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by

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1. The Issue

The early numerical general equilibrium (NGE) models of Scarf [1967] [1973] were modest in size (e.g., two or three producing sectors and two or three primary factors), qualitatively general in the sense of imposing very weak regularity conditions on model structure, and calibrated with hypothetical data. Shoven and Whalley [1972], Shoven [1976] and Whalley [1977] provided the first small, qualitatively restrictive, policy-relevant NGE models. Familiar functional forms were chosen for utility and production functions (e.g., single-level CES), techniques for empirical calibration were developed (viz., the notion of a benchmark equilibrium), and policy issues familiar from the Harberger [1962] [1966] tax incidence literature re-examined. More recent developments have extended this class to include reasonably large models with twenty or more producing sectors and/or four or more primary factors. Variations on the popular functional forms have also been adopted (e.g., multi-level CES, and LES demand systems), and a wide range of policy issues considered. Fullerton, Henderson and Shoven [1984] and Shoven and Whalley [1983] provide surveys of these developments.[1]

The policy relevance of these models, and their avowedly empirical nature, render them open to casual criticism. Most economists are deeply familiar with their underlying neoclassical structure; we are therefore <u>not</u> concerned with their defense from criticisms based on rejection of that structure.[2] On the other hand, criticism based on suspicion of the particular <u>empirical calibration</u> adopted currently leads to non-systematic and/or uninformed debate. The general techniques used to calibrate NGE models are well known.[3] Given, then, that users of NGE models are fairly well informed as to the various sources of data embodied in their simulations, how is one to identify the robustness of the results for some particular decision? Our response to this important question is to urge a *systematic sensitivity analysis* of the policy simulations in question. This paper examines the problems that arise in such studies of the stochastic properties of NGE models.

In the remainder of this section we define the nature of the "robustness" problem and examine three dimensions of the problem: sources of data, computational aspects, and the efficient reporting of results. In Sections 2, 3 and 4, respectively, we examine each of these dimensions in more detail. Section 5 presents several illustrative applications of our suggested approach, and Section 6 provides general conclusions and suggestions for further research.

1.1 Nature of the Robustness Problem

We identify three aspects of the robustness problem. The first is the issue of the *comparative robustness* or reliability of NGE analyses as against numerical partial equilibrium analyses of a given economic policy.[4] Whalley [1975] raised this issue, arguing that the results of "...partial equilibrium analysis seem to serve as unreliable *approximation* measures of the true changes in the economy" (p. 309; emphasis added). There is a maintained hypothesis that the NGE is the "true" model, *conditional* on point estimates for the relevant parameters. The *unconditional* robustness of the alternative approaches, assuming that we can define some weighting scheme for the various sets of parameter estimates and some measure of robustness applicable to both approaches, remains an open issue. One possible measure of robustness is the dispersion of simulation results about the benchmark solution (obtained using parameter point estimates) when there are given variations in parameter values (e.g., one standard error either side of the point estimates).[5]

The second aspect of the problem is the <u>limited robustness</u> of NGE models that is addressed when only performing local and "ad hoc", rather than global and "systematic", sensitivity analyses. In virtually every major policy application of NGE models in recent years there has been some attempt to examine the sensitivity of results, albeit in a restricted domain.[6] Central tendency estimates of certain key parameters are perturbed by "large" changes one-by-one. Rarely is any explicit metric used to determine the significance of these changes, and even less frequently are combinations of such perturbations considered. The reasons for not engaging in or not reporting more exhaustive sensitivity analyses are twofold: the computational expense involved in obtaining the large number of required solutions, and the difficulty of efficiently reporting the results of so many simulations. Moreover, given the non-trivial labour involved in calibrating a detailed NGE model just to some benchmark solution <u>and</u> the relatively high intellectual returns to exploring the response of the model to alternative policy perturbations (rather than alternative parameter perturbations), it is perhaps appropriate that these initial sensitivity analyses be modest.

The third aspect of the problem is the degree of robustness that may be attached to results from NGE simulations, in the sense of the confidence (degrees of belief) we have in those results. The benchmark NGE solution is conditional on certain parameter estimates, typically the point estimates. If there is some (stochastic) uncertainty about those estimates, there is some implied uncertainty about the benchmark calibration. Assume that one can represent the latter uncertainty in terms of a probability density function (this assumption is discussed below). The question posed here is then: are the results of some counterfactual policy simulation significantly different from the benchmark simulation, allowing for the parameter uncertainty of that benchmark? If the answer to such a question is "no", then we cannot attach much confidence to the differences between the benchmark and counterfactual solutions. Note that the answer may be "no" when looking at the policy impact on one endogenous variable (e.g., the relative price of capital) and "yes" when looking at the impact of the same policy on a different variable (e.g., labour use in a certain sector). The general objective, then, is to decide which policy inferences are robust to "reasonable" parameter variations and which inferences are not.[7]

1.2 Dimensions of the Problem

There are three dimensions of our approach to the robustness problem: data sources, the computation of solutions, and the efficient reporting of results.

The policy results of NGE models are clearly conditional on particular sets of parameter estimates. Typical practice is to employ the <u>point estimate</u> from an econometric model (e.g., the elasticity of factor substitution), survey (e.g., household expenditure shares) or hybrid estimation procedure (e.g., input-output coefficients generated by the RAS method). The starting point of our approach to the robustness problem is therefore the assessment of the uncertainty that surrounds those point estimates.

Our approach to the robustness problem, to undertake a systematic sensitivity analysis, requires that we be able to solve NGE models conditional on a large number of sets of parameter estimates. Although the exact number of solutions required depends on various factors, such as the number of uncertain parameters and the desired accuracy of the sensitivity analysis, it is likely to exceed the feasible upper bound using standard algorithms.[8] We develop solution techniques in Kimbell and Harrison [1983] that allow us to solve a certain "rich" class of NGE models the required number of times, and these techniques are examined in Section 3.

Reporting the results of a systematic sensitivity analysis in an efficient and understandable manner is essential if those results are to be of any value. Two steps can assist in dramatically reducing the dimensionality of the reporting problem. The first is to decide on a subset of endogenous variables that one is concerned about, allowing one to disregard the results for the other variables. A typical example of such variables of interest include measures of individual and aggregate welfare loss (consumer's surplus). As a pragmatic matter, of course, it is possible to retain a small set of solution values for certain variables (e.g., factor prices) during the course of the sensitivity analysis computations and use those values in a subsequent analysis to regenerate complete NGE solutions for all other endogenous variables. Our discussion in Section 4 deals with efficient reporting.

The second step in reducing the dimensionality of the reporting problem is to provide simple descriptive summary statistics about the distribution of solution values for the endogenous variables of interest. Thus the mean of the various solution values may be of interest, and need not equal the solution value obtained using the mean of the parameter estimates. However, some care must be exercised in using such statistics that any weighting schemes adopted be made explicit. For example, perturbing a particular parameter estimate one standard error either side of its mean implies a different set of weights than if the perturbation was two standard errors on either side. More generally, a Bayesian interpretation of this "weighting issue" will be proposed in Section 4 in order to avoid the use of implicit weighting schemes.

2. Data Sources

Consider the two main sources of uncertainty about econometric estimates. The first is sampling uncertainty, and is reflected in a typical regression equation by the standard error (or "t-value") of the parameter estimate of interest. The second is specification uncertainty, and is often[9] reflected in a given multiple regression equation by the covariance of parameter estimates (in turn reflecting the correlation of explanatory variables). Thus slight changes in the estimate adopted for one variable that is not of direct interest (e.g., a seasonal dummy) may affect the estimate for the variable of interest. Unfortunately, the existing econometric literature rarely publishes results in a form that permits inferences about such specification uncertainty (see Leamer and Leonard [1981] for further discussion).

In general we may think of all of the parameters of an NGE model as having estimates that are interdependent. Thus the estimate of the elasticity of factor substitution in sector i depends on the corresponding estimate for sector j $(i \neq j)$, on the estimate of the output own-price elasticity for sector k $(i \neq k)$, on the estimated household expenditure share for sector $l (i \neq l)$, and so on. Consider the implied covariance matrix of parameter estimates. Practical considerations based on the limited availability of parameter covariance estimates will force us to arbitrarily set many, if not all, of the off-diagonal elements of this matrix to zero. It is possible to construct covariance matrices for certain subsets of parameters, and therefore we are left with a block-diagonal covariance matrix for the complete set of parameters.

In the remainder of this paper we shall focus on uncertain elasticity estimates, and assume that the available econometric literature provides information on the variance of that estimate. Although it is natural to focus initially on the uncertainty of elasticities, we do not wish to suggest that the remaining data used to calibrate NGE models is any less certain. Consider, for example, the input-output data. Recent work by Gerking [1976a] [1976b], Harrison and Manning [1983], and West [1981] [1982] [1983] provide three distinct approaches to the stochastic properties of input-output estimates. Harrison and Manning [1983] propose a method of aggregating input-output models that minimizes the mean-square-error of aggregate predictions. They find that the usual estimate of the Leontief Inverse transpose, widely used in NGE models, involves a significant bias and inefficiency (in the familiar econometric sense) relative to the alternative estimation procedure they propose. This result is particularly important for applied NGE models that use (heavily) aggregated input-output data.

3. Computational Aspects

A large number of parameters of popular NGE models are subject to uncertain estimation. In many cases we are able to obtain a well-defined (prior) pdf for these estimates, allowing some statement as to the probability of values other than the point estimate (as well as the probability of the point estimate itself). A sensitivity analysis with respect to any <u>one</u> of these parameters consists of examining the robustness of policy results of interest given a number of perturbations of the value of that parameter away from its point estimate. A <u>systematic</u> sensitivity analysis with respect to <u>more than one</u> parameter must take into account combinations of parameter perturbations. Clearly the latter sensitivity analysis will involve many more solutions to the NGE model than the former.

It is convenient to distinguish between a conditional systematic sensitivity analysis (CSSA) and an unconditional systematic sensitivity analysis (USSA). A CSSA is a series of simulations in which each parameter is perturbed from its point estimate a certain number of times (denoted N_e), where we shall assume that N_e includes the point estimate, conditional on all other parameters being set only to their point estimate value. An USSA refers to perturbations of each parameter a certain number of times (N_e) conditional on all other parameters also being perturbed from their point estimate a certain number of times; thus the set of simulations is "unconditional". Clearly an USSA is more complete than a CSSA, but at a severe cost in terms of the number of required solutions.

If we denote the number of parameters subject to perturbation by N_p and assume that we employ the same number of estimates (N_e) for each such parameter, the number of solutions required by a CSSA is $N_s^c = [N_p(N_e - 1)] + 1$ and the number required by an USSA is $N_s^u = N_e^{Np}$. Table 1 presents several sobering numerical examples of the values of N_s^c and N_s^u implied by given values of N_e and N_p. Assuming that the perturbations of parameter estimates are symmetrical about the point estimate, N_e only takes on odd values. The computational burden implied by modest values of N_e and N_p is evidently quite severe for an USSA. By contrast, the computations involved in a CSSA appear quite reasonable. These judgements must be tempered by the importance of the policy impact at issue and the computational budget available. Nonetheless, it is worthwhile considering ways to mitigate the burden of the USSA.

One attractive alternative to a complete unconditional analysis is a <u>semi-conditional</u> analysis in which certain <u>blocks</u> of parameters are perturbed conditionally with respect to other blocks of parameters, but are perturbed unconditionally with respect to other parameters in the same block. Thus we might view the elasticities of factor substitution as one block, import elasticities as another block, and own-price demand elasticities as a third block. Given the point estimates in the second and third blocks, an unconditional analysis with respect to the various factor substitution elasticities could be undertaken. One then holds the values of the first and third blocks constant at their point estimate while unconditionally perturbing the various import elasticities. Finally, the demand elasticities are perturbed conditional on the first two blocks of parameters being held at their point estimates.

An obvious variant on semi-conditional analyses with respect to blocks of parameters is to identify certain parameters as "critical," in the sense that one expects the policy impacts to be particularly sensitive to their values. The literature abounds with examples of such parameters. Fullerton, Shoven and Whalley [1983] and Fullerton and Lyon [1983] emphasize the elasticity of saving with respect to the net rate of return, Fullerton [1982] focuses on the aggregate labour supply elasticity, and Whalley [1980] and Brown and Whalley [1980] indicate clearly the importance of assumed import elasticities. The great danger of such approaches, however, is the "ad hoc"

TABLE 1

Hypothetical Number of Required Solutions

Number of Estimates (Ne)	CONDITIONAL SENSITIVITY ANALYSIS (N_s^c) Number of Parameters (Np)							UNCONDITIONAL SENSITIVITY ANALYSIS (N_s^u) Number of Parameters (Np)				
	2	3	4	5	10	20	40	2	3	4	5	10
3	5	7	9	11	21	41	81	9	27	81	243	59049
5	9	13	17	21	41	81	161	25	125	625	3125	9765625
7	13	19	25	31	61	121	241	49	343	2401	16807	282475250
9	17	25	33	41	81	161	321	81	729	6561	59049	--
11	21	31	41	51	101	201	401	121	1331	14641	161051	--
13	25	37	49	61	121	241	481	169	2197	28561	371293	--
15	29	43	57	71	141	281	561	225	3375	50625	759375	--

Note: A dash indicates a number in excess of one billion.

nature of the choice of parameters to be studied, as is widely recognized. Moreover, any given parameter may be critical in one model for one set of policy simulations and yet be relatively unimportant in another model for different policies (compare Fullerton [1982] and Piggott and Whalley [1984; Ch. 10] with regard to the labour supply elasticity). Nonetheless, it would be foolish to abrogate the use of common sense and/or intuition in trying to isolate the most important parameters, even when combinations of parameter perturbations are considered. We return to this question below.

One major implication of the computational burden of systematic sensitivity analyses (however "conditional" they are) is a renewal of interest in algorithmic speed[10]. In Kimbell and Harrison [1983] we introduced two new algorithms that allow one to rapidly solve a rich class of NGE models.

Our first algorithm is the Analytic Factor Price Solution (AFPS) for any CES class of NGE models that allows: (i) any number of factors and goods; (ii) any pattern of distribution parameters in the single-level CES production functions or (single) utility function; (iii) any pattern of efficiency parameters in the production function; and (iv) any arbitrary pattern of factor taxes across factors and producing sectors. The AFPS does <u>not</u> apply to the CES class that includes: (i) more than one private household; (ii) any interindustry (input-output) flows; (iii) elasticities of substitution in production that vary from sector to sector; (iv) an elasticity of substitution in consumption different from the (uniform) elasticity of substitution in production; and (v) government factor demands that are not proportional to aggregate private industry factor demands. The AFPS is an exact, algebraic, closed-form solution for the GE values of all endogenous variables (i.e., the reduced form of any structured GE model in the CES class defined above). No iterations whatsoever are required to solve GE models for which the AFPS applies. The AFPS motivates our second algorithm, a simple iterative Factor Price Revision Rule (FPRR) for a wider class of popular NGE models that do not appear to have a closed-form solution. The FPRR has proven to be a rapid and efficient solution algorithm for many large-scale NGE models. We illustrate the use of these new algorithms in Section 5.

4. Reporting Results

Assuming that we have been able to construct prior pdf's for the parameter estimates of interest, and that we are able to compute a large number of solutions to the model in question, how are we to report the results of a large sensitivity analysis in a useful way? As noted earlier, two steps can dramatically reduce the dimensionality of the reporting problem. The first is to focus on a subset of the endogenous variables of the model; for example, Harrison and Kimbell [1983] only report a measure of aggregate welfare change due to each policy. The second step is to report several descriptive statistics about the distribution of solution values for those endogenous variables; for example, Harrison and Kimbell [1983] report the mean and standard deviation of the distribution. In this section we examine certain aspects of this second step, especially the question of making explicit the weighting scheme adopted for any sensitivity analysis.

Assume that we are concerned with the sensitivity of a model to different estimates for two parameters, b_1 and b_2. The model may have many more parameters than just these two, in which case the sensitivity results are of course conditional on the estimates used for the other parameters. To simplify matters, assume in Case A that the prior probability density function (pdf) of the second parameter estimate (b_2) is <u>discrete</u> and consists of three values: the point estimate with probability 0.5, one other estimate with probability 0.4, and a final estimate with probability 0.1. We also assume that the prior pdf of the first parameter estimate (b_1) is discrete, but in this case it is uniform and takes on two values only with equal probability.

A complete enumeration of all possible simulations in Case A is presented in Table 2. In simulation 1 the two point estimates are adopted, each with a <u>marginal</u> probability of 0.5. Assuming <u>independence</u> of the random variables b_1 and b_2, we may calculate their <u>joint</u> probability as the product of their marginal probabilities. This is shown in column 4 for Case A. Simulation 2 holds constant the value of b_1 and adopts the second value of b_2, with resulting joint probability 0.2; similarly, simulation 3 adopts the final value of b_2, which has the lowest marginal probability of the three values considered. Simulations 4, 5 and 6 repeat the sequence of b_2 values with the second value of b_1 (which also have marginal probability 0.5). By the laws of

TABLE 2

Hypothetical Numerical Examples of Weighting Procedures

	CASE A				CASE B			
Simulation	Marginal Probability of b_1	Marginal Probability of b_2	Joint Probability	Normalized Joint Probability	Marginal Probability of b_1	Marginal Probability of b_2	Joint Probability	Normalized Joint Probability
1	0.5	0.5	0.25	0.25	0.5	0.5	0.25	0.3968
2	0.5	0.4	0.20	0.20	0.5	0.1	0.05	0.0794
3	0.5	0.1	0.05	0.05	0.5	0.1	0.05	0.0794
4	0.5	0.5	0.25	0.25	0.4	0.5	0.20	0.3175
5	0.5	0.4	0.20	0.20	0.4	0.1	0.04	0.0635
6	0.5	0.1	0.05	0.05	0.4	0.1	0.04	0.0635
Sum			1.00	1.00			0.63	1.00

probability, and the knowledge that we have completely enumerated the joint distribution of the two parameters, we note that the sum of the joint probabilities is one. Thus we do not need to "normalize" the joint probability values, and simply repeat the column 4 values in column 5.

In Case B we consider a more likely situation in which complete enumeration of the pdf of one or more of the parameters is not possible (presumably because it would be too expensive computationally, even if possible). Two interpretations of this case are valid. The first is to think of the prior pdf of b_1 as having three or more discrete values, only two of which are considered (having marginal probabilities that sum to only 0.9), and the prior pdf for b_2 as having four or more discrete values, only three of which are considered (having marginal probabilities that sum to only 0.6). The second interpretation is that we are only evaluating discrete approximations to the <u>continuous</u> prior pdf of each parameter. This latter interpretation is in practice the most likely: in most cases we are able to assume that the prior pdf for each parameter is either rectangular and uniform over a finite interval or Gaussian (e.g., the import elasticities and factor substitution elasticities, respectively, in Harrison and Kimbell [1983]).

Irrespective of the interpretation, we note from Table 2 that the joint probabilities of the six simulations for Case B do not sum to one. Thus we normalize (by the constant of proportionality 1.5873015 = 1/0.63) so that the joint distribution is <u>proper</u>. Alternatively, we could have normalized each of two marginal distributions.

In Case A and Case B, the normalized joint probabilities for each simulation provide the weights used when reporting the results of the simulations. Assume that the endogenous variable we are concerned with is the percentage change in employment in a certain sector from the benchmark equilibrium as the result of some tariff change. Hypothetical values are listed in Table 3 for each simulation. For pedagogic purposes assume that the same employment impacts obtained in Case A as in Case B. The weighted average percent change in employment is zero in Case A and 0.1111 in Case B. Note that other descriptive statistics could be computed once we know the pdf of the employment changes. The comparison of Cases A and B also illustrates the obvious point that the pdf of employment changes is sensitive to the weights attached to given parameter values by the prior pdf.

Several descriptive statistics may be of interest once the pdf for an endogenous variable has been generated. The first two moments, the mean and variance, provide familiar measures of central tendency and dispersion about the mean. Note that there is, in general, no presumption that the pdf for any endogenous variable is Gaussian; one should not therefore assume that the mean and standard deviation are in any way "sufficient statistics" of that distribution. The probability of a positive or negative value for the variable may be obtained by numerically evaluating the pdf over the relevant range of values. This provides a useful measure of the confidence one can attach to qualitative inferences in the NGE model, due account being explicitly made of the weight and uncertainty of the data used to

TABLE 3

Weighting Procedure Applied to Hypothetical Simulation Results

Simulation	Percent Change in Employment	CASE A Normalized Joint Probability	CASE A Weighted Employment Change	CASE B Normalized Joint Probability	CASE B Weighted Employment Change
1	1.00	0.25	0.25	0.3968	0.3968
2	1.00	0.20	0.20	0.0794	0.0794
3	1.00	0.05	0.05	0.0794	0.0794
4	-1.00	0.25	-0.25	0.3175	-0.3175
5	-1.00	0.20	-0.20	0.0635	-0.0635
6	-1.00	0.05	-0.05	0.0635	-0.0635
Sum		1.00	0.0	1.00	0.1111

calibrate the model.

5. Applications

5.1 The Effects of Multilateral Tariff Liberalization

Harrison and Kimbell [1983] present a NGE model of twelve countries (or trading region) that is empirically calibrated to the best available data. Each region produces 20 commodities, using intermediate inputs from its own region and from all other regions as well as primary factors (labour and capital). The model assumes a Cobb-Douglas technology in the use of intermediates and the composite primary factor, and a CES technology in the use of labour and capital. The demand pattern in each trading region is represented by a single private household and a single public household. Each private household maximizes a nested utility function; the top level is Klein-Rubin (leading to an Extended Linear Expenditure System) defined over eight broad commodity groupings and savings), the middle level is CES (defined over the commodities within each of the eight groupings), and the bottom level is also CES (defined over each commodity differentiated by origin). Household savings are allocated entirely to the purchase of a Cobb-Douglas composite of commodities from all regions for the purpose of capital formation.

Harrison and Kimbell [1983; Section 3] report the results of a CSSA of their model with respect to three sets of elasticities: elasticities of substitution between primary factors, import demand price elasticities, and the own-price demand elasticities. In the first and third cases they had available standard errors and a presumption that the distribution of each parameter estimate was well-balanced (i.e., followed a t-distribution), allowing the complete definition of a Bayesian prior distribution for those elasticities.[11] In the case of the import elasticities they adopted a uniform prior over the range of estimates tabulated by Stern, Francis and Schumacher [1976; p. 15 ff.][12] or the same prior as used for the demand elasticities when they had no separate import elasticity available.

Given the size of their model and the large number of parameters subject to perturbation ($N_p = 720$), Harrison and Kimbell [1983] opted for a CSSA of each policy change considered. They considered five values for each parameter, including the point estimate ($N_e = 5$). Thus there were four perturbations for each parameter: two of these were one-half of a standard error above and below the point estimate, and the other two were one standard error above and below the point estimate. The exact marginal probabilities for these values depended on the relevant degrees-of-freedom for the parameter estimate (where it was not possible to infer that value from published data it was assumed to be large enough for asymptotic results to hold). A CSSA in this case requires a total of 2881 simulations for each policy change.

A two-stage procedure was employed to compute the required solutions for this model. In the first stage, the FPRR discussed earlier was applied to a stylized empirical counterpart of an aggregated version of the basic model. This aggregated model employed 7 commodities per region (rather than 20 in the basic model) and weighted averages of the various detailed elasticities. The solution values of factor prices for this model when all parameters were set equal to their point estimate was used in the second stage as starting values for the FPRR applied to the basic model using point estimates. Given the solution values for this simulation as starting values for the sensitivity analysis simulations involving a perturbed elasticity, we are able to find the new solution values extremely quickly.[13]

We now consider the results of a CSSA of the effects of a multilateral "Tokyo Round" tariff liberalization.[14]

Brown and Whalley [1980], Whalley [1982a], and Whalley and Wigle [1983] present simulations of the effect of multilateral tariff liberalization by the U.S., Japan and the EEC. They conclude that terms-of-trade (TOT) effects are extremely important. Specifically, the tariff reductions negotiated during the Tokyo Round, as applied to post-Kennedy-Round tariffs, are heavily concentrated on Manufactured goods. The expansion of trade in those goods which follows the tariff reductions outweighs the direct effect on Manufacturing prices, leading to a net move in the (trade-weighted) TOT <u>against</u> countries that export non-Manufacturing goods. Generally, these countries tend to be LDC's whose export trade is currently oriented towards Agricultural products and/or Mining. Finally, the welfare changes involved are typically "small" for the major trading blocs (the U.S., Japan, and the EEC).

Certain key features of this stylized version of received results are evident in the welfare impact of our "Tokyo Round" tariff reduction simulations shown in Table 4. The tariff reductions employed in this simulation were drawn from Whalley [1982a; Table 2] for the U.S., Japan and the EEC, and from an application of the "Swiss formula" for all other countries.[15] We measure the welfare change for the private household in each region by the Hicksian equivalent variation between the benchmark equilibrium and the various counterfactual equilibria (conditional on various parameter estimates). This measure is then expressed as a percentage of GDP in the base year in order to allow comparisons between regions of such diverse economic size.

Table 4

Welfare Impacts of Tokyo Round Multilateral Tariff Liberalization

Region	Point Estimate	Mean	Standard Deviation	Probability of Welfare Gain
1. Australia	-0.7	0.2	1.2	0.86
2. Canada	-0.3	0.1	0.8	0.62
3. Indonesia	-0.1	-0.8	0.5	0.33
4. Malaysia	0.2	0.9	0.9	0.71
5. Philippines	-0.2	-0.9	0.3	0.27
6. Singapore	1.2	1.4	0.2	0.96
7. Thailand	-1.5	-2.3	0.8	0.09
8. Korea	1.2	1.5	0.7	0.83
9. Japan	0.7	0.9	0.4	0.92
10. U.S.A.	0.2	-0.3	0.4	0.38
11. EEC	0.06	0.03	0.05	0.87

Note: Welfare impact measured by Hicksian equivalent variation expressed as a percentage of GDP.

The Point Estimate column reflects the impacts of the policy in the counterfactual equilibrium conditional on all parameters being set equal to their respective point estimates. The remaining three columns report summary statistics for the set of counterfactual equilibria implied by our sensitivity analysis. The Mean welfare impact is the average change in the welfare impacts, with the prior pdf's discussed earlier being used to weight the results. The Standard Deviation of the welfare impact is similarly computed from the pdf of welfare impacts. Note again that there is absolutely no presumption that the policy impacts (welfare impacts in this case) have a Gaussian distribution; therefore one should not assume that the Mean and Standard Deviation are in any way "sufficient statistics" of that distribution. In fact the vast bulk of the policy impact pdf's implicit in this case are skewed, in some cases significantly. Further research, to be reported in Harrison [1984], indicates that this skewedness is due largely to the use of rectangular uniform prices for the import demand elasticities _and_ the use of the _median_ from Stern, Francis and Schumacher [1977] as our Point Estimate for these parameters. The final column in Table 4 reports the Probability of Welfare Gain, obtained by numerically evaluating the (proper) pdf of welfare gains. This column provides a useful measure of the confidence one can attach to _qualitative_ inferences about welfare impacts in our model.

As noted earlier, the results in Table 4 are consistent in several respects with the received empirical literature. Consider the results for the U.S. first. Whalley and Wigle [1983; p. 66] draw the following conclusion from their simulations of developed country tariff reductions:

> Since the early 1930's, U.S. commercial policy has been dominated by a belief both in the desirability of free trade and the need to achieve that end through multilateral reductions in trade barriers. It was the U.S.

> that initiated bilateral negotiations to reduce protection in [the] 1930's, the U.S. that was the main driving force behind the setting up of the GATT in the late 1940's, and the U.S. that initiated the ensuing rounds of GATT negotiations. In spite of the growing frictions in recent years, the basic belief that multilateral trade liberalization is good for the U.S. appears to have remained unshaken as one of the tenets of foreign trade policy. While the results presented in this paper may be viewed as close to heretical in policy circles, their message is abundantly clear. Further participation in multilateral tariff reductions under a GATT framework of equal proportional reductions of tariffs on manufactures may not be in the U.S. national interest.

One reason for disquiet with this conclusion is that it differs *qualitatively* from the results reported by Brown and Whalley [1980] and Whalley [1982a],[16] as well as the (less comparable) results of Cline, Kawanabe, Kronsjo and Williams [1978], Baldwin, Mutti and Richardson [1980], and Deardorff and Stern [1981]. Our results indicate one way to resolve this disagreement. When our model is calibrated with the point estimates of all parameters, we show a small welfare *gain* to the U.S. from "Tokyo Round" tariff liberalization. However, when we allow for the uncertainty of these parameter estimates we obtain a small average welfare *loss* for the U.S., noting further that there is a qualitative presumption of a welfare loss (with probability 0.62 = 1 - 0.38). Thus the weight of the evidence supports the Whalley/Wigle conclusion, due account being explicitly made for the uncertainty of that evidence.

Several general features of our results in Table 4 may be noted. The welfare impacts computed using parameter Point Estimates are quite small, and are much smaller in absolute terms than the Mean of the sensitivity analysis simulations. With three noteworthy exceptions (Australia, Canada and the U.S.) the

Point Estimate results are the same sign as the Mean results. It is also interesting to note that the impacts on the major trading blocs are smaller than those on the remaining countries (we return to this point later). Finally, it is comforting to be able to attach such high levels of probability to one or other qualitative result, especially in the face of relatively large Standard Deviations about the Mean welfare impact.

The specific results for Australia and Canada reflect two common and conflicting characteristics of the regions. One is the relative significance of Non-Manufacturing exports; thus the deleterious effects of declining TOT reflected in their Point Estimates welfare loss. On the other hand, the backward linkages via trade in intermediates with Japan, the U.S. and the EEC tend to counteract the direct TOT effects. The specific results for the remaining Pacific Basin nations largely reflect direct TOT effects. As the major ASEAN exporter of Agricultural products to the Pacific Basin, Thailand suffers relatively heavily.

5.2 An Unconditional Sensitivity Analysis

In the analysis discussed above the sensitivity of results was examined by setting most parameters at fixed values and then varying only one parameter at a time. Is this conditional sensitivity analysis a reasonably accurate guide to what one would find with an unconditional systematic sensitivity analysis?

Obviously we cannot vary all parameters jointly for the realistic policy relevant model considered above. This section therefore pursues the answer to the question of the adequacy of CSSA by imposing extreme restrictions on a (hypothetical) general equilibrium model, which is then simulated unconditionally. All parameters are permitted to interact jointly since an exhaustive experimental design is pursued.

The general equilibrium model simulated obviously had to be a minimal specification to make the presentation of complete unconditional sensitivity analysis manageable. The model was therefore designed to have as few parameters and exogenous variables as possible. The resulting model features include:

Scope: Two factors are used to produce two goods. There is only one consumer.

There is no government so there are no taxes.

The tastes of the sole consumer are specified by a two-good CES utility function indexed by only one parameter (beta), the distribution parameter (or "weight") on good 1. The weight on good 2 is therefore (1-beta).

Technologies for producing two goods with two factors are specified with two CES production functions, each assumed to have constant returns to scale.

The efficiency parameters (alphas) equal 1.00, so are not explicit.

The distribution parameters are indexed by only one parameter (delta), the weight on factor one in producing good one, and the (same) weight on factor two in producing good two: in matrix notation,

$$\begin{array}{lcc} & \text{Factor 1} & \text{Factor 2} \\ \text{Good 1} & [\ \text{delta} & \text{1-delta}\ ] \\ \text{Good 2} & [\ \text{1-delta} & \text{delta}\ ] \end{array}$$

If delta is one-half, so is one minus delta, the production possibility frontier is linear and tastes become irrelevant to prices, since technology alone determines the tradeoffs.

The elasticity of substitution (sigma) is the same for both production functions and for the one utility function.

The endowment of factor 1 is unity, so the ratio of the endowment of factor 2 to factor 1 (X), a scalar, suffices to specify endowments.

The price of factor 1 (P1) is the numeraire, so there is only one unknown relative factor price, P = (P2/P1).

The core of the entire general equilibrium model can therefore be solved as one relative factor price as a (closed form, exact, global) function of three parameters and one exogenous variable:

P = f(sigma, beta, delta, X)

The experimental design requires that we explore all major combinations of settings of the four determinants. The endowment of factor 1 relative to factor 2 is symmetric, so only one direction needs to be explored. We therefore limit the exploration of endowment effects to two settings, 1.0 and 2.0.

Similar symmetry arguments permit delta to range from 0.5 to 0.9 with increments of 0.2.

The single parameter indexing tastes (beta) is set to three values, 0.1, 0.5 and 0.9.

The span of the elasticity of substitution is made log-linear, ranging from 0.2 to 5 as shown in the row headings of Table 5.

This experimental design means that the model is solved for the relative factor price for all possible combinations of settings of the four parameters, as shown in Tables 5-10 and illustrated in Figures 1-4.

Table 5. Relative Factor Price
Case: Endowment= 1 , Beta= .1

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	1.0	1.2	1.6
0.44	1.0	1.5	2.6
0.99	1.0	1.9	4.5
2.20	1.0	2.3	6.6
4.90	1.0	2.3	7.8

Table 6. Relative Factor Price
Case: Endowment= 2 , Beta= .1

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	0.03	0.04	0.05
0.44	0.21	0.31	0.54
0.99	0.50	0.96	2.2
2.20	0.73	1.7	4.8
4.90	0.87	2.0	6.8

Table 7. Relative Factor Price
Case: Endowment= 1 , Beta= .5

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	1.0	1.0	1.0
0.44	1.0	1.0	1.0
0.99	1.0	1.0	1.0
2.20	1.0	1.0	1.0
4.90	1.0	1.0	1.0

Table 8. Relative Factor Price
Case: Endowment= 2 , Beta= .5

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	0.03	0.03	0.03
0.44	0.21	0.21	0.21
0.99	0.50	0.50	0.50
2.20	0.73	0.73	0.73
4.90	0.87	0.87	0.87

Table 9. Relative Factor Price
Case: Endowment= 1 , Beta= .9

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	1.0	0.83	0.63
0.44	1.0	0.68	0.39
0.99	1.0	0.52	0.22
2.20	1.0	0.44	0.15
4.90	1.0	0.43	0.13

Table 10. Relative Factor Price
Case: Endowment= 2 , Beta= .9

	Deltas:		
Sigmas:	0.50	0.70	0.90
0.20	0.03	0.03	0.02
0.44	0.21	0.14	0.08
0.99	0.50	0.26	0.11
2.20	0.73	0.32	0.11
4.90	0.87	0.37	0.11

Fig. 1 Plot of Relative Factor Price

Case: Endowment = 1, Beta = .1

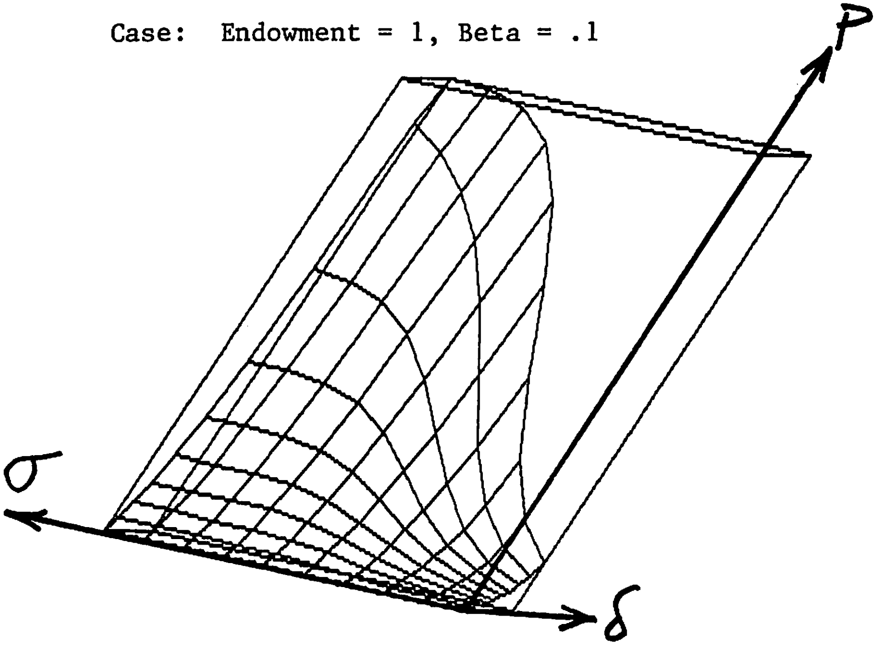


Fig. 2 Plot of Relative Factor Price

Case: Endowment = 1, Beta = .9

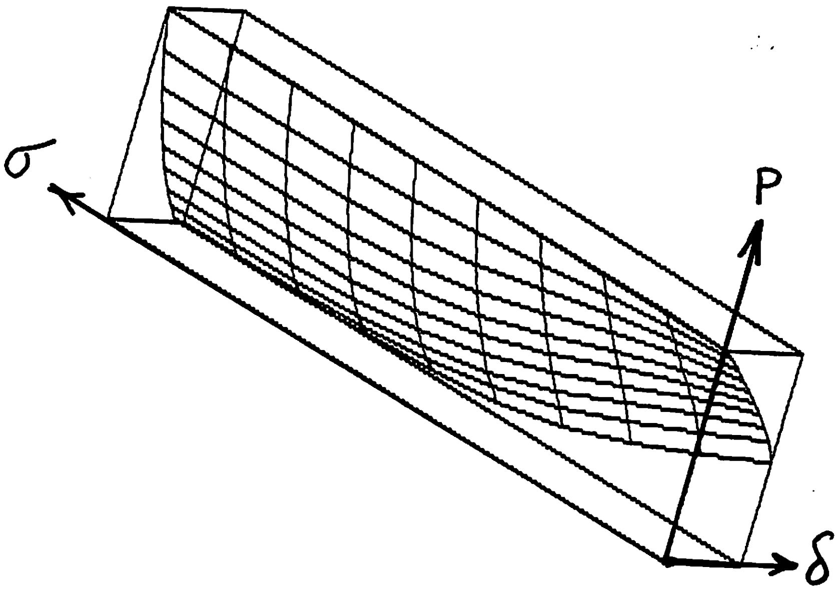


Fig. 3 Plot of Relative Factor Price
Case: Endowment = 2, Beta = .5

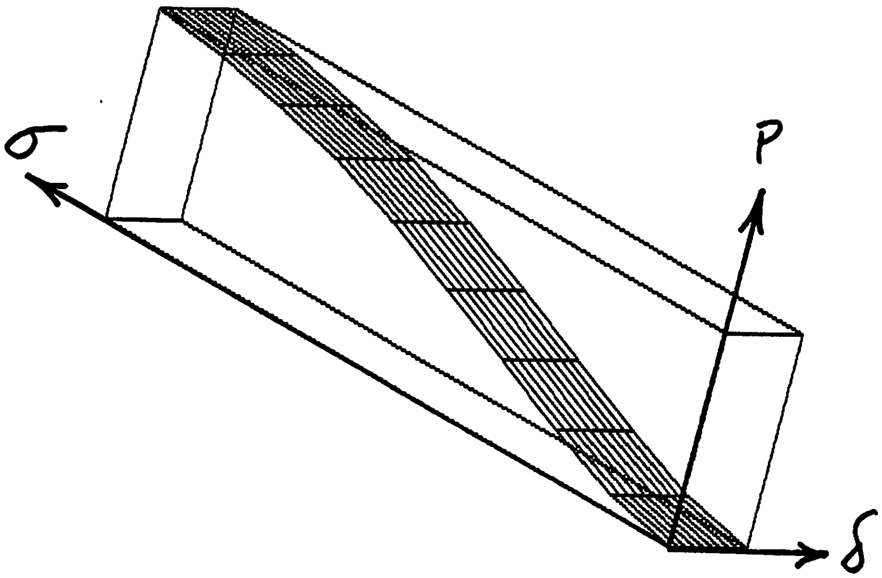
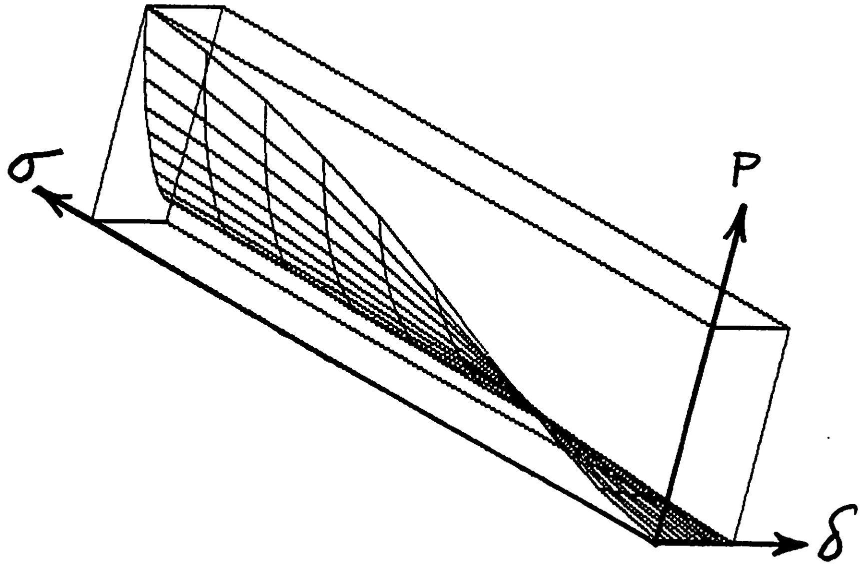


Fig. 4 Plot Of Relative Factor Price
Case: Endowment = 2, Beta = .9



The central question is whether the results of a given setting for two of the parameters influences heavily the interpretation of varying the other two parameters. Specifically, is the role of the elasticity of substitution and the technological distribution parameter on the relative factor price robustly identified regardless of the setting of the endowment and the tastes distribution parameter? That is, if one had only studied a given Table, would the conclusions be the same regardless of which Table one choses? The answer is clear and rather pessimistic, viz., the analysis varies radically across the Tables. The analysis of the role of sigma and delta is extremely sensitive to the conditional values of beta and X.

Consider Table 7. It shows that when X equals unity and beta is one-half, then relative factor prices are completely invariant to changes in delta and sigma. (No three-dimensional figure is drawn since obviously the factor price results would be a perfectly flat "horizontal" plane.) But compare this simple pattern with that of the case where the endowment is two and the distribution parameter in the utility function is .9, shown in Table 10 and Figure 4. Here higher sigmas raise the price of factor 2 relative to factor 1, and higher deltas lower factor prices. When the endowment is unity and beta is .9, however, higher sigmas lower factor prices at deltas of 0.7 or 0.9 but have no effects when delta is 0.5.

The contrasts are perhaps most obvious in the various Figures. Clearly the relationship of sigma and delta on relative factor prices depends acutely on joint interactions with the endowment and beta. The figures show hardly any resemblance to one another.

If further analysis with more realistic models confirms these pessimistic suggested results, then some form of unconditional sensitivity analysis may be required for robust policy conclusions, regardless of the higher cost and greater complexity of presentation imposed by USSA.

6. Directions for Further Research

The objective of this paper is to present and illustrate one approach to the question of the robustness of NGE models that we have found useful. In this section we identify several directions in which research along these lines is proceeding.

We are currently applying our approach to examine the robustness of certain major policy findings from Whalley's international trade model (see Walley [1984]) and the GEMTAP tax model for the U.S. (see Ballard, Fullerton, Shoven and Whalley [1983]). We are also studying the extent to which a CSSA can approximate the results of an USSA. This approximation will clearly be improved if we are able to reliably identify certain "critical" parameters from a CSSA and then conduct a semi-complete SSA (as discussed earlier). Finally, we are reviewing and updating many of the elasticity estimates employed in Whalley's international trade model and GEMTAP. Where possible we are also generating new estimates using system-wide methods (from a theoretical and econometric perspective), leading to the construction of non-diagonal covariance matrices of estimates.

Footnotes

[1] Our remarks pertain directly to the class of models mentioned above. A variant on this class is the so-called "Johansen-like" model--see Dixon, Parmenter, Sutton, and Vincent [1982] for a complete review. The general thrust of our remarks below also apply to these NGE models: see Cook [1980; Chapter 4], Pagan [1983] and Pagan and Shannon [1983].

[2] Our lack of concern stems from the absence of any well-defined alternative capable of addressing comparable policy issues at the empirical level desired.

[3] Apart from the references cited earlier, see Mansur and Whalley [1983], St.-Hillaire and Whalley [1980], Piggott and Whalley [1983], Fullerton, Shoven and Whalley [1978], and Ballard, Fullerton, Shoven and Walley [1983].

[4] In his paper two "...explicit characterizations of partial equilibrium analysis are developed and used to assess the impact of the removal of distortionary capital income taxation in the United Kingdom. The solutions are compared to those obtained using more complicated devices for the computation of competitive equilibria. The exercises are repeated for different parameterizations of the model. The partial equilibrium techniques perform somewhat erratically as <u>approximate</u> methods. This suggests that although there is a considerable gain in computational simplicity in the use of partial equilibrium analysis, the reliability of results using <u>more satisfactory</u>

general equilibrium techniques is considerably increased." (p. 310; emphasis added.)

[5] We may wish to consider only variations in parameters that are common to both partial and general equilibrium approaches, since the typical NGE model contains a significantly larger number of parameter estimates.

[6] For example, see Brown and Whalley [1980; Table 13], Dervis, De Melo and Robinson [1982; Chs. 8-13], Dixon, Parmenter and Rimmer [1982], Fullerton, King, Shoven and Whalley [1981; Tables 3-5], Hartigan and Tower [1982; Tables 1-5] and Whalley [1980; Table 6].

[7] There are many ways to pose the question of robustness. For example, we could ask the qualitative question: what is our confidence in this policy impact being positive (or negative)?

[8] Clearly this also depends on the research budget provided for the exercise. Note that Johansen-style methods are very attractive for this type of exercise.

[9] But not always: often the specification that is reported is the result of an interpretive search in which one or more possible explanatory variables have been constrained (e.g., eliminated) using prior information that is not communicated. It is possible that such a search was in fact a simplification search with an implicit objective of (non-causally constrained) conditional prediction, but this is not typical in the relevant econometric literature. Moreover, the end result from the

reader's perspective is a distorted summary of the sample evidence. See Leamer [1978; Chs. 5 and 6] for further discussion.

[10] Engles [1979] examines a separate algorithmic issue: the connectedness of equilibrium paths between discrete parametric deformations of NGE models. Arguably, this is only a substantive issue if multiple equilibria exist for certain parameter configurations; see Kehoe [1980] and Kehoe and Whalley [1982] on the question of multiple equilibria.

[11] There is an implicit presumption here that the off-diagonal elements of the covariance matrix of our elasticity estimates are all zero. Although non-zero elements are theoretically available for certain blocks of elasticity estimates (e.g., the demand elasticities) we adopt this presumption in the present model.

[12] Those authors are quite explicit in eschewing any probabilistic interpretation of their point estimates or range of estimates: "It should be reiterated that the ranges shown are not meant to be interpreted as confidence intervals. Rather, they refer to point estimates. In using either the ranges or 'best' estimates for analytical purposes, it is therefore advisable to avoid attaching probability statements to any conclusions." (p. 14). Our prior corresponds to the Bayes-Laplace diffuse prior in Bayesian analysis: see Zellner [1971; pp. 41-53] for further discussion.

[13] A procedure for computing "good" starting values for large

GE problems, based on the AFPS for a stylized version of the original GE model, is proposed in Kimbell and Harrison [1983; Section 6.3]. Indeed this method was employed to solve the seven-sector model (parameters equal to their point estimates) with substantial savings in execution time compared to a "cold start" (initial solution values equal to the benchmark solution values). Using the seven-sector solution values as starting values for the twenty-sector model proved more efficient (in all cases studied) than using the analytic approximation technique (we did not have the time to waste on a further comparison with the "cold start" method!). On a technical note, all of the computations reported in this sub-section were undertaken on a North Star Horizon microcomputer. This is a 8-bit machine, with 64K RAM and a clock-speed of 4 MHZ. The complete set of 2881 simulations required 32 days of execution time. Two features of recent 16-bit hardward would reduce this time dramatically: clock-speeds of 8 MHZ and the availability of "electronic memory" (i.e., treating an area of RAM "as if" it were a disk file, allowing orders of magnitude faster access to data in the course of solution iterations).

[14] The following discussion is a minor modification of Harrison and Kimbell [1983; Section 3.1]. The results reported here differ in one important conceptual respect, however: we "re-benchmarked" the complete model after perturbing each elasticity. The numerical results of this procedure were identical to those obtained in our earlier paper at the level of significance reported in Table 4 below. Preliminary research

indicates that "re-benching" does have some noticeable effect on results in the case of an USSA.

[15] The "Swiss formula" is a general formula used to provide "ball-park" tariff reductions upon which further (complex) negotiations could proceed. See Brown and Whalley [1980] for an account of the alternative formulae proposed. The Swiss formula is of the form $t'_i = \pi t_i / (\pi + t_i)$, where π is a constant (assumed equal to 0.14 here), t_i is the initial (pre-cut) tariff in sector i, and t'_i is the final (post-cut) tariff in sector i. Following Brown and Whalley [1980; p. 851] we applied this formula for all commodities except "Agriculture, Forestry and Fishing" and "Textiles, Clothing, Footwear and Leather" (sectors 1 and 5 in our twenty-sector aggregation).

[16] With the qualification, noted by Whalley and Wigle [1983; p. 66], of the simulations reported by Whalley [1982a; Table 4] in which a residual Rest of World region is assumed to have a tariff reduction of only 25% or less.

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