Fuel

ISSN 0316-5078

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A Model of Energy Supply From Western Canada*

by

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May, 1979

Discussion Paper No. 344

ABSTRACT

This paper discusses a static multiregional linear programming model of energy supply from western Canada. This model has been constructed as part of an effort to measure production labour requirements, regional wealth accrual and economic resource rents associated with different energy resource development scenarios. Demands and prices are exogenous to the model and supplies are determined to maximize the increment to gross domestic product generated by energy resource production. The optimal solution yields a pattern of production and economic rent distribution which would obtain if actual prices were specified exogenously and energy markets functioned in a perfectly competitive manner to meet demands. Thus the most economic supply alternatives are utilized most intensively, low-cost producers rewarded most heavily and highest rents awarded to production capacities and reserves in particularly short supply. Two major advantages of the approach are. (i) the most economic patterns of production and transport of energy products can be determined independently of the externally imposed restrictions characterizing Canadian energy product markets, allowing inefficiencies to be pinpointed and quantified, and (ii) it allows the price of each energy product to have a direct impact on the shadow prices of constraints on energy production and consumption, in turn allowing empirical estimation of changes in natural resource rents as energy product prices change. The model can be used to address such supply-oriented questions as the short term consequences to provincial wealth accrual and economic rents of energy price adjustments in international markets, the impact of increased or reduced restrictions on energy product supply or transportation, the implications of technical developments in product supply or co-product yields, or the outcome of government attempts to promote economic development of specific provincial energy industries.

1. Introduction

This paper describes work carried out in 1977 on the construction of an energy model for Canada. See [5] for details. An inquiry into the role of natural resources in regional economic disparities, production labour employment potential and regional economic growth has provided the impetus for this work. Two other studies forming a part of this inquiry are Copithorne [1] and Copithorne and Quiroga [2]; the modelling approach of this paper is very similar to the approach of these two studies.

The central objective of the modelling effort has been to construct a vehicle capable of examining, within a single consistent framework, the interrelated issues of: (i) regional economic activity associated with the production of crude oil, natural gas, coal and electrical energy; (ii) regional economic disparities flowing from differential natural resource rents attaching to conventional energy forms in relatively short supply, namely crude oil, natural gas and hydroelectric potential; (iii) the influence upon these natural resource rents of transport costs and technological change in energy production; and (iv) the consequences for economic activity in the energy production industries and natural resource rents regionally of government imposed restrictions on the way in which energy can be produced. Resource rents and wealth accrual from resource production have been singled out for particular attention because of their role in regional economic disparities, their potential for widening or narrowing such disparities, and their size relative to federal equalization payments. Furthermore, given the present federal-provincial jurisdictional dispute concerning the capture of resource rents, it has become imperative to quantify these resource rents and analyze the impact upon their magnitude of restrictions on production and transportation to understand better how resolution of the jurisdictional issue will affect the economic position of the governments concerned and energy product suppliers.

To examine these issues a general model is essential. In the case of Alberta thermal coal, for instance, restrictions on strip mining and shipment of coal outside the province may have numerous and far-ranging effects, including increased cost of coal to Ontario Hydro customers, a possible shift toward nuclear power in Ontario, hastened exploitation of lignite coal deposits in southern Saskatchewan to supply Ontario markets, and possibly slowed development of an Alberta industry devoted to coal gasification, with corresponding implications for the regional distribution of income and jobs. A comprehensive model must have the detail and generality to trace these consequences. Furthermore, potential rents accruing to conventional oil and gas require measurement in a framework which allows for adjustments to production and transport costs, price variations in domestic and export markets, differential exploitation of these resources according to different growth rates in demands through time, the consequences for such rents of additions to reserves through exploration, and shifts toward alternative energy supply sources. Similarly, hydro rents depend crucially upon the costs of alternative sources of electrical energy, and must fluctuate with the cost of capital, the cost of thermal fuels, social discount rate, and the price charged for electrical energy. All these elements require a place in the framework.

Linear programming has been adopted for modelling the necessary breadth of diverse elements and the detail of specific elements. The research effort has so far yielded a static energy model embracing the individual western provinces of Canada. The multiple time-period framework essential for examining questions of intertemporal adjustment and measuring economic rents is therefore not yet present. Model structure is described in Section 2, with brief attention to differences between the approach adopted and other modelling efforts. Illustrative comparative static results from the model are presented in Section 3. Concluding observations appear in Section 4.

2. Structure of the Model

2.1 Preliminaries

The static linear programming model embraces energy production and transportation in western Canada and does not yet constitute a national model. Since western Canada possesses more than 95% of indigenous known reserves of natural gas, crude oil and coal, and all of Canada's heavy oil and oil sands, the model captures the most important elements of the Canadian supply system for these energy resources. Hydro resources, however, are more widely dispersed across the country. Activity in the energy industries is represented in the model for the year 1974, the most recent year for which data have been available.

Model construction has been much simplified by largely avoiding the processing of crude energy into refined products. Energy products included are: (1) light/medium crude oil, consisting of conventional light and medium crudes, field condensate, the generic category of pentanes plus, and synthetic crude from the oil sands of Alberta; (2) heavy crude oil; (3) natural gas; (4) bituminous, subbituminous and lignite coals; and (5) electric power. Hydro resources are included only as existing supplies of hydroelectric energy. The model has a high degree of aggregation; model production sources, consumption centres and transportation networks are stylized representations of western Canadian production-transport-consumption systems. For instance, each supply activity represents production from numerous spatially dispersed sources, such as oil wells, gas wells, coal mines or electric power generating facilities.

For the light/medium crude oil network of the model, each province of western Canada has one representative producing centre save for Alberta, which with oil sands production capacity at Fort MacMurray has two. Vancouver, Edmonton, Regina, Winnipeg and Sarnia-Toronto are representative consumption centres in Canada, while Cherry Point (Washington), Billings (Montana) and Chicago are representative consumption centres for the U.S. Petroleum Administration for Defense Districts V, IV, and II, respectively.

Other resource networks exhibit similar detail. For heavy crude oil, production sources are confined to Alberta and Saskatchewan, and foreign export is confined exclusively to P.A.D. District II in the United States. The natural gas network is very similar to that for light/medium crude (henceforth simply light crude), two major differences being that there is no transmission link from Alberta production sources to British Columbia consumption centres and that Manitoba produces no natural gas. The coal network embraces both metallurgical coal and thermal coals, markets for the former consisting almost exclusively of Japan and southern Ontario, while markets for the latter consist primarily of power utilities in the prairie provinces. Finally, the electric power network of western Canada has been constructed around the three publicly-owned provincial electric utilities of B.C. Hydro, Saskatchewan Power and Manitoba Hydro, and an aggregate of the four principal Alberta power utilities.

2.2 Activities and Constraints

Model activities for coal, crude oil and natural gas are confined to: extraction variables, representing quantities of resources extracted on a provincial basis and brought to a central location for distribution; transport variables, representing the movement of these products from one domestic location to another within Canada or to representative locations in the United States; marketing variables, representing resource products consumed in any particular location; and variables measuring production labour requirements associated with resource extraction. For electric power an additional set of variables measuring the conversion of coal or natural gas into electrical energy is included.

Model structure is displayed schematically in Table 1. For each province there are constraints (where applicable) on reserves of oil, natural gas and coal, which require that aggregate intertemporal extraction of these fossil fuels cannot exceed exogenously specified reserves. Such reserves constraints are redundant in a static model since reserves cannot be exhausted in a single time period. Next, there are constraints on provincial productive capacity of oil and gas wells or coal mines, which limit the quantity of oil, gas and coal which can be extracted in any particular year. Constraints on market demand specify upper limits on the quantity of energy products which can be absorbed by consumption centres at exogenously specified prices. Constraints for oil, gas and coal comprise either mass balance constraints, which require that product supply equal demand, or accounting constraints, which record production labour requirements, transportation costs or volumes of co-products associated with crude oil or natural gas production. Only the mass balance constraints require elaboration. For example, the balance constraint for natural gas in Alberta equates supplies of natural gas, namely marketable gas produced from natural gas wells and associated gas derived as a co-product from crude oil production, to demands for natural gas, which consist of shipments of natural gas south to the United States and east to Saskatchewan, domestic nonelectric demands for natural gas within Alberta, and demands in Alberta for natural gas for electric power generation. For different products

TABLE 1: Schematic Diagram of Linear Programming Model Constraints*

Constraint Name \ Activity Type		OIL, GAS & COAL: Production	Transport	Marketing	Co-Products	Labour Use	ELECTRIC POWER: Generation	Transmission	Conversion	Marketing	Labour Use	Constraint Type	Constraint Right Hand Side
Objective Function		■	■	■	■	■	■			■	■		
Oil Gas & Coal	Demands			■								$\leq$	Specified Demands
	Prod$^{\underline{n}}$ Capacity	■										$\leq$	Capacity Estimates
	Reserves	■										$\leq$	Reserve Estimates
	Mass Balances	■	■	■					■			=	0
	Labour Req'ts	■				■						=	0
	Transport Costs	■	■									=	0
	Co-Products	■			■							=	0
Electric Power	Demands									■		$\leq$	Specified Demands
	Power & Energy Generation						■					$\leq$	Generating Capabilities
	Mass Balances						■	■		■		=	0
	Conversion						■		■			=	0
	Labour Req'ts						■				■	=	0

* Shaded entries denote nonzero activity and objective function coefficients.

and regions the form of the balance constraint is similar but not identical. There is, for instance, no direct conversion of crude oil into electrical energy in the model for any province.

Similar constraints apply for electric power provision: constraints on power capacity and energy generation limit supply from each provincial source, marketing constraints establish maximum quantities of power to be absorbed in each domestic or American consumption centre, while conversion constraints transform quantities of electric power generated into requirements for natural gas, coal and fuel oil. Mass balance constraints require that power consumed exactly equal power supplied, and accounting constraints aggregate quantities of operating labour required for electric power generation. Power demands have required special attention because of their variability over time, both daily and seasonally. In this model a highly simplified representation has been adopted: a peak load demand extending for one percent of the year, and a base load demand extending for the full year.

To illustrate actual matrix entries, Table 2 lists input requirements and co-product yield ratios associated with light/medium crude oil production in each province. Production activities for coal and natural gas have similar kinds of entries, but with certain differences. Coal, for instance, has no associated co-products, whereas natural gas has co-products of condensate, propane, butane and sulphur, with co-product ratios varying considerably between provinces. Likewise, electric power generation has a similar structure but with constraints on both power and energy generation and a mass balance constraint for each of the base and peak demands.

2.3 The Objective Function

The increment to gross domestic product (GDP) in all energy industries

TABLE 2: Energy Model Per-Unit Data for Light/Medium Crude Oil Production

Type	Constraint Name	Units	Light Crude in B.C.	Light Crude in Alberta	Synthetic Crude in Alberta	Light Crude in Sask.	Light Crude in Manitoba
$\leq$	Productive Capacity	10^3 BBL	1.0	1.0	1.0	1.0	1.0
$\leq$	Crude Oil Reserves	10^3 BBL	1.0	1.0	1.0	1.0	1.0
=	Mass Balance	10^3 BBL	1.0	1.0	1.0	1.0	1.0
=	Labour Requirements	Man-Years	0.005481	0.005458	0.244727	0.005245	0.005896
=	Gathering Costs	10^6 \$	0.000800	0.000300	0.000250	0.000250	0.000100
=	Fuel and Materials	10^6 \$	0.000116	0.000136	0.004500	0.000286	0.000139
=	Co-Product: Gas	10^6 MCF	0.000769	0.000707	0.0	0.000475	0.0
=	Co-Product: Sulphur	10^3 L.T.	0.0	0.0	0.007000	0.0	0.0

Sources: Coefficients in this table have been calculated using data from Statistics Canada, the National Energy Board, the Alberta Energy Resources Conservation Board, provincial ministries of energy and mineral resources, and discussions with various individuals. See Appendices A & B of Rowse [5] for further information.

is to be maximized. For each industry and province, this aggregate consists of the value of the energy product sold less: (i) payments to other industries for fuel, materials and supplies (save for electric power, where fuel choice is made explicitly by the model); and (ii) wage payments for production labour, which are incurred as a result of energy product supply, with appropriate credit for any co-products produced. This aggregate consists of value added net of payments to production labour, and will be abbreviated to "net value added". Attainment of this objective in fact rewards the low-cost producers and awards highest rents to their production capacities and reserves in particularly short supply, yielding a pattern of production and rent distribution which would obtain if prices were truly specified exogenously and energy markets functioned in a perfectly competitive manner to meet the ceilings on demands. Two major advantages of the approach selected are: (i) the most economic patterns of production and transport of energy products can be determined independently of the externally imposed restrictions characterizing Canadian energy product markets, allowing inefficiencies to be pinpointed and quantified, and (ii) it allows the price of each energy product to have a direct impact on the shadow prices of constraints on energy production and consumption, in turn allowing empirical estimation of changes in natural resource rents as energy product prices change.

Interaction of the electric power industry and the other industries may well play a role in shaping model demands and supplies. For instance, the increment to GDP in the coal industry and electric power industry together will have an important influence upon which types of existing generating capabilities are selected for use. If net value added in coal production is high but that of coal-fired generation for electric power is not -- relative to some other type of generation -- the model may still select the coal-fired generation since the combined increment to GDP is higher.

Although the model displays some similarities to other supply models, it also displays some notable differences. For instance, it embraces minimal processing of energy resources (excluding oil refining entirely) and maximizes net value added in energy industries subject to ceilings on demands instead of minimizing costs of energy provision subject to floors on demands, as does the LORENDAS model [4], which also exhibits far greater detail in the modelling of energy supply capabilities. Another element that differs somewhat from other models is the attention paid to the dual variables emerging from the optimal solution, a focus that formed a central part of Nordhaus's study [3] on optimal world energy resource depletion. The economic rent or windfall gain attaching to a resource in scarce supply depends upon many factors, including the price of the final product or products for which the resource is used, the timing of resource production and sale, costs of co-operating factors and the technology used in production, the quantity and value of co-products in resource extraction, and the costs of transport of the product to consumption centres. The linear programming approach allows for all these separate factors and at the optimum the dual variables provide estimates of their combined quantitative importance. See [5, App. F] for an algebraic statement of how, in a highly simplified energy model, the shadow price of reserves is related to these factors. Finally, one minor difference between the present model and other models is its emphasis upon employment of production labour. This emphasis could also be supplemented with allowance for job creation potential for professional labour if desired, and stems from an interest in the employment growth potential of energy resource development.

3. Illustrative Model Solutions and Comparative Statics

Because a dynamic version of the model is not yet available, the results which it is capable of providing must be regarded as illustrative. Furthermore, since the solution detail which it generates is considerable, only salient results will be discussed.

Tables 3 and 4 provide selected model statistics and shadow prices respectively for the Base Case and Low Price Scenario. The solution results for the Low Price Scenario -- if they differ from the Base Case -- are recorded in parentheses. The Base Case solution indicates how the energy model would supply 1974 demands for crude oil, natural gas, coal and electric power using prices and productive capacity constraints for that year. All details of the actual, Base Case and Low Price Scenario results are set forth in [5, Ch. 3]. The Base Case solution basically replicated the actual western Canadian energy supply pattern. There are, however, some notable exceptions, stemming from such causes as government-imposed restrictions on the functioning of product markets, simplifications such as linearity inherent in the model, and problems arising from quality variations in energy products existing in the real world but assumed away in the model. Particular supply features characteristic of western Canada were duplicated, such as the dominance of Alberta in oil and gas supply, followed by British Columbia as a natural gas producer and Saskatchewan as an oil producer. Model net values added for oil and gas were relatively close to those actually observed for all provinces except B.C., the difference for the latter province owing in large part to noncompetitive gas pricing for gas producers. Net values added for the coal industry were not relatively close to what was actually experienced, however, in part because the model sought to use as much natural gas for electric power generation and as little thermal

TABLE 3: Selected Model Energy Statistics - The Base Case and Low Price Scenario (Entries for the Low Price Scenario are listed in parentheses if they differ from the Base Case)

Production, Labour or Value Statistic	British Columbia	Alberta	Saskatchewan	Manitoba
Net Value Added* - Oil & Gas (10^6\$)	216.2 (94.2)	4006.3 (2140.4)	407.5 (212.7)	27.9 (16.6)
Labour - Oil & Gas (Man-Years)	271.	3805. (3795.)	424.	28.
Production of Oil** (10^3 BBL)	10,713.	582,551.	77,409.	4749.
" " Gas (10^6 MCF)	407.2	2117.0 (2093.6)	56.4	--
" " Propane (10^3 BBL)	613.	34,058. (33,682.)	702.	--
" " Butane (10^3 BBL)	683.	22,619. (22,369.)	299.	--
" " Sulphur (10^3 L. Tons)	65.	7038. (6960.)	3.	--
Net Value Added*† - Coal (10^6 \$)	105.0 (38.0)	47.0 (16.8)		--
Labour† - Coal (Man-Years)	1937. (1822.)	1307. (1371.)		--
Production of Bituminous (10^3 S. Tons)	8076. (7792.)	3652.	--	--
" " Subbituminous (10^3 S. Tons)	--	3722. (4657.)	--	--
" " Lignite (10^3 S. Tons)	--	--	3414.	--
Generation of Electrical Energy (10^6 KWH)	25,696.5	13,513.3	7126.7	14,271.1
Labour - Electrical Energy (Man-Years)	2130.	1882.	965.	1341.
Prime Motive Source: Gas (10^6 MCF)	29.7	82.9 (60.7)	15.9	0.43
" " " Subbit. Coal (10^3 S. Tons)	--	3491.7 (4426.5)	--	--
" " " Lignite Coal (10^3 S. Tons)	--	--	2810.9	--
" " " Fuel Oil (10^3 BBL)	--	--	--	--
Net Energy Transmission (10^6 KWH):				
To Ontario	--	--	--	1814.4
To Manitoba	--	--	273.	--
To Saskatchewan	--	--	--	--
To Alberta	--	--	--	--
To British Columbia	--	--	--	--
To United States	1348.7	--	--	1495.3

* Net value added consists of value added less production labour wage payments.

** Oil production includes light, medium and heavy oil, condensate and pentanes plus; for Alberta, also synthetic crude.

† Alberta and Saskatchewan net values added for coal production have been aggregated to derive a single figure for comparison with actual data compiled by Statistics Canada, which for reasons of confidentiality does not differentiate between Alberta and Saskatchewan. The same procedure has been followed for coal production labour.

TABLE 4: Selected Model Shadow Prices - The Base Case and Low Price Scenario (Entries for the Low Price Scenario are listed in parentheses if they differ from the Base Case)

Consumption Centre \ Shadow Price		Demand for Light Crude Oil ($/BBL)	Demand for Heavy Crude Oil ($/BBL)	Demand for Natural Gas (¢/MCF)	Demand for Bituminous Coal ($/S. Ton)	Demand for Thermal Coal* ($/S. Ton)	Hydro Energy (Mills/KWH)
British Columbia		5.37 (2.99)	--	30.58 (5.83)	8.16 (0.00)	--	4.03 (4.20)
Alberta		5.37 (2.99)	4.50 (2.12)	44.30 (20.77)	8.16 (0.00)	0.10	1.71
Saskatchewan		5.37 (2.99)	4.50 (2.12)	44.30 (20.77)	--	0.28	2.03
Manitoba		5.37 (2.99)	4.50 (2.12)	44.30 (20.77)	8.16 (0.00)	--	3.18 (4.83)
Ontario		5.37 (2.99)	4.50 (2.12)	44.30 (20.77)	8.16 (0.00)	--	--
Exports to U.S.	South from B.C.	5.37 (2.99)	--	30.58 (5.83)	--	--	--
	South from Alta.	5.37 (2.99)	--	44.30 (20.77)	--	--	--
	South from Man.	5.37 (2.99)	4.50 (2.12)	44.30 (20.77)	--	--	--
Exports to Japan		--	--	--	8.16 (0.00)	--	--

* Thermal coal denotes subbituminous coal in Alberta and lignite in Saskatchewan.

coal as possible since the combined increment to net value added from gas production and gas-fired power generation exceeded the combined increment with coal. This result would not arise in a dynamic model which recognized an explicit opportunity cost for natural gas in the form of future production and sale, and could have been eliminated had such an opportunity cost been specified in the static model. Hydroelectric power generation has been excluded from the table. Regarding Table 4, only those shadow prices attaching to maximum demands for crude oil, natural gas and coal, and to available hydroelectric energy have been included. Shadow prices of light and heavy crude and bituminous coal are identical for all model demands because wherever incremental demands occur in the respective networks, the marginal supply source is the same. For crude oil this source is Alberta, while for bituminous coal this source is British Columbia. Thus, for example, wherever a barrel increase in demand for crude oil is registered in the oil networks, Alberta production will increase by one barrel. Shadow prices for natural gas and thermal coals do differ according to demand location, however. For gas, there is no transmission link between Alberta and British Columbia and hence there are two marginal sources in the gas network; for each of lignite and subbituminous coal there is only a single demand centre and a single supply source. Hydro energy shadow prices differ for several reasons, a principal one being that electrical energy prices differ considerably across provinces.

To examine how energy industries might have performed in the absence of the sharp upward adjustment in oil, gas and coal prices that occurred during 1974, and to measure the consequences for net values added provincially, the Low Price Scenario was analyzed. Oil, gas, propane, butane, sulphur and bituminous coal prices were adjusted downward to their 1973 averages while thermal coals and electrical energy were taken unchanged in price. In this case, therefore, the same production technology actually used during 1974 was implicitly assumed available for use when lower prices were taken to prevail. In the new solution, all figures for net value added shrink. For example, oil and gas in British Columbia experiences a decline of almost 56% and in Alberta a decline of 47%, the latter representing a reduction of $1866 million. Results for the coal industry are similar despite the fact that more subbituminous and lignite coal is produced under this scenario. But there is minimal change in the quantities of production labour employed; demands remaining unchanged and there being little provincial shift in production patterns, labour employment registers virtually no change. The only substantial adjustment is that lignite and subbituminous generating sources substitute for natural gas because gas production and transformation into electrical energy is less attractive than that for coal under lower gas prices. Shadow prices are seen to adjust downward sharply for all nonelectrical demands, even to zero for bituminous coal, exhibiting the direct influence of product sale price on constraint shadow prices. Hydro energy shadow prices for B.C. and Manitoba rise slightly because an extra KWH of hydro energy would displace one KWH of natural gas generation, now no longer as attractive as before; an extra KWH of hydro in Alberta and Saskatchewan would displace one KWH of thermal coal generation as before, and since thermal coal is unchanged in price, the shadow price of hydro energy remains unchanged for these two provinces.

The most notable result of the Low Price Scenario is that, mirroring reality, the model has generated consequences for disparities in provincial wealth accrual stemming from fossil fuel price increases from 1973 to 1974 that are enormous, indeed almost staggering. Such disparities are, of course, caused primarily by the huge windfall gains to oil production in Alberta and natural gas production in British Columbia that are wrought by these price increases.

4. Concluding Remarks

This paper has discussed the construction of a static economic model of energy supply from western Canada. This model is intended to lie at the core of a dynamic national energy model to trace and analyze regional and temporal adjustments to wealth accrual, natural resource rents, production labour requirements and economic growth potential associated with different energy resource development scenarios. Model construction has been tempered by the goals motivating study of the Canadian energy system. Hence, for example, the representation of energy resource processing has been minimized and emphasis placed upon measuring production labour requirements associated with resource production and quantifying economic rents through dual shadow prices. Although the objective has been to model competitive market behaviour for energy supply, the model can readily be used as a planning tool for assessing different strategies shaping energy resource development, both at the national and regional levels.

Model solutions displayed above exhibit a part of the detail generated by model use, notably the provincial aggregates of net values added, resource production, labour requirements and certain of the dual shadow prices. In its present form the model can only be used to address such supply-oriented questions as the short term consequences to provincial wealth accrual and economic rents of price adjustments in international markets, the impact of increased or reduced restrictions on energy product supply or transportation, the implications of technical developments in product supply or co-product yields, or the outcome of government attempts to promote economic development of specific provincial energy industries. Several questions of this sort have been examined in Rowse [5, Ch. 3] .

*ACKNOWLEDGEMENTS

Without implicating him, I would like to express my deep appreciation to Dr. Lawrence W. Copithorne of the Economic Council of Canada for many helpful suggestions relating to conceptual and practical problems of the modelling approach described here and for helpful comments on a preliminary draft of this paper. I am also grateful to Bill Ziemba for very helpful editorial assistance. This paper is a highly condensed version of [5], and is forthcoming in:

W.T. Ziemba, S.L. Schwartz and E. Koenigsberg, Energy Policy Modeling: United States and Canadian Experiences, Volume 1 - Specialized Energy Policy Models, Martinus Nijhoff, Boston, 1980.

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