma_{TRN,C}$ in an intuitive way. The higher $\sigma_{TRN,C}$, the higher the decrease in car purchases in response to the higher car prices due to higher fuel efficiency. The reduction in CO_2 emissions is thus higher, but welfare losses are smaller because of better substitution possibilities.

When we turn to the tax scenarios under different values of $\sigma_{TRN,C}$, we must keep in mind that they cannot exactly be compared with each other in welfare terms, because CO_2 reduction is not the same across scenarios but taken from the respective fuel efficiency scenario. A reasonable comparison is, by contrast, between a tax scenario and its respective fuel efficiency scenario. Here we can see that the higher $\sigma_{TRN,C}$, the lower the tax rate that is necessary to implement the CO_2 reduction target. Consequently, the induced fuel efficiency is lower, and a larger part of the required CO_2 reduction is brought about by a decrease in the car stock. Again with respect to welfare, we have the two central results: (1) The higher $\sigma_{TRN,C}$, the lower are welfare losses through CO_2 regulation. (2) The higher $\sigma_{TRN,C}$, the higher the relative benefits from using a tax instead of a relative real standard as policy instrument.

Second, we perform a sensitivity analysis with respect to the elasticity of substitution in the production of transport services between automobile capital and fuel, $\sigma_{TC,F}$. The benchmark value of this elasticity is 0.25, and we report alternative scenarios for $\sigma_{TC,F} = 0.15$ (Tables 9 and 10) and $\sigma_{TC,F} = 0.35$ (Tables 11 and 12).

Contrary to the case where we vary the elasticity of substitution in consumption, the model now reacts highly sensitive to elasticity changes (where a higher value of $\sigma_{TC,F}$ corresponds to a flatter technology cost curve). In the scenarios with a relative, real standard (Tables 9 and 11), the main consequence of a lower $\sigma_{TC,F}$ is that more fuel efficient cars are now more expensive than in the benchmark scenario (Table 1). This means that the car stock shrinks more and overall CO_2 reduction is higher. With a $\sigma_{TC,F}$ of 0.15, welfare losses of a mandatory fuel increase of 30% are about three times as high as with $\sigma_{TC,F} = 0.25$.

When we compare the tax scenarios with varying $\sigma_{TC,F}$ (Tables 10 and 12), the differences are markedly smaller than in the scenarios with fuel efficiency standards. Here, too, the automobile price increase is the higher, the smaller the value of $\sigma_{TC,F}$. But now, as there is no fixed standard for the fuel efficiency, when $\sigma_{TC,F}$ is small, the total stock of cars is reduced more, and a larger part of the overall CO_2 reduction is achieved by traffic reduction than by a rise in fuel efficiency. In welfare terms this means: (1) The lower $\sigma_{TC,F}$, the higher are the welfare losses from fuel efficiency standards of a given value. (2) The lower $\sigma_{TC,F}$, the more can the welfare loss be reduced by using a tax instead of a fuel efficiency standard.

Table 5: Standard scenario with EOS(consumption) = 0.4 (instead of 0.6)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	30.00	30.00	30.00	30.00
average fuel efficiency (all cars)	11.50	23.07	27.56	29.16
total stock of cars	-2.18	-2.26	-2.26	-2.27
total number of cars added to stock	-2.33	-2.27	-2.27	-2.27
average price of new cars	11.44	11.50	11.52	11.55
total expenditure for transport services	2.01	1.96	1.95	1.96
share of fuel expenditures	-4.78	-4.81	-4.82	-4.83
total emissions of CO_2	-12.27	-20.58	-23.38	-24.33
welfare of representative consumer	-0.63			

Table 6: Tax scenario with EOS(consumption) = 0.4 (instead of 0.6)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	16.91	19.63	20.30	20.49
average fuel efficiency (all cars)	6.48	15.09	18.65	19.92
total stock of cars	-6.58	-8.59	-9.09	-9.26
total number of cars added to stock	-9.88	-9.37	-9.34	-9.35
average price of new cars	4.49	4.53	4.50	4.51
total expenditure for transport services	11.07	12.92	13.41	13.58
share of fuel expenditures	11.11	13.27	13.81	13.98
total emissions of CO_2	-12.27	-20.58	-23.38	-24.33
endogenous tax on fuel use	2.73	3.45	3.65	3.71
welfare of representative consumer	-0.29			

Table 7: Standard scenario with EOS(consumption) = 0.8 (instead of 0.6)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	30.00	30.00	30.00	30.00
average fuel efficiency (all cars)	11.25	22.96	27.52	29.15
total stock of cars	-3.73	-3.88	-3.90	-3.91
total number of cars added to stock	-4.02	-3.91	-3.91	-3.91
average price of new cars	11.42	11.50	11.52	11.56
total expenditure for transport services	0.38	0.26	0.25	0.25
share of fuel expenditures	-4.78	-4.81	-4.82	-4.83
total emissions of CO_2	-13.46	-21.83	-24.64	-25.59
welfare of representative consumer	-0.60			

Table 8: Tax scenario with EOS(consumption) = 0.8 (instead of 0.6)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	12.94	15.78	16.52	16.74
average fuel efficiency (all cars)	4.85	12.07	15.15	16.26
total stock of cars	-9.27	-12.39	-13.22	-13.49
total number of cars added to stock	-14.33	-13.67	-13.63	-13.64
average price of new cars	3.47	3.58	3.57	3.58
total expenditure for transport services	2.79	2.87	2.91	2.93
share of fuel expenditures	8.15	10.25	10.81	10.98
total emissions of CO_2	-13.46	-21.83	-24.64	-25.59
endogenous tax on fuel use	1.87	2.49	2.66	2.72
welfare of representative consumer	-0.18			

Table 9: Standard scenario with EOS(production) = 0.15 (instead of 0.25)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	30,00	30,00	30,00	30,00
average fuel efficiency (all cars)	9,86	22,33	27,29	29,07
total stock of cars	-11,50	-12,12	-12,21	-12,25
total number of cars added to stock	-12,66	-12,28	-12,27	-12,27
average price of new cars	32,61	33,01	33,10	33,19
total expenditure for transport services	6,01	5,50	5,44	5,43
share of fuel expenditures	-6,65	-6,70	-6,71	-6,73
total emissions of CO_2	-19,44	-28,17	-31,04	-32,01
welfare of representative consumer	-1,97			

Table 10: Tax scenario with EOS(production) = 0.15 (instead of 0.25)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	13,70	15,38	15,84	15,98
average fuel efficiency (all cars)	4,50	11,45	14,41	15,48
total stock of cars	-15,81	-19,94	-21,10	-21,49
total number of cars added to stock	-22,45	-21,72	-21,68	-21,70
average price of new cars	2,93	3,00	2,93	2,98
total expenditure for transport services	12,86	14,30	14,79	14,96
share of fuel expenditures	20,00	23,44	24,43	24,72
total emissions of CO_2	-19,44	-28,17	-31,04	-32,01
endogenous tax on fuel use	4,92	6,24	6,66	6,80
welfare of representative consumer	-0,45			

Table 11: Standard scenario with EOS(production) = 0.35 (instead of 0.25)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	30,00	30,00	30,00	30,00
average fuel efficiency (all cars)	11,56	23,09	27,57	29,17
total stock of cars	-1,80	-1,85	-1,85	-1,85
total number of cars added to stock	-1,96	-1,86	-1,86	-1,85
average price of new cars	8,91	8,95	8,97	8,99
total expenditure for transport services	0,59	0,55	0,55	0,56
share of fuel expenditures	-4,52	-4,55	-4,56	-4,57
total emissions of CO_2	-11,98	-20,26	-23,06	-24,01
welfare of representative consumer	-0,44			

Table 12: Tax scenario with EOS(production) = 0.35 (instead of 0.25)

Germany & Austria	2005	2015	2025	2035
average fuel efficiency (new cars)	16,94	20,01	20,74	20,96
average fuel efficiency (all cars)	6,53	15,41	19,06	20,38
total stock of cars	-6,23	-7,98	-8,40	-8,53
total number of cars added to stock	-9,14	-8,63	-8,60	-8,60
average price of new cars	4,46	4,57	4,57	4,58
total expenditure for transport services	4,53	5,06	5,20	5,25
share of fuel expenditures	6,26	7,50	7,80	7,89
total emissions of CO_2	-11,98	-20,26	-23,06	-24,01
endogenous tax on fuel use	1,65	2,06	2,16	2,20
welfare of representative consumer	-0,21			

III Appendix: Analytical Core Model

In this appendix, we describe a simplified "model of the model" that contains the key mechanisms that play a role when we compare relative real standards to an environmental tax policy. In the model, there is a representative household whose utility depend on the consumption of two goods, X_1 and X_2 (where X_1 is to be thought of as a macro good, and X_2 is transport services):

$U = U(X_1,X_2)$.

The household is endowed with a single factor of production, labour, in a fixed quantity, L. Commodity X_1 is produced with labour alone:

$X_1 = L_1$,

while for the production of X_2 labour and energy are used:

$X_2 = f(L_2,E)$.

Energy is imported at a fixed price (given as a quantity of X_1; which is chosen as numéraire), so that the resource constraint reads:

$L_1 + L_2 + E = \overline{L}$.

The first-best situation in this economy is characterised by

$U_1 = U_2 f_L = U_2 f_E$.

When we turn to a situation, where the country faces an exogenous constraint on energy use, $E \leq \overline{E}$, we find that a second-best strategy of implementing this constraint is a tax or permit policy with

$U_1 = U_2 f_L \neq U_2 f_E$:

Assume now that neither energy taxes nor permits are at the disposal of the government. Instead, the constraint on energy use must be implemented by a relative, real standard that fixes $e = E/X_2$, but leaves all further economic adjustment at the disposal of the decentralised agents. While it is clear that a relative standard of this type must be inferior to a second-best policy, we are interested in the question of what determines the scope of the welfare loss. Specifically, we want to check whether the following two hypotheses hold:

- The lower the elasticity of substitution in the production of X_2, the higher the welfare loss (because then it is more expensive to impose an input coefficient that deviates from the one optimally chosen under a tax or permit policy).
- The higher the elasticity of substitution in consumption, the higher the welfare loss (because then it matters more that the shift from X_2 to X_1 is not used as part of the policy strategy to implement the resource constraint).

For an analytical answer to these questions, a two-step strategy seems necessary:

1. Set up an analytical model in X_2, L_2, and p_2, to determine the value of $e = E/X_2$ that is needed to implement a given E:

$X_2 = f(L_2,E)$

$U_1(\overline{L} - L_2 - \overline{E}, X_2)\, p_2 = U_2(\overline{L} - L_1 - \overline{E}, X_2)$ (1)

$p_2 = E/X_2 + f^*(E/X_2)$

where we have chosen $p_1 = p_L \equiv 1$; and f^* is the function that gives the labour intensity of X_2 at a certain standard for e. (For a linear homogenous production function, f^* is independent of X_2, i.e. $f^* = f^*(e)$.) Assuming that the problem is well-behaved, it will exhibit a unique equilibrium point whose comparative static properties can be studied.

2. Compare dU/dE in the model without relative standard with dU/de×de/dE in the model with relative standard. This comparison must start at a point that is not first-best, because in the first-best point both these expressions are zero.

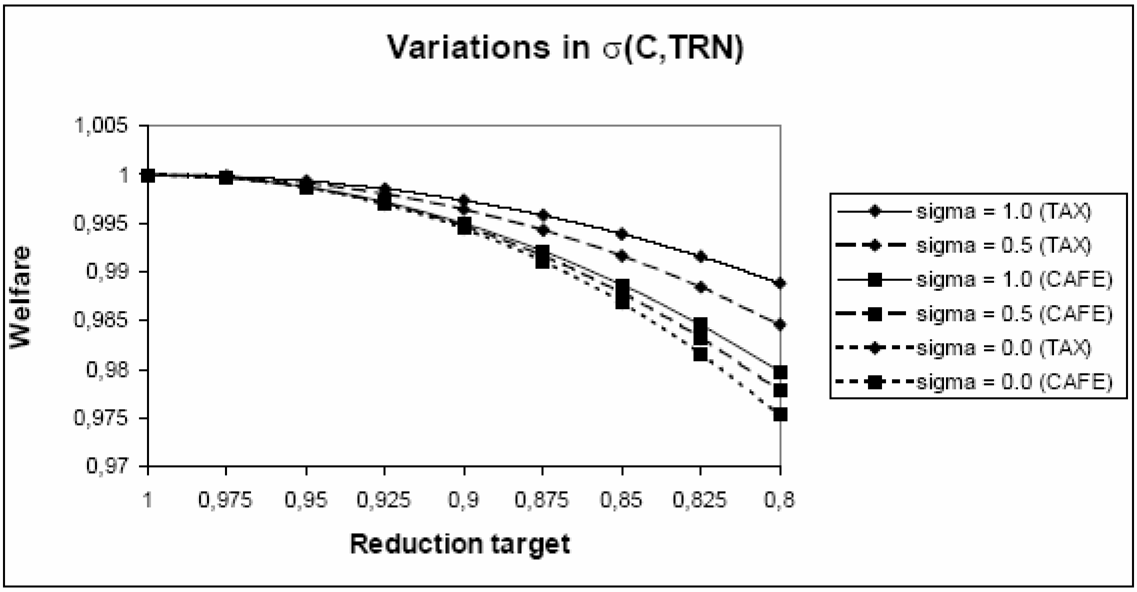

Figure 1: Welfare Effects of a variation in $\sigma_{X1,X2}$

Given that the system 1 cannot further be simplified (it would be possible to substitute X out, but this would not facilitate the analysis), analytical computations are cumbersome. Instead, in Figures (1) and (2), we report some illustrative simulations that show welfare changes over a certain range of reduction targets and with different assumptions about the two key elasticities that we are interested in.

All welfare curves are, as expected, concave in the strictness of the reduction target. Figure (1) shows the effects of variations in the elasticity in consumption between transport services and other consumption. We can observe:

- The lower $\sigma_{X1,X2}$, the larger the welfare losses when E is reduced.
- The lower $\sigma_{X1,X2}$, the lower the relative loss of using a relative standard instead of a tax. (In the extreme case of $\sigma_{X1,X2} = 0$, both instruments are equivalent.)

Figure (2) shows the effects of variations in the elasticity of substitution in the production of X_2 between L and E:

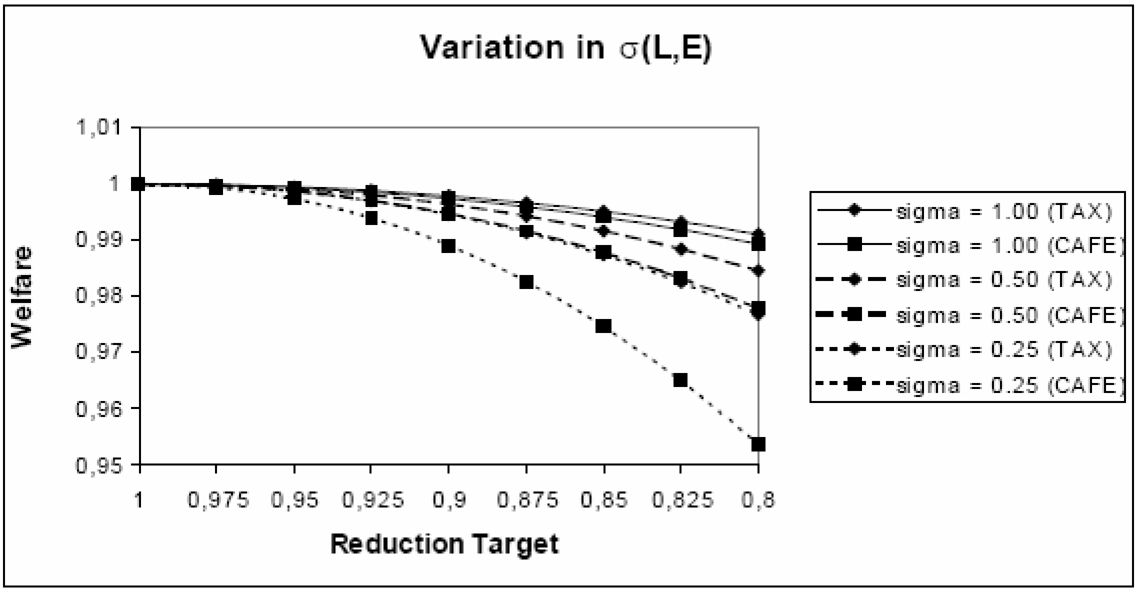

Figure 2: Welfare Effects of a variation in $\sigma_{L,E}$

- The lower $\sigma_{L,E}$, the larger the welfare losses when E is reduced.
- The lower $\sigma_{L,E}$, the larger the relative loss of using a relative standard instead of a tax.