

Background, Context and Reaction to
Studies in the Economics of Transportation

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Overview

- Origins and Publication of:
Studies in the Economics of Transportation
- Earlier, Concurrent and Subsequent Research
- Forecasting Urban Travel for Planning and Policy Making
- Summary and Lessons Learned

Origins and Publication

- Contributions of Beckmann, McGuire and Winsten (BMW)
- Publication History
- Book Reviews

Contributions of BMW



Project initiation	1951
Working Papers	1952
Discussion Paper	1953
Completed equilibrium and efficiency formulations	1954
Publication of <i>SET</i> by Rand	1955
Publication of <i>SET</i> by Yale University Press	1956
Publication of <i>SET</i> in Spanish	1959
Beckmann, paper <i>Traffic Quarterly</i>	1967
Recognition at Montréal Symposium	1974

Contributions of BMW

- Discussion Paper Rand-P-437, 1953, remarkable for its insights regarding urban transportation systems; submitted to *Traffic Quarterly* and rejected.
- Formulation and analysis of an optimization problem relating variable O-D flows to user-equilibrium route flows over a network, 1951-1954. One starting point was Knight (1924); another was Kuhn and Tucker (1951).
- Formulation and analysis of a related problem with system-optimal route flows based on marginal costs; applied to the study of road pricing.
- Publication of *Studies in the Economics of Transportation (SET)* as Rand-RM 1488, May 1955.
- Publication of *SET* by Yale and Oxford University Presses in 1956, followed by a Spanish version in 1959.

- M. J. Beckmann, On Optimal Tolls for Highways, Tunnels and Bridges, *Vehicular Traffic Science, Proceedings of the Third International Symposium, 1965*, Herman et al., eds., Elsevier, 1967; cited Johnson, Walters and Wardrop, as well as BMW.
- M. J. Beckmann, On the Theory of Traffic Flow in Networks, *Traffic Quarterly*, **21** (1967); a synopsis of the main results of *Part I* of *SET*, and a review of related developments, including Wardrop, Prager, Almond, Charnes-Cooper, and Walters.
- Recognition of the contributions of BMW at the International Symposium on Traffic Equilibrium Methods held at the Université de Montréal, November, 1974 (Florian, *Traffic Equilibrium Methods*, Springer, 1976).

Publication History of *SET*

- Rand Corporation issued *SET* in 1955 as RM-1488-PR; it has recently been listed as a *Rand Classic*; the 359 page monograph can be downloaded at no charge at: <http://www.rand.org/publications/RM/RM1488.pdf>
- Yale University Press made three printings of *SET*, 1956-1959; the number of copies is unknown; the price was \$4. The book will soon be listed on the Cowles Foundation website <http://cowles.econ.yale.edu/>.
- Aguilar, Madrid, published *Economía del Transporte*, 1959.
- *SET* was offered by University Microfilms in the 1960s, and can be purchased for \$79.40 (print) or \$39.70 (microfilm).
- *WorldCat List of Records* shows 356 libraries currently hold the Yale University Press edition of *SET*, 13 libraries hold the Rand edition, and six libraries hold the Spanish edition.

Summary of Book Reviews

- *Operational Research Quarterly*, 7 (1956), by D. J. R.
- *American Economic Review*, 46 (1956): book notice only.
- *Wall Street Journal*, January 2, 1957, p. 8, column 6: “.. this is a ‘heavy’ theoretical work by a group of economists searching for the optimum efficiency of highway systems.”
- *The Economic Journal*, 67 (1957) by R. J. Smeed
- *Quarterly J. of Applied Math.*, 14 (1957) by W. Prager
- *Econometrica*, 26 (1958) by R. M. Thrall
- *KYKLOS*, 11 (1958) by C. Ponsard
- *Operations Research* 7 (1959) by G. D. Camp
- *Journal of Political Economy*, 67 (1959) by E. Mansfield
- Among nine reviews published, no reviewer identified the significance of the formulation achieved in *Part I*, and none linked BMW’s formulation to the need to forecast travel for urban transportation planning.

Details of Book Reviews

- *Operational Research Quarterly*, 7 (1956), by D. J. R.:
“..probably the most important contribution, Ch. 4 discusses efficiency and considers how far the individual road user, left to his own free decision, will make the most efficient use of a given road network. .. if any criticism can be made, it is that the work on highway economics is too ambitious. The authors make few simplifying assumptions ... and they find it difficult to produce conclusions.”
- *American Economic Review*, 46 (1956): a notice, no review.
- *Wall Street Journal*, January 2, 1957, p. 8, column 6:
“Sponsored by the Cowles Commission, this is a ‘heavy’ theoretical work by a group of economists searching for the optimum efficiency of railroad and highway systems. In the chapters on highways, the authors analyze intersection and road capacity, stop-sign and traffic light delays, tolls, and the costs and demands for highway use.”

- *The Economic Journal*, **67** (1957) by R. J. Smeed: .. “the selection by drivers of routes that minimize their own individual costs does not result in the division of traffic between alternative routes which minimizes the total costs incurred by road users. .. it is refreshing to read a book that attempts to tackle the subject of road transport in a comprehensive and fundamental way.” (Smeed’s review is by far the longest and most thoughtful.)
- *Quarterly Journal of Applied Mathematics*, **14** (1957) by W. Prager: “This reviewer found the book extremely stimulating; his only complaint is that the analysis is almost exclusively concerned with static situations.”
- *Econometrica*, **26** (1958) by R. M. Thrall: “useful as an example of ‘operations research;’ good illustrative material; welcome addition to the literature.”

- *KYKLOS*, 11 (1958) by C. Ponsard, who was an eminent French spatial economist: “A model of the whole ensemble appears premature to the authors. .. the *Studies* expose diverse ramifications in a stream of thought which has been linear up to now. The enrichment of knowledge in this domain is at this price.”
- *Operations Research* 7 (1959) by G. D. Camp: *Part I* “furnishes a clear picture of a highway system as a servo-mechanism with complex feedback interactions among its parts, activated by the behavior of many drivers. Strong on concept and theory but very weak on data, ... because they are not available. .. a must in the library of any operations researcher interested in highway transportation.”
- *Journal of Political Economy*, 67 (1959) by E. Mansfield: “the concept of demand is introduced, the existence and stability of an equilibrium in the system are discussed, and efficiency conditions are determined (using the Kuhn-Tucker theorem). Highly recommended for economists interested in the analysis of transportation systems.”

- *Journal of Business*, 32 (1959) by S. P. Sobotka: “The analysis of the difference between private and social costs is particularly valuable, but .. lack of concern with long-run problems tends to make the resulting conclusions rather empty.”
- Altogether, nine reviews were published; none of the reviewers identified the significance of the formulation achieved in *Part I*. Moreover, none linked BMW’s formulation to the emerging need to forecast travel for planning urban transportation systems.
- Bart McGuire to his co-authors on Mar. 18, year unknown:
“Here are copies of the reviews of our Chicago book. I think they’re pretty entertaining, don’t you?”

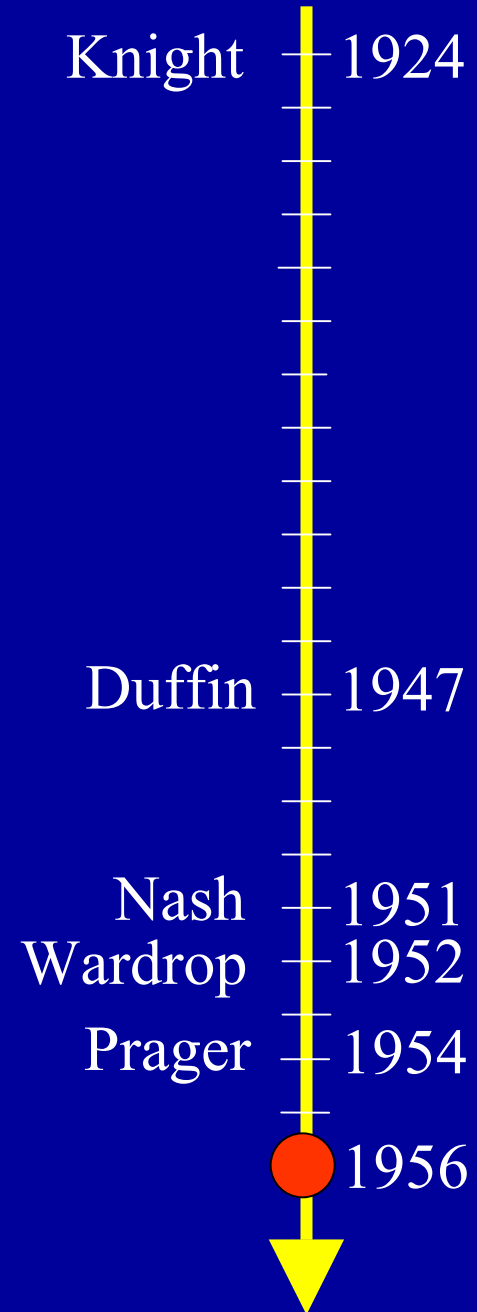
Earlier, Concurrent and Subsequent Research

- Traffic Assignment Problem (TAP) Preceding and Concurrent with BMW
- TAP with Fixed OD Flows Independent of BMW
- TAP with Fixed OD Flows Partially Based on BMW
- TAP with Variable OD Flows Following and Based on BMW

Traffic Assignment Problem

Preceding and Concurrent

with BMW



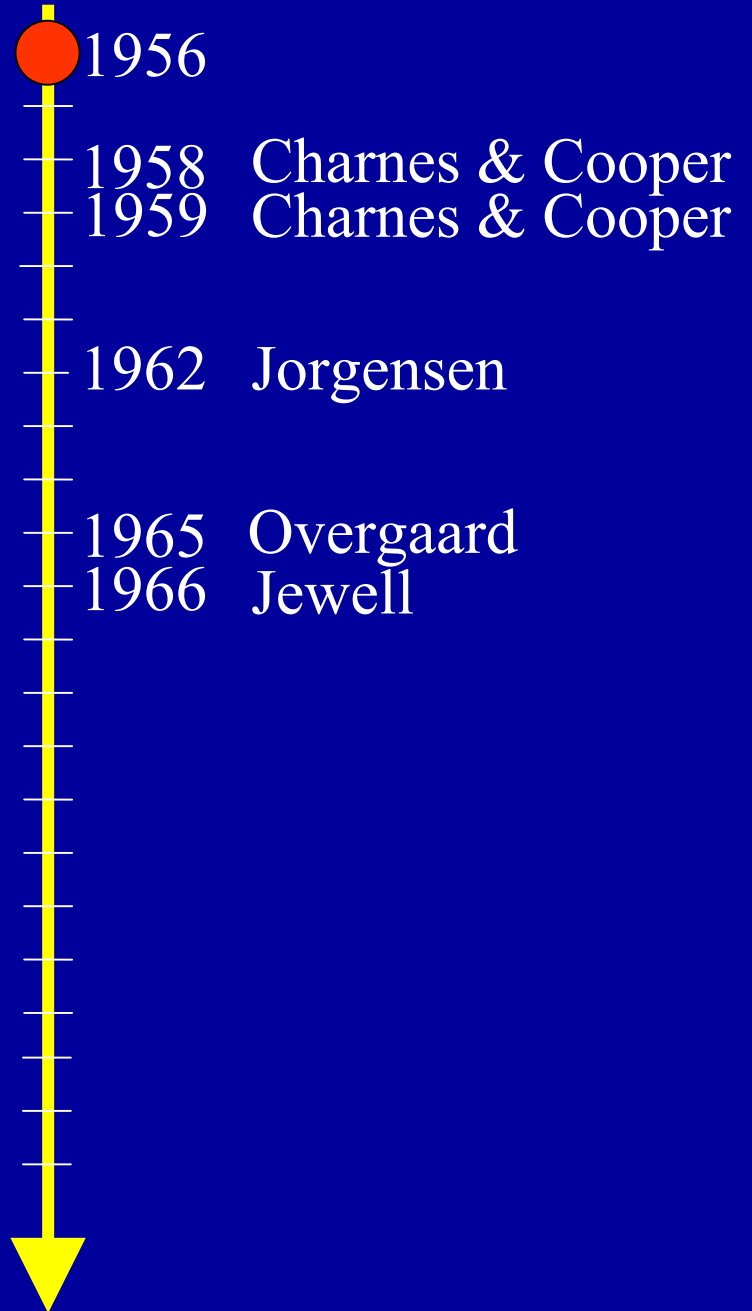
Traffic Assignment Problem

Preceding and Concurrent with BMW

- F. H. Knight, *Quarterly Journal of Economics* 38 (1924); cited by BMW.
- R. J. Duffin, Nonlinear Networks II, *Bulletin AMS* 53 (1947) formulated a related problem for electrical networks; not cited by BMW; Duffin was one of the creators of geometric programming, among his many accomplishments.
- J. Nash, Non-cooperative Games, *Annals of Mathematics* 54 (1951); not cited by BMW.
- J. G. Wardrop, *Proceedings ICE* (1952); cited by BMW, but not for his principles of route choice.
- W. Prager, Problems of Traffic and Transportation, *Proceedings of Symposium on OR ...* (1954); informal discussion of user-equilibrium problem; cited Wardrop.

Traffic Assignment Problem

Independent of BMW



TAP with Fixed OD Flows

Independent of BMW

- A. Charnes and W. Cooper, Extremal Principles for Simulating Traffic Flow in a Network, *Proceedings of the N.A.S.* (1958); cited Duffin, Nash, Prager and Wardrop, but not BMW; clear understanding of assignment from a practitioners' point of view.
- A. Charnes and W. Cooper, Multicopy Traffic Network Models, *Theory of Traffic Flow, Proceedings of the First Symposium, 1959*, R. Herman, ed., Elsevier, 1961. Clear statement of principles of user-equilibrium and formulation of the problem; a toy problem with 11 OD pairs, 22 nodes and 54 links was solved using piecewise linearization. Cited Duffin, Nash, Prager and Wardrop, as well as their own 1958 paper, but not BMW.

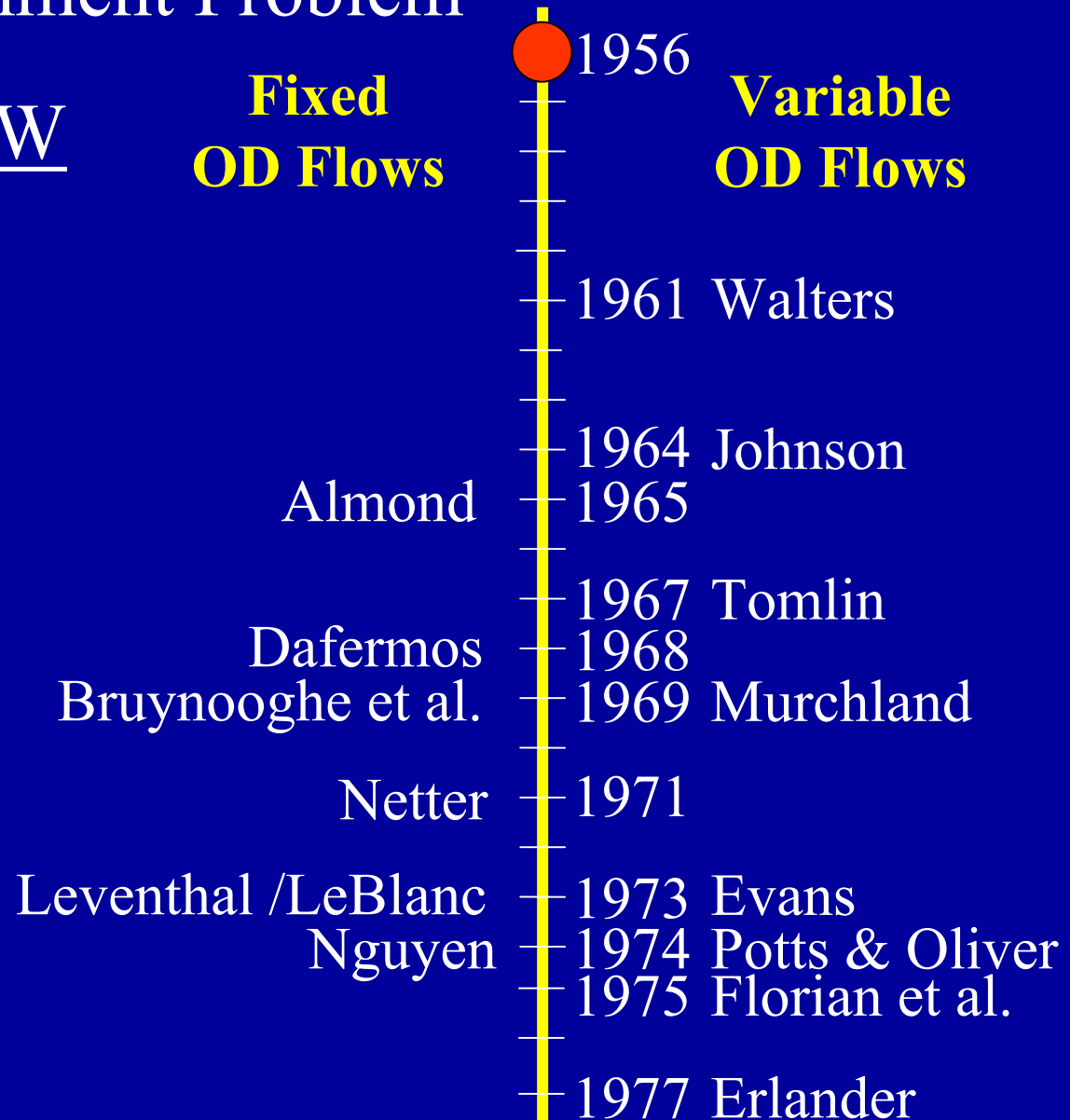
- N. O. Jorgensen, *Some Aspects of the Urban Traffic Assignment Problem*, M.S. thesis, U.C. Berkeley (1962); independent formulation and analysis of TAP. Cited Wardrop, and Charnes-Cooper, 1961, but not BMW.
- K. R. Overgaard, *Testing a Traffic Assignment Algorithm*, *Vehicular Traffic Science, Third Symposium, 1965*, Herman et al., eds., Elsevier, 1967; presented a formulation of TAP based on Jorgensen and a heuristic method of assigning traffic. Smock's heuristic method seems to be the basis of the study. Cited Irwin-von Cube, Jorgensen, Smock and Wardrop.
- W. S. Jewell, *Models for Traffic Assignment*, SEMA, Paris (1966), TR 1 (1967); formulated UE problem for a single OD pair and network; did not cite BMW or Jorgensen.

Traffic Assignment Problem

Based on BMW

**Fixed
OD Flows**

**Variable
OD Flows**



TAP with Fixed OD Flows

Partially Based on BMW

- J. Almond, Traffic Assignment with Flow-Dependent Travel Times, *Vehicular Traffic Science, Proceedings of the Third Symposium, 1965*, Herman et al., eds., Elsevier, 1967; described solution methods for TAP, but did not give a formulation. Cited Wardrop and BMW.
- S. Dafermos, *Traffic Assignment and Resource Allocation in Transportation Networks*, Ph.D. thesis (1968) and paper with F. T. Sparrow, *J. of Research, NBS* (1969); cited BMW, Jorgensen, Almond, Beckmann (1967); starting point appears to be Jorgensen's thesis.
- M. Bruynooghe, A. Gibert and M. Sakarovitch (BGS), A Traffic Assignment Method (in French), *Beiträge zur Theorie des Verkehrsflusses* (1969); clear statement of optimality conditions, but no objective function; described two algorithms; cited Jorgensen, Jewell and BMW.

- M. Netter, Traffic Assignment and Social Marginal Cost Pricing, *ISTTT* (1971) and TR 6 (1972); properties of user-equilibrium and system-optimal solutions; cited Wardrop, BMW, BGS, Dafermos, etc.
- T. Leventhal, G. Nemhauser and L. Trotter, Jr., A Column Generation Method for TAP, TS 7 (1973); extended Dafermos's algorithm so that generation of all routes is not required; cited three papers by Dafermos, but not BMW.
- L. J. LeBlanc, Approach to Equilibrium Traffic Assignment, part of Ph.D. thesis (1973); TR 9 (1975); formulated TAP and proposed algorithm based on Frank-Wolfe (1956); cited BMW, Charnes-Cooper, Dafermos, Jorgensen and Wardrop.
- S. Nguyen, *Unified Approach to Equilibrium Methods for Traffic Assignment*, Ph.D. thesis, 1974; TS 8 (1974); Traffic Equilibrium Symposium, 1974 (1976); stated and tested three algorithms for solving TAP; cited BMW, BGS, Dafermos, Jewell, Jorgensen, etc.

TAP with Variable OD Flows

Following and Based on BMW

- A. A. Walters, Theory and Measurement of Private and Social Cost of Highway Congestion, *Econometrica* **29** (1961); analysis of a single route and OD pair, deferring to BMW for network model; cited Knight, but not Wardrop.
- M. B. Johnson, Economics of Road Congestion, *Econometrica*, **32** (1964); explored a simple model of road congestion for one link; cited BMW and Walters.
- J. A. Tomlin, *Math. Programming Models for Traffic Network Problems*, Ph.D. thesis, 1967, TS **5** (1971); formulated a combined trip distribution and assignment model with fixed link costs and capacities; proposed an algorithm based on Dantzig-Wolfe decomposition; cited Charnes-Cooper, Jorgensen, Wardrop, but not BMW.

- J. D. Murchland, Road Network Traffic Distribution in Equilibrium, presented at Math. Methods in the Economic Sciences, 1969; first variable demand formulation after BMW, including a proposed solution algorithm; cited Beckmann's early papers, BGS, Prager and Wardrop.
- S. P. Evans, *Some Applications of Mathematical Optimization Theory in Transport Planning*, Ph.D. thesis (1973), TR 10 (1976); formulated a model combining trip distribution and assignment, proposed a partial linearization solution algorithm and proved convergence; cited BMW, BGS, Florian, Jorgensen, Murchland, Tomlin, Wardrop, etc.
- R. B. Potts and R. M. Oliver, *Flows in Transportation Networks*, Academic; considered the traffic assignment problem, but did not give a formulation, and then described a combined model for system-optimal route flows; cited BMW, Beckmann (1967) and Tomlin.

- M. Florian and S. Nguyen, Computing Network Equilibrium with Elastic Demands, TS 8 (1974); proposed an algorithm for solving the model of BMW based on Benders decomposition; cited BMW, Murchland, Dafermos.
- M. Florian, S. Nguyen and J. Ferland, Combined Distribution-Assignment of Traffic, TS 9 (1975); applied Benders decomposition to the same problem with a doubly-constrained trip distribution model and user-equilibrium assignment; cited BGS, Dafermos, Evans's thesis, Murchland, Potts-Oliver, but not BMW.
- S. Erlander, Accessibility, Entropy and the Distribution and Assignment of Traffic, TR 11 (1977); new interpretation of the entropy function in the combined model formulation; cited Florian et al., Potts-Oliver, and Tomlin.

Efforts to Forecast Urban Travel for Planning and Policy Making

- Urban Transportation Studies Concurrent with Publication of *SET*
- Early Practitioner Efforts to Solve TAP
- Status of the Travel Forecasting Field Today

Urban Transportation Studies

Concurrent with Publication of *SET*

- The first urban transportation study took place in Detroit under the direction of J. Douglas Carroll, Jr.; initially, an origin-destination desire line analysis was performed with no network analysis.
- The first urban transportation study using models of origin-destination and route flows (trip distribution and traffic assignment) was in Chicago, 1955-1962, also led by Carroll. The Chicago Area Transportation Study (CATS) innovated with respect to the formulation and application of an intervening opportunities model and the use of a tree-based algorithm to assign OD flows to shortest routes through the road network.

- Carroll and his associates also initiated the concept of the sequential travel forecasting procedure; as stated in an abstract for the January 1957 Highway Research Board Meeting: “a continuous, integrated analysis and planning process consists of three major parts, each a considerable advance in itself:

- Estimating traffic generation from land use;
- Predicting future lines of travel desire;
- Predicting flows on a transportation network.”

Although mode choice is not included, testing of a mass transit facility is described.

- Carroll was proactive in searching for research innovations that could strengthen the computer-based analysis he envisaged, which led to the identification and application of shortest route methods. Evidently, he was not aware of *SET*; moreover, it appears he and his associates did not grasp the significance of Charnes’s formulation of TAP.

- Irwin and von Cube, Capacity Restraint in Multi-Travel Mode Assignment Programs, *Trip Characteristics and Traffic Assignment, Bulletin 347*, Highway Research Board, 1962; described a sequential procedure including assignment to links whose costs increase with flow, and a “feedback procedure repeated until equilibrium is reached.” Cited BMW.
- The Bureau of Public Roads likewise adopted the sequential approach in its consideration and dissemination of travel forecasting procedures following the Highway Act of 1962, which required preparation of transportation plans to qualify for federal aid for road construction.

Early Practitioner Efforts to Solve TAP

- Early analyses of the impact of major road improvements applied an empirical diversion curve approach, which sought to reallocate traffic on the basis of time savings.
- As larger computers and shortest route methods became available in the U.S. in the late 1950s, solving the Traffic Assignment Problem was viewed as a procedure for “loading” origin-destination flows onto shortest routes of the road network
- Wardrop’s principles of route choice were unknown to practitioners in the U.S. Likewise, the route choice formulations of Beckmann, Prager, and Charnes-Cooper were generally unknown to practitioners.

- Iterative, heuristic schemes known as capacity-restrained assignment to solve TAP were proposed and compared; as no measure of convergence was available, and mathematical formulations were not recognized as pertinent, the results were crude and difficult to interpret. An example is given by Smock (1963).
- Formulations and convergent solution algorithms were introduced to practitioners during the 1970s by Florian, Dial, and Eash-Janson-Boyce; these methods were superior and quickly became the state of practice, although few iterations were performed initially.
- Ironically, the method that provided the basis for these convergent algorithms was published by Frank and Wolfe in 1956, the same year as the publication of *SET*.

Status of the Urban Travel Forecasting Field Today

- From its beginnings in the 1950s, the sequential procedure became the dominant paradigm for travel forecasting throughout the world; it is widely accepted in nearly all academic textbooks and practitioner-oriented papers and manuals.
- Some 40 years after its emergence, calls for solving the sequential procedure with “feedback,” to reduce the inconsistencies between travel costs, on which origin-destination-mode flows are based, and user-equilibrium route costs resulting from assignment of those flows, began to be expressed in court cases and legislation. Practitioners were ill-prepared to respond, still being unaware of the formulation of the model originally proposed by BMW.

- From 1975 onwards, researchers have studied and implemented models based on the formulation of BMW and the solution algorithm of Evans. Among these are: Boyce and his students; de Cea and Fernandez; Horowitz; LeBlanc and his students; Lam and Huang; Lundqvist; Magnanti and his students; Nagurney and her students; Oppenheim, Powell and Sheffi. Patriksson (1994) synthesized the extensive literature on the topic and the mathematical basis for formulations and solution algorithms.
- Bar-Gera (1999) devised an Origin-Based Assignment algorithm to solve TAP to fine convergence for large networks with reasonable computing effort; he has since combined OBA with two O-D-mode flow models.
- ESTRAUS, a newer software system, solves directly combined models of O-D, mode and route choice on congested road and transit networks; other systems (EMME/2, TransCAD, VISUM) can be programmed to solve combined models, but with considerable effort.

- ? Travel forecasting practice is slowly moving from 50 years of empirically-based models and rough heuristics implemented on early computers, using integer arithmetic and lacking in rigorous solution criteria, to well-formulated models and efficient solution algorithms able to achieve precise answers that are required for comparing planning and policy alternatives.
- ? The transition is painful for all concerned, but also exciting for those who have devoted their careers to this relatively esoteric pursuit. Continued progress will require much patience and effort.

Summary and Lessons Learned

- A brilliant theoretical formulation of urban travel models was achieved in the early 1950s; its significance was not fully appreciated even by its authors, and not understood by others for nearly 20 years.
- Related and partial formulations were proposed by several others during the same period, but poor scientific communication restricted their assimilation. In particular, until 1967 there were no scientific journals directly serving this field of research.
- Transportation planners, unaware of these developments, sought to make travel forecasts by empirical and heuristic methods, sometimes with striking similarities to convergent solution methods proposed somewhat later.

- Solution algorithms, model implementation, parameter estimation, validation and useful software systems have slowly emerged, providing a more rigorous basis for solution of practical planning problems.
- This story illustrates the chaotic path that scientific research often follows in the evolution of a field. Interdisciplinary in nature, this field has probably experienced more chaos than others. Hopefully, as the field matures during the next 50 years, through the publication of reviews, textbooks, and improved software and training for practitioners, the promise of young, insightful researchers and visionary practitioners during the first 50 years will finally be realized.