Computing Game-theoretic equilibria in GTAP: Optimising regional climate change policies

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Abstract

This paper outlines an approach to modelling strategic behaviour in the Global Trade Analysis Project's computable general equilibrium model GTAP-E. This modelling innovation has been motivated by the desire to compute game-theoretic equilibria for climate policy analysis to gain insights into the potential outcomes of international climate change negotiations and optimal burden sharing arrangements. Demonstrations of the model applied under a permit trading regime and independent carbon taxation are given. The demonstrations show that, for the same value placed on emissions abatement, an international permit trading scheme results in a higher payoff for all regions. We also find that, for the same level of abatement, optimal differential carbon taxes lead to a significantly lower total welfare loss than uniform taxes imposed under international permit trading, due to pre-existing taxes. The technique can be applied more broadly to any numerical optimization of GEMPACK models.

Introduction

Negotiations of international agreements, such as post-Kyoto agreements on climate change response policy, are strongly influenced by the national interests of the participants. The anticipated impact of the agreements on the economic welfare of each negotiating region is a key interest. So is the level of greenhouse gas concentrations due to climate change effects. Future gas concentrations are a function of global emission levels, so this national interest is highly dependent on the action of other regions. It is therefore reasonable to expect that negotiators would behave strategically and that the final outcome would approximate a strategic equilibrium.

In most previous climate change policy general equilibrium modelling, outcomes of negotiations on international agreements have been exogenously assumed (for examples see Garnaut 2008 and Australian Government 2008). Mechanisms such as delayed entry for developing nations and differentiated permit allocations have been used to stylize the possible forms of international agreements. The GTAP-E model has lacked the capacity to determine the negotiated outcomes endogenously and hence the outcome has not been consistent with strategic behaviour.

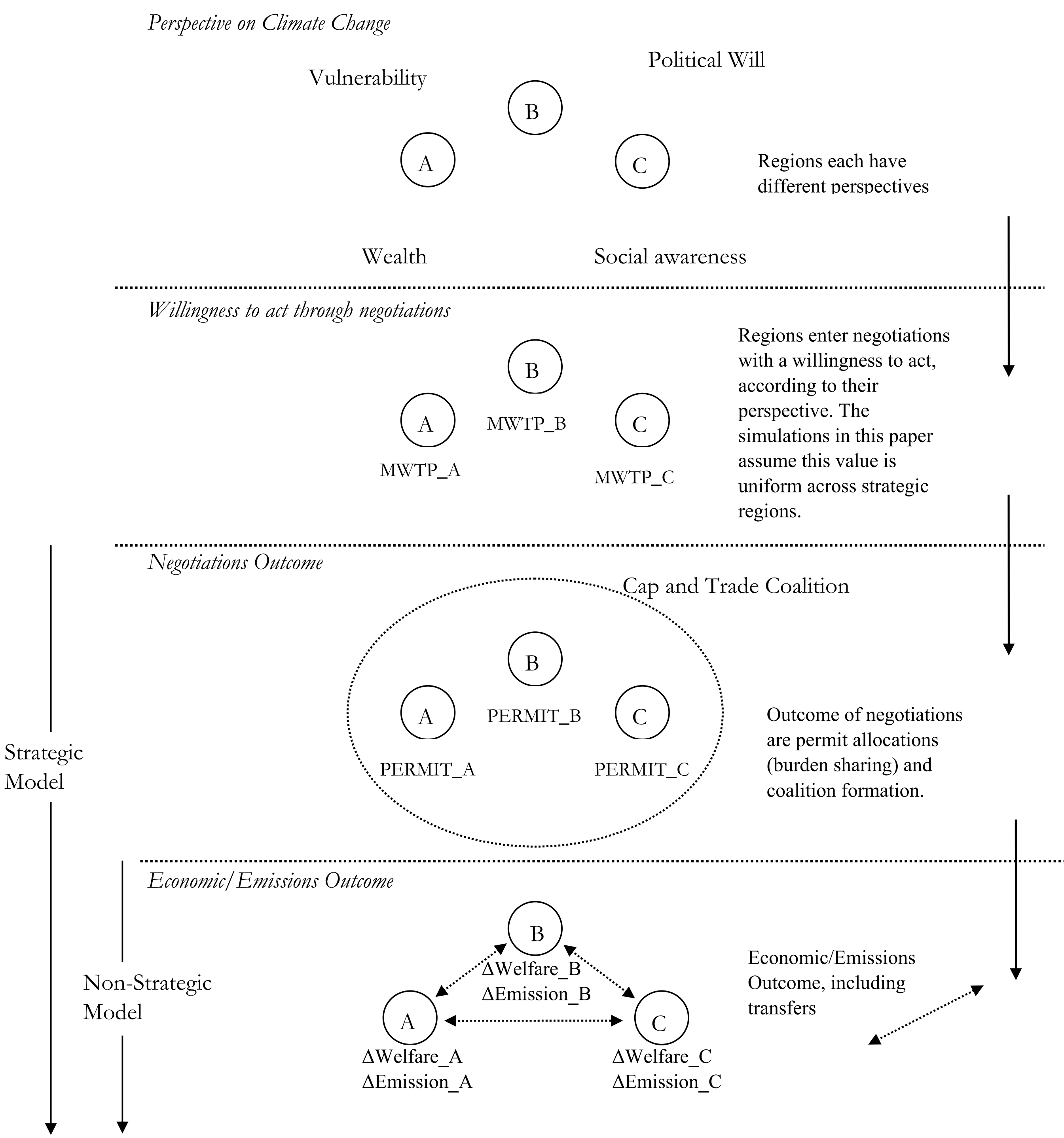
In this paper a '*strategic version*' of the GTAP-E model has been developed in which a game-theoretic framework has been embedded to solve for strategic equilibria. This enables insight to be gained into the potential emission policy measures that will be implemented through international negotiations along with their economic impacts. It also enables derivation of the optimal burden sharing arrangements from a group or global perspective.

Embedding strategic behaviour

GTAP-E (Burniaux and Truoung 2002) is an Energy-Environmental version of the GTAP model (Hertel 1997). Like other Computable Generated Equilibrium (CGE) models, GTAP endogenously adjusts consumer and producer behaviour to maximize utility and profit respectively. Government policy decisions resulting from international negotiations, such as carbon taxes, are generally set exogenously. To endogenise these decisions we construct a regional payoff function that we then assume is maximized in the outcome of the negotiation process. We have described this payoff function in detail in the "Modelling Approach" section that follows.

Figure 1 is an idealized flowchart of climate change negotiations involving countries A, B and C forming an international permit trading coalition.

Figure 1: Modelling negotiation



Each region has a different perspective on climate change, reflected by the top quartile of Figure 1. Issues such as perceived vulnerability to climate change impacts, national wealth, social awareness and political circumstances play a role in the formation of these perspectives.

We assume that these perspectives translate into a quantifiable measurement of the degree to which each country is willing to take action, with which they enter negotiations (second quartile of Figure 1). This willingness is represented by the use of a Marginal Willingness to Pay (MWTP) variable, reflecting the welfare cost that each region is willing to bear to reduce global emissions by one tonne of carbon. We make two points on this variable, which is not calculated by the model but is taken as an exogenous input. Firstly, we do not investigate what values of MWTP should be assigned in this paper, but assume constant (not a function of abatement levels) uniform values between regions for the demonstration. Secondly, climate change damage is a function of greenhouse gas concentrations, rather than emissions. As we are using static simulations, we do not consider gas accumulation or other dynamic effects in this paper.

In the *'strategic version'* of GTAP-E developed for this paper, the value of MWTP determines the abatement policies adopted by strategic regions. The policy variable adjusted for payoff optimization - henceforth referred to as the "climate policy variable" - depends on the environment of the simulation. Under independent carbon taxation, the regional carbon tax is the climate policy variable. In a permit trading coalition, the strategic model calculates the permit allocations for the participating regions. This is the case displayed in the third quartile of Figure 1. That is, the model endogenously adjusts each country's permit allocation (climate policy variable) to maximize the payoff function, reflecting the outcome of the negotiating process. Membership decisions are not modelled – the cap and trade coalition is assumed from the outset.

The economic/emission outcomes are calculated simultaneously along with the climate policy variable by the model. The separation in Figure 1 into the third and fourth quartiles illustrates the difference between the strategic model and the non-strategic model. The climate policy variable is exogenously shocked in the non-strategic model, whereas it is endogenous in the strategic model and the MWTP is exogenously specified.

With the construction illustrated above in mind, we embed a numerical framework within the GTAP-E model, in a similar vein to Carbone, Helm and Rutherford (2008). Calculation of perturbed solutions to the General Equilibrium model allows approximation of the derivative of the payoff function. To our knowledge this numerical optimization technique has not been used in GEMPACK (Harrison and Pearson 1996).

Modelling Approach

Payoff Function

Changes in regional economic welfare in GTAP-E are calculated within the model as an Equivalent Variation (McDougall 2002). To guide the regional choice of permit allocation or carbon tax, we construct a regional payoff function (Equation 1) which accounts for both economic welfare and the perceived environmental benefit of emissions abatement.

Equation 1: Payoff Function

$$\text{Payoff}_r(\tilde{v}) = \text{Welfare}_r(\tilde{v}) - \text{MWTP}_r * e(\tilde{v})$$

$\tilde{v} = (v_1, v_2 \dots v_n)$ = climate policy variable vector for n strategic regions

r = strategic region index

e = global carbon emissions

MWTP_r = Marginal Willingness To Pay constant

Welfare and global carbon emissions depend upon the values of the climate policy variable in all strategic regions. Equation 1 includes an exogenous term reflecting the perceived environmental cost of global carbon emissions. We write this as Marginal Willingness to Pay (MWTP): the marginal willingness of a region to forego welfare in the simulation period to reduce global emissions (as discussed previously). For this paper, we assume this is a constant, independent of emissions abatement.

Unlike the optimisation of consumer utility and producer profit functions in GTAP-E, the optimisation of the payoff function is not analytically tractable: we cannot write down an equation for the climate policy variable which ensures payoff optimisation. Instead, we use an approximation of the partial derivative of the payoff function in each region with respect to that region's climate policy variable, and rely on a numerical step-wise technique to converge to a finite global maximum. The optimum point occurs when the marginal cost of abatement (MCA) equals MWTP, shown in Equation 2. MCA is defined as the reduction in regional welfare through adjustment of the climate policy variable sufficient to achieve one tonne of global carbon abatement.

Equation 2: Payoff optimisation

$$\frac{\partial\ \mathrm{Payoff_r}(\tilde{\mathrm{v}})}{\partial \mathrm{v_r}} = 0 \rightarrow \mathrm{MCA_r}(\tilde{\mathrm{v}}) \equiv \frac{\partial\ \mathrm{Welfare_r}(\tilde{\mathrm{v}})}{\partial \mathrm{v_r}} \left[\frac{\partial \mathrm{e}(\tilde{\mathrm{v}})}{\partial \mathrm{v_r}}\right]^{-1} = \mathrm{MWTP_r}$$

MCA_r = Marginal Cost of Abatement

$MWTP_r$ = Marginal Willingness To Pay constant

Sufficient conditions for convergence would be strict concavity of the payoff function and a continuous MCA function passing through the desired MWTP value at a finite point. We have not proven that such sufficient conditions exist within the GTAP-E model, but our demonstrations have converged adequately and our analysis of the simulations we have run is consistent with these conditions. The convergence relies on the MCA strictly rising as the carbon tax increases or permit allocation decreases. Taking the tax case as an example, as a region raises its carbon tax it needs to use increasingly costly abatement options. Provided the chosen value of MWTP is above the initial MCA[1], the tax will rise and convergence will occur. If MWTP is less than MCA, a subsidy will be introduced.

The derivative MCA in each strategic region is approximated by calculating the payoff function for two marginally different values of climate policy variable in that region, holding the actions of other strategic regions fixed. The GEMPACK software optimises the strategic actions simultaneously, making the solution a Nash equilibrium. The implementation is described below.

Implementation in GEMPACK

The following describes the implementation of the strategic framework with n strategic regions and independent carbon taxation. The permit trading implementation is similar. To simplify the explanation, we assume the model has only n regions, so all regions are strategic.

Firstly, we run the standard GTAP-E model statically n times, shocking carbon tax in each strategic region up by half a dollar. We shall refer to the resulting n solutions as the initial perturbed databases, and the standard GTAP-E database as the initial base database.

[1] This is true for a single strategic region, but may not hold for multiple strategic regions as MCA is also a function of taxes in other strategic regions.

We adjust the GTAP-E model code so that each coefficient and variable includes an extra index. The set that defines this index has n+1 elements, one base element and one element for each of the n strategic regions. The adjusted (strategic) model reads in coefficient values from the base and perturbed databases. The initial solution or database of this strategic model is the combination of the base database and the perturbed databases.

At this stage, we effectively have n+1 GTAP-E "models" in one model (tablo) file and one database. For example, there are n+1 carbon taxes for each region, all of which are read in to begin with. For a strategic model with two regions, the following matrix shows the starting carbon tax levels.

Table 1: Carbon tax initial matrix in an example with 2 regions

	Region 1	Region 2
Base	0	0
Region 1 perturbed	0.5	0
Region 2 perturbed	0	0.5

Correspondingly, the carbon tax variable in the strategic model is a vector of (n+1)*n scalar variables (6 in our example). We refer to the scalar variables corresponding to the base row as the base tax variables, and to those corresponding to the other rows as the perturbed tax variables. We introduce n^2 scalar equations into the strategic model code that link the n^2 perturbed tax variables to the n base tax variables, so that the perturbation is maintained (Equation 3).

Equation 3 Tax Linking Equation

$$\Delta v_r^s = \Delta v_r^b \ \forall \ s = 1 \dots n \text{ and } r = 1 \dots n$$

Δv_r^b = change in base tax scalar variable for region r

Δv_r^s = change in region s perturbed tax scalar variable for region r

As we have introduced n^2 equations, for proper closure we endogenise the n^2 perturbed scalar tax variables, leaving the n base tax variables exogenous. For illustration, if we shocked the base carbon taxes in Region 1 and Region 2 up by \$x and \$y respectively we would arrive at the final values shown in Table 2.

Table 2: Hypothetical Carbon tax solution in an example with 2 regions

	Region 1	Region 2
Base	x	y
Region 1 perturbed	x+0.5	y
Region 2 perturbed	x	y+0.5

We introduce n MWTP variables in the strategic model and add n payoff optimisation equations into the model code (Equation 4). These link perturbed values of welfare and emissions with base values to define the MCA which is set equal to MWTP. We calculate our initial MCA values from the initial base and perturbed databases and use these to initialise MWTP. This ensures the combination of our initial base and perturbed databases is a solution of the strategic GTAP-E model.

Equation 4 Payoff optimisation implementation

$$\mathrm{MCA}_r\left(\tilde{v}^b\right) \equiv \frac{\mathrm{Welfare}_r(\tilde{v}^r) - \mathrm{Welfare}_r(\tilde{v}^b)}{e(\tilde{v}^r) - e(\tilde{v}^b)} = \mathrm{MWTP}_r$$

$\tilde{v}^b = (v_1^b, \dots, v_n^b)$ = base carbon tax

$\tilde{v}^r = (v_1^r, \dots, v_n^r) = \left(v_1^b, \dots, v_r^b + 0.5, \dots, v_n^b\right)$ = region r perturbed carbon tax

$\mathrm{Welfare}_r$ = welfare in region r

e = global emissions level

Finally, we exogenise the regional MWTP variable and endogenise the base carbon tax variables. Thus the regional base carbon taxes are set by the MCA equation. We shock the MWTP to our target value. The model then finds a set of base taxes $\tilde{v}^b$ such that the regional MCA values equal our target MWTP values. As the base taxes shift to satisfy all payoff optimisations, the outcome is a Nash equilibrium and takes into account effects such as carbon leakage and trade effects.

We have not applied any other shocks as part of the demonstration below. To simultaneously apply other shocks and optimise the payoff function, the other shocks should be applied uniformly across the base and perturbed exogenous scalar variables, such that the only difference in exogenous state variables remains the carbon tax perturbation. For instance, a dynamic simulation could involve making MWTP a function of greenhouse gas concentrations which accumulate over time according to previous emission levels. In this case, shocks (such as to population and technology) should be applied to both the base and perturbed variables. The model would then derive the strategic equilibrium for each period taking into account the economic changes over time.

Database

We have used the database and parameter files provided by Burniaux and Truoung (2002) in our simulations. All values are in 2001 $US. The regions and sectors in this database are shown in Table 3 and Table 4. We have assumed the United States, European Union, Japan and other Annex 1 countries are strategic for our simulations.

Table 3: Regions

Description	Abbreviation	Strategic Region?
United States	USA	Yes
European Union	EU	Yes
Japan	JPN	Yes
Other Annex 1 Countries	ROA1	Yes
Eastern Europe and Former Soviet Union	EEFSU	No
Net Energy Exporters	EEX	No
China and India	CHIND	No
Rest of the World	ROW	No

Table 4: Sectors

Description	Abbreviation
Primary Agriculture, Forestry and Fishing	Agriculture
Coal Mining	Coal
Crude Oil	Oil
Natural Gas Extraction	Gas
Refined Oil Products	Oil_Pcts
Electricity	Electricity
Energy Intensive Industries	En_Int_Ind
Other Industry and Services	Oth_Ind_Ser

Closure

We have assumed a fixed supply of factors of production for our simulations. The numeraire is the global factor price index. Regional investment is set by a fixed expected regional rate of return on capital.

Initial MCA values

It is useful to analyse starting MCA values under independent taxation and a permit trading scheme, as this provides insight into what will happen if these values are forced to adjust to target MWTP values. We assume a uniform MWTP value of $150[2] per tonne carbon as in our scenarios below.

Independent carbon taxation

Under independent taxation, the MCA is the regional welfare cost of increasing the regional carbon tax sufficient to reduce global emissions by one tonne. As an illustration of the economic impact of increasing a tax in GTAP, consider a single isolated economy with no taxes which produces two commodities with two fixed factors of production: labour and capital. Introducing a tax on labour inputs for the production of one commodity will distort the economy and introduce an allocative cost (i.e. reduce welfare) as the ratio of factor inputs between the commodities changes.[3] However, by implementing a similar tax on labour in the production of the other commodity such that factor inputs return to their pre-tax levels, this distortion is removed and welfare rises back to the original level. That is, the introduction of the second tax creates an allocative benefit to the economy. Therefore, the direction of the economic impact of increasing or introducing a new tax is dependent on the pre-existing tax burden.

In addition, the degree of allocative effect is dependent on the degree of the pre-existing tax distortion. In our example, as the level of tax on labour inputs for one commodity rises, production of that commodity uses a higher level of capital and less labour. The labour to capital input ratios in the production of both commodities moves further from the efficient no-tax starting point. As this occurs, the allocative cost rises at an increasing rate. Thus the marginal allocative cost of increasing a tax grows as the pre-existing level of the tax rises.

In the initial GTAP-E database the EU, Japan and ROA1 regions start with a high pre-existing tax distortion on fuels. For example, the ad valorem tax rate for private domestic consumption of refined oil products in the EU is 467%. In contrast, this rate is zero in the USA. These two regions have comparable GDP values. The introduction of a $1 carbon tax in the EU has a high allocative cost ($330 million) due to this pre-existing distortion, whereas introducing the same

[2] This value is has been chosen arbitrarily such that all countries introduce positive carbon taxes, rather than subsidies.

[3] This result depends on mobile factors between commodity production and labour-capital substitution.

tax in the USA has a relatively low cost ($6 million). These allocative welfare effects are shown in the first row of Table 5. The welfare breakdown is an output of the model, described in Huff and Hertel (2001).

Table 5: Initial MCA breakdown for independent carbon taxation

		USA	EU	JPN	ROA1
∂Welfare/∂tax	Allocative	-5.8	-329.6	-117.8	-66.8
	TOT	32.6	2.2	-16.4	-8.8
	Total	26.8	-324.6	-130.6	-73.2
∂e/∂tax		-7.74	-2.52	-0.94	-1.02
∂Payoff/∂tax (MWTP=150)		1067.8	53.4	10.4	79.8
MCA		-3.5	128.8	138.9	71.8

In addition to allocative effects, there are TOT effects from the introduction of a carbon tax. This is due to the assumption of differentiated commodities in the treatment of trade in GTAP. The TOT welfare effect for each commodity is calculated by multiplying the quantity of exports/imports by the change in export/import price. For example, when the USA introduces a small carbon tax it receives a welfare benefit from TOT, largely due to an increase in the USA fob price of energy intensive industry commodities. That is, foreigners pay more for energy intensive industry commodities from the USA. This dominates the allocative effect in the USA, resulting in a net welfare benefit. The TOT and allocative effects combine with small Investment and Savings effects, which we omit, to give the total welfare change.

Table 5 shows that a $1 tax in the USA induces around three times the global abatement than the same tax in the EU (7.7 vs 2.5 million tonnes carbon). This is due to a lower emissions intensity in the EU.

The USA has a much higher payoff gain from a tax increase than other regions, mostly due to high abatement. Using an MWTP value of $150 per tonne means that all regions have a payoff gain from a small tax increase.

Unlike the other terms in Table 5, the MCA does not depend on the size of the region. The EU and Japan have by far the largest MCA values, while the US has a small negative value reflecting a benefit from introducing a carbon tax.

International Permit Trading

Under permit allocation, the MCA is the regional welfare cost of reducing regional permit allocation sufficient to reduce global emissions by one tonne. A one tonne reduction in the permit quota[4] for any region will induce the same uniform tax across regions, as total bloc emissions determine the tax rate. Therefore the MCA values reflect the welfare cost of introducing the same tax in each of the strategic regions.

Table 6 breaks down the welfare effect into "own tax" and "rest of bloc tax" components. The "own tax" components are the same as the values in Table 5. For example, there is a minus $5.8 million allocative loss in the USA from introducing a $1 tax in the USA. However, there is a small allocative gain of $0.6 million in the USA from introducing a $1 tax in the rest of the trading bloc; the EU, JPN and ROA1. Together these combine to give the total allocative impact on the USA. A similar breakdown is shown for the TOT and total welfare effects.

Table 6: Initial MCA breakdown for international permit trading

		USA	EU	JPN	ROA1
	Allocative	-5.2	-149.8	-74	-55.8
		-5.8 : 0.6	-329.6 : 179.8	-117.8 : 43.8	-66.8 : 11
∂Welfare/∂tax	TOT	69.8	85.8	56	-49.2
(Own tax : Rest of bloc tax)		32.6 : 37.2	2.2 : 83.6	-16.4 : 72.4	-8.8 : -40.2
	Total	66.4	-66.2	-22.2	-103
		26.8 : 39.4	-324.6 : 258.4	-130.6 : 108.4	-73.2 : -29.8
∂e/∂tax		-12.22	-12.22	-12.22	-12.22
(Own tax : Rest of bloc tax)		-7.74 : -4.48	-2.52 : -9.7	-0.94 : -11.3	-1.02 : -11.2
∂Payoff/∂tax (MWTP=150)		1899.4	1766.8	1810.8	1730
MCA		-5.4	5.4	1.8	8.4

The driver of the "rest of bloc tax" effect is the change in terms of trade induced by other regions lowering their consumption of fossil fuels, driving down the global supply price. This leads to a TOT benefit for the USA, EU and JPN – the EU and JPN benefit the most as the USA does the most abatement. However

[4] This will induce a global emissions fall of slightly less than one tonne due to carbon leakage.

the "rest of bloc tax" TOT component for the ROA1 is negative – as an energy exporter it loses welfare from a reduction in fuel prices.

The change in terms of trade induces a "rest of bloc" allocative adjustment in each region, counteracting the pre-existing distortionary effect of fuel taxes. This is welfare enhancing for all bloc regions, and is particularly large in the EU where the allocative loss of introducing a tax is more than halved when other bloc regions introduce the same tax.

The total "rest of bloc tax" welfare effects are significant for all regions and thus have an impact on strategic behaviour. Compared with the "own tax" effects, the welfare benefit in the USA more than doubles while the losses in the EU and Japan are reduced by around 80%. In the ROA1 region, the "rest of bloc tax" effect compounds the "own tax" welfare loss by an additional 41%.

The total change in emissions is 12.22 million tonnes of carbon for a $1 bloc carbon tax. The USA is responsible for 63% of this abatement. This shared abatement burden is therefore particularly beneficial for the EU, JPN and ROA1 regions.

The payoff gain for a $1 carbon tax is higher for each region due to the uniform tax arrangement, mostly due to the increase in global abatement. The MCA values are much lower for the EU and JPN in particular as this increase in abatement and reduction in welfare loss from the "rest of bloc tax" effect combine. The MCA drops to a lesser extent in ROA1 due to the negative "rest of bloc tax" TOT effect. In the USA, the marginal benefit of abatement increases.

In addition to the effects described, the MCA reflects the purchase of permits required after reducing permit quota, as the drop in regional emissions is necessarily less than the quota reduction (drop in bloc emissions) due to the uniform tax. As the carbon price is initially zero and we have reduced quota values by a marginal amount to derive initial MCA values, the welfare effects from permit purchases are insignificant. However, this permit effect is significant for strategic behaviour as the carbon price increases, particularly for the smallest region ROA1. This is shown in our demonstration scenarios.

Demonstration

To demonstrate convergence of the framework and provide a flavour of some results, three simple static scenarios are run. All scenarios assume the MWTP value is uniform across strategic regions. We do not estimate MWTP values in this paper. Uniform values are consistent with an efficient outcome from a global perspective. Alternatively, one could equalise values per head or per unit of GDP if one assumed that the benefits of global abatement are distributed in this manner, and that MWTP values are due to consideration of these national benefits. Equalising MWTP values per head or unit of GDP would imply that the MWTP by our definition would be higher for large or rich countries relative to small or poor ones. The consequences of this are of interest, but we assume uniform MWTP values for the following advantages.

Firstly, it implies that the tax simulation will approximate the most efficient tax distribution from an aggregate global or trading bloc welfare perspective, as MCA values are equalised. This allows us to check how much more efficient unequal carbon taxes across regions can be than a permit trading scheme which enforces equal carbon taxes. As the analysis of initial MCA values demonstrated, regions which have equal (zero) carbon taxes have vastly differing MCA values due mostly to pre-existing distortionary taxation.

Secondly, using uniform MWTP values implies that strategic regions which are equivalent in all aspects except in size would introduce the same tax under independent taxation. Thus variations in tax outcomes between regions are due to economic structural differences, such as differing initial MCA values, rather than due to scale effects as already discussed. This makes interpretation of results easier for our carbon tax scenario. A similar property does not hold under permit trading, due to the effect of permit transfers.

Scenario 1 assumes a MWTP of $150 per tonne under independent carbon taxation. Scenario 2 also assumes an MWTP of $150 per tonne but in a permit trading scheme. Scenario 3 assumes a trading scheme amongst the strategic regions, but MWTP is set so that the global emissions reduction is the same as in Scenario 1. This is done to compare the efficiency, in terms of welfare loss for a given level of global abatement, between a permit trading scheme and optimised carbon taxes.

Scenario 1: Independent carbon taxes and MWTP=150

In the first scenario, the carbon tax is the climate policy variable that is independently but simultaneously endogenised for the USA, EU, JPN and ROA1. All of these regions are assumed to have equal MWTP values of $150 US per tonne carbon. Other regions are not strategic and do not introduce an emissions tax.

Since the USA has a much lower MCA than the other strategic countries, equalizing MCA at $150 across strategic regions leads to a relatively high carbon tax of $123 in the USA, shown in the second row of Table 7. The EU and JPN introduce small taxes while the ROA1 introduce a moderate $33.5 tax.

In the same row, we show the tax value that would be adopted by each region if other bloc regions did not introduce a carbon tax. In the EU, JPN and ROA1 this "acting alone" tax is significantly lower than the tax adopted when other bloc regions also act. Thus collective action has induced an increased tax adoption in these regions. The main reason for this is a lower marginal global emissions reduction for an increase in tax when acting alone. In the ROA1, carbon leakage to the USA is the major cause. While this effect is also significant for the EU and JPN, the major factor for these regions is that they don't reduce their own emissions levels as much (at the margin) when acting alone, as their emissions intensity has not been increased by the USA adopting a huge carbon tax. In the USA, the "acting alone" tax is not significantly different from that adopted in the main scenario as the leakage and interdependence effects are not strong.

We include the consumption price of oil products in Table 7 to indicate the combined impact of the domestic carbon tax and fall in global supply price of fossil fuels[5]. The consumption price of oil products rises by 50.5% in the USA due to the high tax. Despite the introduction of a $6.9 carbon tax in the EU, the price of oil products falls by 2.7% due to the fall in global demand. Although Japan introduces the smallest carbon tax of $4.2, the consumption price of oil products falls by 1.3%, less than the fall in the EU of 2.7%. This is due to a higher proportion of refined oil products imported in the EU than in Japan, so the reduction in import price has a greater effect.

The abatement effort is mostly due to the USA, where regional emissions drop by about a third. In fact the level of abatement is higher in the USA than the global total, due to carbon leakage of around 7% in non strategic regions. Emissions in the EU drop marginally as the price of coal increases. Japan increases emissions marginally, while emissions in ROA1 drop significantly by 10.8%. The global emissions fall is 8.5%.

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[5] For example, the world price index for oil supplies falls by 4.5%.

Table 7: Scenario 1 Carbon Tax (MWTP=150) Results

		USA	EU	JPN	ROA1	CHIND	EEX	EEFSU	ROW	World
MWTP (exogenous)		150	150	150	150					
$ real Carbon Tax (acting alone)		123.4 (123.6)	6.9 (0.5)	4.2 (2.9)	33.5 (30.2)	0	0	0	0	
% change in Consumption price of refined oil products		50.5	-2.7	-1.3	2.2	-2.7	-3.7	-3.1	-3.1	
% change in Emissions (million tonnes carbon)		-35.9 (-539)	-0.1 (-1)	0.6 (2)	-10.8 (-28)	0.7 (7)	1.8 (12)	1.3 (10)	2.0 (13)	-8.5 (-524)
$ billion welfare effect	Allocative	-26.9	10.1	2.2	-2	0.5	-0.1	0	1.4	-14.7
	TOT	1.6	5.7	4.2	-2.2	0.5	-11.7	-0.9	2.8	0
	Total	-25.4	15.7	6.1	-4.1	1.1	-11.8	-0.8	4.5	-14.7
$ billion change in Payoff (ΔWelfare+150*Δe)		53.1	94.2	84.6	74.4					

The USA and ROA1 suffer allocative welfare losses due to the adoption of carbon taxes, while the EU and JPN benefit from allocative gains due to reduced fuel supply prices. The TOT effect is positive for the USA, EU and JPN and negative for energy exporting ROA1 (and EEx). The aggregate global welfare loss is $14.7 billion. The difference in payoff values simply reflects the welfare differences, as all regions benefit to the same degree by the global abatement.

Scenario 2: Permit Trading scheme and MWTP=150

The second scenario assumes a trading coalition of the USA, EU, JPN and ROA1. The MWTP in these regions is set at $150 per tonne of carbon. Other regions do not have an emissions budget. The initial perturbation (between the base and perturbed databases) is 0.25% of regional quota reduction relative to the emissions level in 2001. The scenario results are shown in Table 8. We have combined the non-strategic regions together as the effects in these regions are qualitatively the same as in Scenario 1.

Table 8: Scenario 2 International Permit trading (MWTP=150) Results

		USA	EU	JPN	ROA1	Non Strategic	World
MWTP (exogenous)		150	150	150	150		
Change in Permit Quota	%	-38.5	-8.9	-20.7	-17.6		
	(acting alone)	(-43.6)	(-81)	(-173)	(-138)		
	million tonnes	-578	-81	-70	-45		
	(acting alone)	(-655)	(-453)	(-586)	(-352)		
$ real Carbon Tax		101.5	101.5	101.5	101.5	0	
(acting alone)		(78)	(46.7)	(48.3)	(45.8)		
% change in Consumption Price of refined oil products		+40.7	+5.0	+6.9	+13.2		
% change in Emissions		-31.6	-18.4	-19.2	-26.1	2.5	-11.3
(million tonnes carbon)		(-474)	(-168)	(-65)	(-67)	(79)	(-695)
$ billion change in welfare		-27.9	-8.2	-7.2	-8.4	-8.1	-59.6
(Permit income)		(-10.5)	(8.8)	(-0.5)	(2.2)		
$ billion change in Payoff (ΔWelfare+150*Δe)		76.7	96.4	97.4	96.2		

Scale effects are significant when interpreting quota choices. The same percentage quota reduction in a large region results in a higher bloc carbon tax than a small region. The same levels quota reduction in a large region results in the same bloc tax (percentage welfare effect) but the permit transfer is the same in levels terms (levels welfare effect). Thus a large region will generally adopt a smaller percentage quota reduction but a larger levels quota reduction than a small region.

However, the USA chooses the largest percentage (and levels) reduction in permit allocation, similar to Scenario 1 where it chose the largest carbon tax. Unlike Scenario 1 the EU and JPN take on a significant abatement burden by lowering their permit quotas.

As in Scenario 1 we also show the permit quota each would choose if they "acted alone", to understand the impact of other bloc regions taking action. By "acting alone" we mean that other strategic regions do not change their permit allocation. When acting alone all regions undertake greater reductions in permit quotas. This is particularly true for the smaller emitters JPN and ROA1, as they reduce permit quotas by more than 100%.

To reduce bloc emissions to the combined bloc quota a uniform carbon tax of $101.5 is introduced. At this price, the cost of permit transfers makes up more than two thirds of the MCA (set at 150) for each region from further quota reduction. The "acting alone" taxes are much less: interestingly, they are similar for the EU, JPN and ROA1.

Global emissions fall further than in the carbon tax scenario, dropping by 11.3% compared with 8.5%. This is mainly due to the increased abatement burden undertaken by the EU and JPN.

Global welfare falls by around $59.6 billion compared with $14.7 billion in Scenario 1. All strategic regions have a lower economic welfare relative to Scenario 1. However, more importantly all four strategic regions attain higher payoff values than in Scenario 1 due to greater global abatement. Therefore in terms of Payoff, the international permit trading coalition is Pareto optimal for the strategic regions over the independent carbon tax and is consistent with strategically optimal behaviour[6].

Scenario 3: Tax burden optimality (Permit Trading scheme)

Scenario 3 has been designed to check tax burden optimality, rather than investigate strategic behaviour. Thus we compare Scenario 1 with a new international permit trading scenario with identical global emissions abatement (rather than MWTP value). Maintaining MWTP uniformity between strategic regions, we find that an MWTP value of $95 per tonne achieves the same emissions fall as in Scenario 1. The results are shown in Table 9. We omit the strategically relevant payoff values, as well as price effects as the results are qualitatively similar to Scenario 2.

[6] We do not consider bloc formation incentives in this paper.

Table 9: Scenario 3 Permit trading (MWTP=95) Results

		USA	EU	JPN	ROA1	Non Strategic	World
% change in Permit Quota		-30.7	-5.2	-15.3	-7.3		
(million tonnes carbon)		(-460)	(-47)	(-52)	(-19)		
$ real Carbon Tax		65.2	65.2	65.2	65.2	0	
% change in Emissions		-23.8	-13.5	-14.0	-19.5	1.7	-8.5
(million tonnes carbon)		(-357)	(-123)	(-47)	(-50)	(54)	(-523)
$ billion change in welfare	Allocative	-10.3	-14	-6.2	-4.7	-6	-33.5
	TOT	2.4	5.1	2.7	-2.1	-8.1	0
	Permit income	-6.7	5	-0.3	2	0	0
	Total	-14.8	-4.1	-3.9	-4.6	-6	-33.5

Welfare changes in non-strategic regions are similar to those in Scenario 1. The USA makes a large transfer payment to the EU and to ROA1. As Japan reduces its emissions by almost the same level as its emissions quota (14% versus 15.3%), it makes a small transfer outward payment.

The permit trading scheme in Scenario 3 results in a global welfare loss more than double that of the independent carbon tax approach (Scenario 1) (with the same global reduction in emissions). The aggregate welfare loss to the trading bloc countries is more than triple ($27.4 billion versus $7.7 billion). The reduction in welfare for EU and Japan in Scenario 3 contrasts with the gain experienced in these regions in Scenario 1.

The international permit trading case is less efficient primarily because the marginal allocative costs (via tax increases) between regions are not equalised by a uniform carbon tax. The same carbon tax is applied on top of different pre-existing taxes on fuels. This MCA disparity is shown in Table 10. For Scenario 1, the MCA is $150 per tonne by design. In Scenario 3, the MCA values for each strategic region with respect to quota reduction are uniformly set to $95 per tonne. To consider the efficiency of the total scheme from the perspective of tax burdens, we look at the MCA with respect to independent regional tax increases at the final uniform level of $65.2 resulting in Scenario 3. In contrast with Scenario 1, the MCA values in the EU and Japan approach $350 per tonne, while the MCA in the USA is $73 per tonne.

Table 10: Final MCA values (tax increases)

	USA	EU	JPN	ROA1
Scenario 1	150	150	150	150
Scenario 3	73	348	343	234

It is straight-forward to construct a Pareto optimal solution relative to a permit trading scheme by specifying optimal carbon taxes (as in Scenario 1) and using income transfers. Income transfers do result in allocative and TOT effects due to differing income elasticities between commodities, but the welfare effect of this distortion is minor in comparison with the transfer itself. For a simple calculation let us consider that an income transfer is not distortionary so that the change in welfare is equal to the transfer received. Using the same tax rates in Scenario 1 and the welfare results from Table 7, if the EU, Japan and ROA1 made income transfers (to the USA) such that their welfare was invariant, the USA would receive around $17.7 billion in transfers and be only $7.7 billion worse off overall. Running the actual simulation as specified led to about $14 billion transferred to the US and it was $9 billion worse off overall. This compares with the USA losing $14.8 billion in welfare in Scenario 3. Such a scenario is Pareto-optimal for all trading bloc countries.

Finally, whilst the carbon taxes resulting in Scenario 1 are far more efficient than those resulting from a permit trading scheme, they are not the optimal set of carbon taxes in terms of minimising aggregate trading bloc (or global) welfare loss. To derive this set, each region would have to act in the trading bloc's interest so that marginal reductions in aggregate bloc welfare are equalised. This could be calculated using the strategic framework by adjusting the payoff function accordingly. In addition, we have equalised MCA values between regions but not between industries in each region. This is of interest for future analysis.

Discussion and Potential Future Work

The demonstrations given in this paper highlight the importance of understanding the difference in the regional impacts of carbon taxes. The main determinant of this difference is the pre-existing tax distortion in the database. One consequence of introducing a carbon tax may be that pre-existing taxes are adjusted by governments as compensation. For example, a country may reduce the excise rate on fuel in conjunction with introducing a carbon tax. This paper highlights the importance of including these parallel adjustments in modelling analysis as it may significantly mitigate the distorting impact of the carbon tax.

Just as there are pre-existing differences in these costs between regions, there are likely pre-existing differences between industries in each region also. Equalisation of these costs could be analysed with an adjustment to this framework.

The payoff function can be adjusted to reflect the group rather than regional economic welfare. Using this technique, experiments in maximising efficiency can be done, such as finding the optimum tax configuration to minimise aggregate welfare loss. Income transfers can be used in parallel to achieve Pareto optimal results. Alternatively, the MWTP values could be defined on per head or unit of GDP. This would introduce scale effects into the regional choice of climate policy variable.

As discussed, convergence relies on certain properties of the payoff function. This ensures the numerical technique leads to a global optimum value. Proof of the existence of these properties within the GTAP-E model could be investigated.

Choosing MWTP values is a challenge for further analysis. Carbone, Helm and Rutherford (2008) based their values on revealed preference through historical positions in climate change negotiations. One of the factors which may influence MWTP is the perceived economic impacts of climate change. It may be considered worthwhile to endogenise MWTP by introducing a climate change impact function. This would be done dynamically with greenhouse gas accumulating over time depending on emission levels.

The technique described in this paper is a general numerical method of optimisation, and therefore can be used in other applications. For example, optimising import duties to maximise regional welfare could be applied to international negotiations around trade liberalisation.

Conclusion

This paper outlined a novel technique to compute game-theoretic equilibria within GTAP-E. This allows inclusion of strategic behaviour computation and leads to a Nash Equilibrium outcome. As a demonstration, we used the model to undertake a comparative analysis of implementing regionally optimised carbon taxes versus a permit trading scheme. We reported large differences in initial marginal costs of abatement between regions under independent taxation, mostly due to pre-existing distortionary taxation within the database. We find that, for the same value placed on emissions abatement, an international permit trading scheme results in a higher payoff for all regions. However, we also find that optimally chosen carbon taxes are more efficient in terms of global welfare loss and aggregate trading bloc welfare loss, mainly due to pre-existing tax distortions. This technique can be applied more broadly within GEMPACK models, such as optimizing import duties in trade liberalisation negotiations.

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