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An integrated, dynamic approach to travel demand forecasting

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Abstract. This paper presents a unified approach for improving travel demand models through the application and extension of supernetwork models of multi-dimensional travel choices. Proposed quite some time ago, supernetwork models solved to stochastic user equilibrium can provide a simultaneous solution to trip generation, distribution, mode choice, and assignment that is consistent with disaggregate models and predicts their aggregate effects. The extension to incorporate the time dimension through the use of dynamic equilibrium assignment methods is proposed as an enhancement that is necessary in order to produce realistic models. A variety of theoretical and practical problems are identified whose solution underlies implementation of this approach. Recommended future research includes improved algorithms for stochastic and dynamic equilibrium assignment, new methods for calibrating assignment models, and the use of Geographic Information Systems (GIS) technology for data and model management.

I. Introduction

During the past two decades, it has become increasingly apparent that it is necessary to reformulate the travel demand forecasting process in order to meet the needs of transportation planners and managers in a more effective fashion. The problems to be addressed with travel demand models have certainly not diminished in scale, importance, or complexity. In fact, there is far stronger motivation now than ever before to pursue demand models for guiding traffic management, environmental control purposes, and to support Intelligent Vehicle Highway Systems (IVHS) development and implementation. Apart from the need for greater model accuracy and specificity, there is a pressing need to address gross inconsistencies among the modeling components that are utilized in prevalent forecasting approaches.

This paper, a version of which was originally prepared as a report to the U.S. Federal Highway Administration (FHWA), describes a conceptual approach and research effort that will generate both short term and long term improvements in travel demand modeling. The approach builds upon research performed during the last twenty years, but which has seen little application.

It represents a continuation of the paradigm shift toward disaggregate modeling, yet addresses significant deficiencies in existing aggregate and disaggregate methodologies. Limited empirical testing has already demonstrated the possibility of bringing about improved models through this approach.

The proposed approach is based upon the work of (Sheffi & Daganzo 1978, 1980), but represents an extension and synthesis of several threads of travel demand research. In summary, the approach makes use of the basic concepts of disaggregate choice models and stochastic user equilibrium on supernetworks extended in the form of dynamic, multi-period models of travel choices.

The organization of this paper is as follows. The paper begins with a summary of recent developments in travel demand research and the basis they provide for this approach to modeling. In this discussion, and elsewhere in the paper, mathematical details are purposely avoided in the hopes of making the discussion broadly accessible.

Section III presents a unified approach to a reformulation of the travel demand modeling process. This approach can be implemented in concert with other attempts to reformulate models such as the activity approach or detailed simulation models, but focuses on the achievement of a mathematically consistent forecasting approach that addresses the core problems of interrelated travel choices and the aggregate traffic effects of individual travel behavior that any new approach must conquer. This is followed in Section IV by a description of research required to resolve outstanding difficulties with the approach and to render it suitable for implementation in a broad array of settings. The paper concludes with some additional remarks concerning the relationship of the proposed research to other endeavors and to the ongoing needs of planners.

II. Literature review

The following review focuses on needed improvements in travel demand modeling and centers on the problems and prospects for disaggregate models. The review begins with some historical background on travel demand modeling. This includes a summary of the reasons why aggregate models have failed as demand forecasting tools and an assessment of the contribution of disaggregate demand models during the past two decades. The second section discusses the literature on traffic assignment models. The third part of the review focuses on extensions of traffic assignment methods for modeling joint travel choices.

Travel demand research overview

In the past, travel demand models were constructed for the purpose of evaluating major capital projects. The earliest major urban transportation studies focused on highway improvements. In the landmark studies in Detroit, Chicago, and elsewhere in the immediate post-war period, the first systematic methods were introduced for demand forecasting. The innovations of the Fifties rapidly became the dogma of the Sixties. Advances in computers made it possible to systematize planning models, to promulgate modeling software for analyzing major highway and transit projects, and to require that models be applied in order to gain funding. Through PLANPAC and UTPS (Mainframe Computer Software) a generation of planners were schooled in what is often called the conventional, four-step method for predicting the demand for large scale transportation improvements.

The four-step method decomposes the demand prediction problem in order to deal with its multi-dimensional character. In making travel choices, travelers decide whether or not to travel (trip frequency or generation), where to travel (destination choice), what mode or combination of modes to utilize (mode choice), and the route to be utilized for the chosen mode (route choice or trip assignment). From a theoretical point of view, the decomposition of choices was never appealing. Rather, it was a way to simplify the models for estimation and forecasting.

Some dimensions of travel behavior such as trip timing or trip chaining were totally ignored. Also, related phenomena, such as choice of residential location and auto ownership, were not treated, leading to biased predictions (Lerman 1975).

The earliest models were aggregate in nature and were estimated at the zonal level. Within the aggregate framework, some of the simplifications of the four-step model were disguised as there was no clear theory to explain aggregate travel behavior. The use of econometric methods for model estimation was nevertheless introduced, although inconsistently and incompletely. Numerous ad hoc calibration methods were introduced by practitioners when model predictions failed to replicate base case measurements.

As the era of rampant highway building came to an end, predicting the demand for transit became both an intellectual challenge and a priority for modelers. As a result, the mode choice problem became the focus of intense scrutiny.

By the mid 1970s, disaggregate models were being aggressively pursued by researchers as a conceptually appealing framework with which to explain mode choice behavior. Couched in terms of utility maximization, travel demand modeling found a home in economic theory and both stimulated and inherited econometric estimation tools for discrete choice models (McFadden 1977).

The approach was sufficiently appealing that research continued on its application to modeling other travel choices. These efforts established the role of behavioral and attitudinal factors in influencing travel behavior (Spear 1976) and migrated the research community further from a purely engineering view of demand modeling.

By the middle of the Seventies, a full-fledged and damaging critique of the aggregate four-step demand model was completely internalized by the research community (Mannheim 1979), but largely unappreciated by most consultants and planners. Among the advantages cited for the disaggregate approach were its behavioral base, improved model specification, more efficient use of data, and parameter estimates which are free of the distributions of explanatory variables.

In order to carry the disaggregate revolution forward, research tackled an array of practical matters. These topics included joint choice models, alternative functional forms, model aggregation and prediction (Koppelman 1976), and estimation under alternative sampling strategies (Lerman & Manski 1979).

As today, the multinomial logit model was the basis for most disaggregate models. A key criticism of logit choice models was the property of independence from irrelevant alternatives (IIA). Because of the independence assumed among alternatives, logit models produce inappropriate results when alternatives are similar. This property and criticism applies to aggregate mode choice, gravity, and assignment models as well, but was seen with greater clarity in disaggregate logit choice models.

When IIA was fully diagnosed, various alternative choice models were investigated including probit models (Daganzo et al. 1977; Albright et al. 1977; Sparmann & Daganzo 1982). Although the subject of concerted research, probit models remain more of a research topic than a popular alternative today, due to the computational burden of parameter estimation.

Nested logit models were established as a practical means of treating choice among alternatives with correlated attributes. Efficient estimation methods for nested logit followed (Brownstone & Small 1985; Daly 1987) although they are not in widespread use.

Not all the problems with disaggregate models were solved (Daly 1979). Choice models did not really explain tripmaking, rather they focused on the alternatives that would be selected for trips that were made. Taste variation and habit influence behavior, but present conceptual and empirical difficulties.

Trip chaining (Adler 1976) was particularly vexing from a theoretical perspective and overly cumbersome to model. Nevertheless, various new model formulations were proposed and implemented (Adler & Ben Akiva 1975; Lerman 1979; Horowitz 1980; Goulias & Kitamura 1989). Slavin formulated a model for urban truck trips that incorporated the trip chains that are characteristic of urban goods movement (Slavin 1979).

The various choices associated with tripmaking take place at different time scales and involve different considerations. Residential choice behavior is intertwined with car ownership and the choice of mode for the journey to work (Lerman 1975). Estimation of a subset, perhaps an arbitrary subset, of equations from a simultaneous system is hard to justify on econometric grounds, leaving difficulties which may be insurmountable.

Since the demand for travel is derivative of the demand for activities, it became logical to investigate activity patterns for insights and methodological alternatives as well as model enhancement strategies. This research has tended to focus on issues as intrahousehold demand relationships, choice set formulations and constraints, and activity duration and scheduling models (Jacobson 1979; Damm & Lerman 1981). Activity models utilized a variety of simulation and econometric estimation methods, but were not successfully operationalized for forecasting. Gaming and experimentation also were pursued as possible forecasting methods (Jones 1977). Activity analysis also implicated conventional travel survey techniques as underestimating tripmaking and has stimulated use of travel diary survey methods. More recently, activity models have been estimated from survey data indicating opportunities for refined trip frequency and destination choice models. In the activity perspective, travel choices such as mode choice may be predetermined for many trips and therefore not a choice at all. Longitudinal panel data analysis is clearly needed to understand habit and changes in travel choices.

From the perspective of transportation planning practice, revealed preference models of the logit form estimated from survey data recording individuals' actual travel choices migrated from research projects into alternatives analysis. However, the problem of predicting demand for a new transit mode raised issues that challenged the logic and practicality of revealed preference modeling.

In particular, the problem of predicting demand for a totally new service could not be treated effectively when it had features that did not previously exist in the market place. This is a problem that arises commonly in market research on new products and has stimulated the development of conjoint analysis and other forms of stated preference models. In these approaches, respondents to surveys are asked to make tradeoffs among hypothetical alternatives that are constructed for model building. This type of analysis has been shown to be reliable and to reduce the deficiencies of relying solely on reported behavioral intentions, which tend to overstate the demand for new services (Couture & Dooley 1981).

Louviere provides a comprehensive overview of conjoint analysis of stated preference data (Louviere 1988). Stated preference models have been utilized in numerous planning studies and with good results. In particular, this methodology makes it possible to identify the coefficients of new mode demand models and may also give more accurate predictions than revealed preference models when both are feasible. Hybrid models combining revealed preference and stated preference data can also be attractive.

Disaggregate demand modeling has matured to the point where it is an established and accepted method in econometrics (Maddala 1983). The application of choice models to travel demand has been codified in textbooks (Ben Akiva & Lerman 1985) and in thousands of research papers. The fact that such methods remain underutilized and often incorrectly applied in transportation forecasting is unfortunate and ironic in light of the origins of these methods in transportation research.

Practitioners have failed to appreciate these advances in the state-of-the-art, and it is worth noting that barriers to implementation still exist. The econometric underpinnings of disaggregate models are complex, and as (Daly 1979) has noted, they are used by only those planners with advanced modeling skills.

It would also seem that the state of practice of travel demand modeling was limited substantially by the fact that most planning software was suited only for aggregate models. While some packages (e.g. mainframe UTPS, EMME/2, and TransCAD) permit user modifications and provide toolbox support for alternative methods, this can require more effort than following the conventional approach dictated by some software packages. Surprisingly, or perhaps not, some Metropolitan Planning Organizations (MPOs) use sketch planning (i.e. quick response) techniques in place of empirically estimated models based on travel behavior data measured in their region.

Traffic assignment models

In the traditional aggregate approach to modeling, traffic assignment may not be viewed as strictly a demand model. Rather, traffic assignment is the process by which transportation supply and demand are equilibrated. In the aggregate formulation, traffic assignment is the last stage of the model in which pre-determined modal origin-destination flows are assigned to links in the respective modal networks. The fact that traffic assignment models traveler route choice is obscured in the aggregate paradigm.

Various methods have been devised for assigning trips to network links, but have significant limitations. See Sheffi for a comprehensive review (Sheffi 1985). In the simplest method, all flow is assigned to the shortest path between the origin zone and the destination zone. This method is clearly inadequate because there are invariably numerous alternative paths that are utilized for travel between a single origin and a single destination.

While the need for realistic multipath assignment methods was recognized a long time ago, the problem has proven to be extremely challenging for several reasons. The first reason is that the level of service that influences route assignment is dependent upon the volume of flow assigned. The second reason is that the number of paths that are used in realistic networks is so large as to preclude their enumeration. Third, the problem involves prediction of human behavior. Moreover, the factors that influence travelers' choice of route are multiple in nature, of varying importance, subject to missing or imperfect information, and not directly observable or measurable. Furthermore, there are other complex factors influencing level-of-service such as capacity limitations, intersections, traffic signals and queues that make it difficult to predict link or path level-of-service conditions even at specified volume levels. Volumes, of course, are not fixed and presumably vary with network performance as well as with other demand determinants. Lastly, many different groups of users and vehicles make contemporaneous use of network links with non-neglible interactions.

In an *equilibrium* assignment there is consistency between the level-of-service used in assigning flow and the level-of-service that results from the assignment. Apart from any theoretical niceties, this would appear to be a bare minimum requirement for any traffic assignment model.

Early attempts to achieve equilibration through mere iteration in assignment proved to be overly optimistic. For example, neither the widely utilized capacity restraint or incremental assignment methods are assured to result in an equilibrium solution (Sheffi 1985). Mathematical programming methods were invoked to develop models for which the existence of equilibrium solutions could be established and for which convergent solution methods could be implemented.

The most commonly encountered equilibrium traffic assignment model is referred to as the *User Equilibrium* (UE) model. At user equilibrium, no traveler can unilaterally choose a different path from his origin to his destination without increasing the cost of his trip. A characteristic of the UE solution is that the costs of all used paths for an O-D pair are equal and are no greater than the costs of any unused paths. This is the Wardrop principle that has dominated conceptual approaches to traffic assignment.

In the UE world, travelers are assumed to treat route choice deterministically and identically. Daganzo and Sheffi noted extreme sensitivity of UE flow patterns to small changes in uncongested networks (Daganzo & Sheffi 1977). In a related result Caliper (1987) found that UE predictions systematically assign flow to too few links.

Daganzo & Sheffi (1977) proposed an alternative and more realistic equilibrium formulation known as *stochastic user equilibrium* or SUE. SUE produces assignments in which alternative paths receive flow levels that are a function of their relative generalized costs. As a result, less attractive routes are utilized, but less heavily utilized than more attractive paths. Under SUE, no user believes that he or she can increase his/her expected utility by choosing an alternative path. Because of variations in perceptions among travelers or variations in the level-of-service experienced, utilized paths are not required to have equivalent generalized costs.

Sheffi & Powell (1982) provided a comprehensive formulation of the equilibrium assignment with random link times, a solution method, and some algorithmic guidance for computing SUE. The method avoids the need for path enumeration, which is impractical in realistic size networks. The solution method is referred to as the method of successive averages (MSA) and is not hard to implement.

SUE should not be confused with the stochastic loading assignment method found in some UTPS-type packages in which the link costs are not flow dependent and equilibrium is not achieved. SUE is also different from the STOCH algorithm, which is a logit route choice model in which flow is assigned to a subset of the paths that connect an origin and a destination.

There has been limited practical experience with SUE. However, in several cases, it has proven to provide better results than other methods (Caliper 1987; 1991). While it has been argued that SUE should dominate other methods for highway assignment, these implementations were for transit. After SUE was made available in the TransCAD package (Caliper 1990), SUE has been utilized more broadly for both road networks and transit.

There are numerous other issues associated with generating realistic traffic assignments. These include incorporation of multiple criteria (Dial 1994), interactions among vehicles of different types that share the road network (Daganzo 1983) and treatment of other modes such as assignment methods for transit and for trucks (Speiss & Florian 1989; Mahamassani & Mouskos 1988).

To the extent, that multicriteria assignments can capture the appropriate diversity in route choice, similar benefits to those from stochastic equilibrium models can be achieved (Dial 1994). Whether or not some small stochastic perturbations are helpful in multicriteria assignment and calibration will need to be investigated.

A critical research area is in accurate representation of real world networks and traffic control systems. Traditionally, detailed modeling of intersections and vehicles on small networks has been by means of simulation or queuing models. There have been several assignment models developed that include intersection modeling (e.g. CONTRAM and SATURN), but these models are suitable principally for small area analysis (Leonard et al. 1978; van Vliet 1982).

The most natural way of treating these issues is to perform a time dependent model for traffic assignment. Time dependent or dynamic models have been the subject of limited theoretical investigation for some years, but apparently have not yet been used for a metropolitan planning model. Early work on dynamic assignment focused on models which had only one origin and destination (Merchant & Nemhauser 1978) or other significant network restrictions (Zawack & Thompson 1987). Dynamic assignment clearly can provide significant insights into congestion phenomena (Hendrickson & Kocur 1981; Ben Akiva et al. 1984) and there is now general acceptance that travelers' choice of departure times are interdependent with route choice.

There has recently been a rapid expansion of theoretical research on dynamic models stimulated to at least some degree by IVHS concerns. For example, a special issue of Transportation Research Board (December, 1990) was devoted to dynamic flow control and equilibrium issues. Dynamic traffic assignment models have been proposed by many researchers including (Janson 1991; Kroes & Hamerslag 1990; Drissi-Kaitouni & Hameda-Benchekroun 1992).

Heuristics for time-dependent assignment are not complicated to propose. For example, incremental assignment by time period can be easily applied. However, dynamic assignment models pose theoretical questions of a complex nature. In particular, attempts to formulate mathematical programming models for dynamic equilibrium assignment must confront issues of the existence and uniqueness of optimal solutions. Also, constraints associated with trip timing appear to require first-in, first-out behavior with respect to vehicle traffic on links. At the end of any discrete time period, complex bookkeeping is required to ascertain how many vehicles will transition to the next links downstream in the next time period. Finally, there is the need to represent congestion, intersections, and queuing delay in a manner that is realistic yet mathematically tractable.

Despite these difficulties, a complete formulation of the UE dynamic traffic assignment model for multiple origins and destinations was developed by (Janson 1991) who also provides a review of the literature circa 1990. Janson provides a formulation of the dynamic user-equilibrium (DUE) traffic assignment problem with variable departure times and describes a bi-level mathematical programming approach for its solution (Janson 1992).

While it appears that dynamic assignment models will bring greater insights and more accurate representations of traffic flows, there is insufficient practical experience at this point to make this case convincingly. Accordingly, there is a need for an ongoing effort to distill theoretical research on dynamic traffic assignment and to begin large scale empirical testing of alternative approaches.

Extensions of assignment models for joint choices

The search for consistency in trip assignment pointed up the lack of consistency in the treatment of network level-of-service in mode choice, trip distribution, and trip generation models. In particular, it has been problematical to represent modal level of service in mode choice models or trip distribution models. Similarly, there are difficulties in capturing the effect of network performance on trip generation. Addressing these inconsistencies and the impacts on travel that are at issue has been a priority in recent discussions about modeling transportation and air quality interactions (Harvey & Deakin 1991).

In the aggregate schema, various joint models were proposed and/or implemented (Wilson 1974; Evans 1976; Florian et al. 1975; Dafermos 1976; Safwat & Magnanti 1988), but these formulations bear the substantial difficulties of aggregate models. A less aggregate, complex joint dynamic model with multiple groups of travelers has been proposed by (Boyce et al. 1993). All of these models rely on logit and/or gravity-entropy models and can have severe problems with IIA.

The formulation of a unified disaggregate model involving choice of route as well as other travel choices was proposed by (Sheffi 1978). This represented a major advance in that it offered a comprehensive solution to joint choice, aggregation, and equilibrium. This was done through the introduction of the hypernetwork concept.

A hypernetwork represents multiple travel choices as a heterogeneous network comprised of links representing the various choices. In this formulation, a path consists of all the travel choices that are made simultaneously. Hypothetical or dummy links represent choices or decision branches that may not have physical reality. This is a natural way of representing elemental alternatives in joint choice models.

The hypernetwork model is consistent with and premised upon the economic concept of utility maximization with probit random utility models. The link costs or disutilities are assumed to be random variates with multivariate normal distributions with zero means. As a result, the composite alternative or path alternative utilities are the sum of the link disutilities and are, therefore, also multivariate normal variates.

A key insight was the recognition that the hypernetwork formulation could be solved with the same method as stochastic user equilibrium for traffic assignment. Moreover, the network structure could be adapted to represent many necessary joint choice problems. This represented the necessary synthesis of choice models, aggregation, and stochastic user equilibrium on networks. The method was also sufficiently general to encompass aggregate joint choice models when no disaggregate data are available. Improved solution methods and extensions to logit models followed (Sheffi 1981; Daganzo 1982; Sheffi & Powell 1982), but these methods have been little appreciated or utilized. Nevertheless, it is this approach that appears to offer an extremely promising avenue for developing an improved generation of travel demand forecasting models.

III. A unified modeling approach

Introduction

This paper proposes a fundamental reformulation of travel demand modeling process based upon a richer spatio-temporal conceptual and empirical approach. The proposed approach focuses on improvements and extensions to traffic assignment models, and combines the following four elements:

- Modeling joint choices as supernetworks
- Dynamic, stochastic network equilibrium models
- Integration of traffic engineering models
- GIS technology for database management and model integration

Each one of these elements represents an innovative and potentially significant advance in the practice of travel demand modeling. As an integrated whole, they have the potential for achieving significantly improved forecasting models that can be used for operations management as well as capital project evaluation. While the focus of the proposed research is long term, there are also many near term improvements in modeling that would result. In the remainder of this section, we discuss the details of the proposed approach. Each component is explained, illustrated, and rationalized.

Supernetwork models of joint choice

The proposed disaggregate spatio-temporal modeling approach is based upon the concept of a supernetwork or hypernetwork with dynamic (i.e. time-dependent) extensions. In a supernetwork, travel choices are represented as a network whose links reflect the travel alternatives such as access modes, destinations, available travel modes, and all of the possible modal network travel paths. The term supernetwork is used to describe the more general case of random link disutilities with alternative disturbance terms whereas the hypernetwork will be used to refer strictly to the case in which probit choice is assumed.

The supernetwork model thus relates traffic generators and attractors to flows by explicit treatment of trip frequency by purpose, access and egress mode, destination choice, mode choice, and network path choice. The model can be applied at varying spatial scales and certainly can be utilized at the traditional scale at which demand forecasting is usually pursued (Sheffi & Daganzo 1980).

Depending upon the empirical setting, the specific network formulation will vary. Thus, in an area with no public transit, there could be a joint model of trip generation, distribution, and route assignment. In a major metropolitan area, there could be very detailed treatment of transit including multiple transit modes and pedestrian trips. If an activity model is used to mode trip frequencies, trip chaining, and distribution, the supernetwork could be restricted to simultaneous prediction of mode and route.

An abstract example of a supernetwork is depicted in Fig. 1. Illustrated is a supernetwork for joint choice of mode and route for a few origin-destination pairs. The transit network itself could contain access and egress modes and links as well as multiple transit modes. An example of a subset of a supernetwork for commuter rail transit is shown in Fig. 2 from a study conducted for the Long Island Rail Road (Caliper 1987). In the Figure, origin zones are connected by highway and through a complex access network to multiple commuter rail stations. Access links are distinguished for commuters who drive to stations and park. A direct connection between the origin zone and a station represents all other access modes, principally walk access. Figure 3 illustrates the subnetwork for parking utilized in the same study. The subnetwork contains each and every parking lot that is utilized by commuters. Note that lots may be restricted by residence-based permits, and that the supernetwork formulation is flexible enough to handle these restrictions by use of the appropriate network geometry.

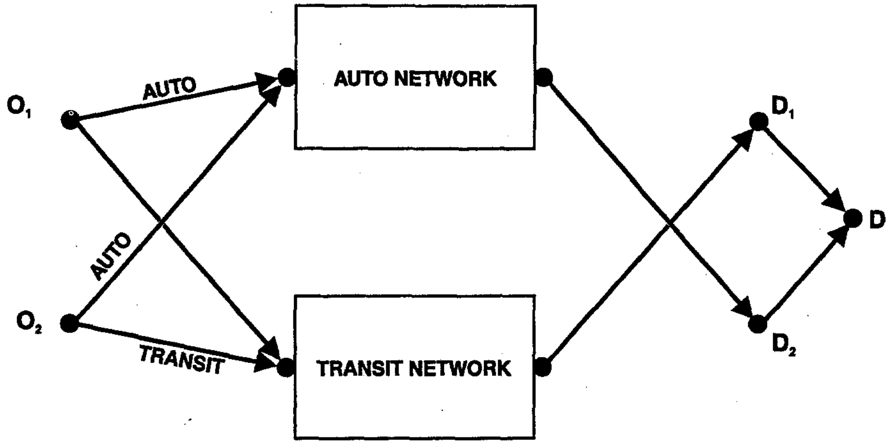
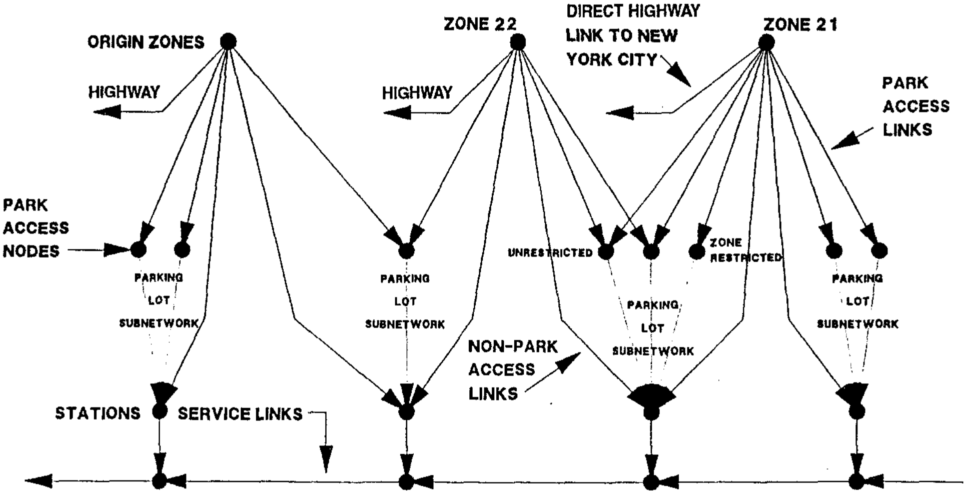
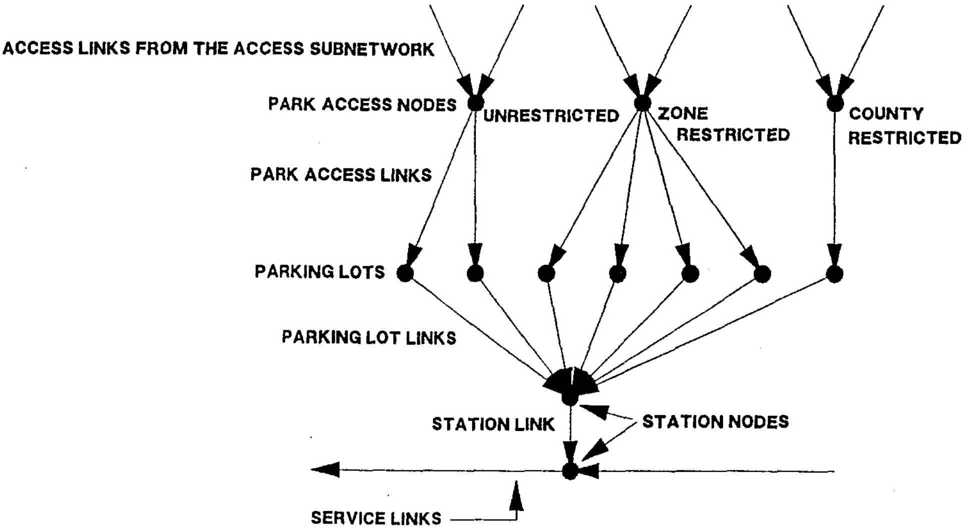


Fig. 1. A supernetwork for mode and route choice.



Source: (Caliper Corporation 1987) (p. 38).

Fig. 2. Supernetwork representation for commuter rail access modes and parking for auto access.



Source: (Caliper Corporation 1987) (p. 36).

Fig. 3. The parking lot subnetwork.

The specification of joint choice models as supernetworks is given a full description in (Sheffi 1985) which contains a mathematical treatment of model formulations and solution approaches. When solved to stochastic user equilibrium, these models have the desirable property of providing a consistent extension to choice models that incorporates aggregation over individuals and a solution to the problem of feedback among model components. This approach achieves consistency with most of the theoretical work on disaggregate models, but without the worst theoretical problems associated with sequential models.

Operationalization of SUE for supernetworks

Implementation of SUE models of joint choices requires estimation of utility functions for the various types of links in the supernetwork. At a minimum this calls for quantification of factors underlying choice of alternative routes for the various modes. At its fullest extent, disaggregate choice models are needed for the travel choices that appear in the supernetwork. Consequently, this approach makes greater, not lesser, demands for developing an understanding of travel behavior determinants and for quantifying their effects. It is a strength of the approach that it can benefit from many forms of research that have this goal.

To the extent that information is required that traditionally has been elusive, there is recourse in terms of new measurement approaches. In particular, conjoint analysis of stated preference data is one attractive and practical way to provide the necessary utility functions, especially for travel choices where revealed preference models are weak or difficult to implement. Also perceptions that influence travel behavior may differ significantly from engineering measurements of the same phenomena. Transformation functions may need to be estimated for accurate forecasting.

There are also desirable extensions to SUE for static assignment which would improve the supernetwork approach. These include the incorporation of hard limits on link flows and the development of calibration methods.

Dynamic traffic assignment models

The static one-period traffic assignment model represents a gross simplification in demand modeling. Among its difficulties is the notion that travel is instantaneous from origin to destination. A major problem is that traffic conditions are considered to be at average values over long periods of time. This misrepresents the nature of congestion and its effects on travel behavior (Ben Akiva 1985).

In contrast, in the dynamic model, routes are determined based on link traffic levels during the appropriate time intervals, and trips have a duration that will vary with their departure time. In the dynamic user equilibrium model, it is assumed that all utilized paths between an O-D pair for the same departure time interval have equal impedances, and that all paths that are not utilized have higher impedances than the utilized paths for that departure time interval. Of course, our premise is that only a stochastic or multicriteria version of a dynamic assignment model is appealing. The reason is that the heterogeneity of the costs of utilized paths seems to be an important empirical aspect of urban traffic networks. In other words, the Wardrop principle seems to be antithetical to a reasonable traffic assignment model, and is even less appropriate in the supernetwork context. In any event, temporal aggregation problems preclude easy justification of static models. For example, it can been seen that very different and more accurate results are generated by dynamic models.

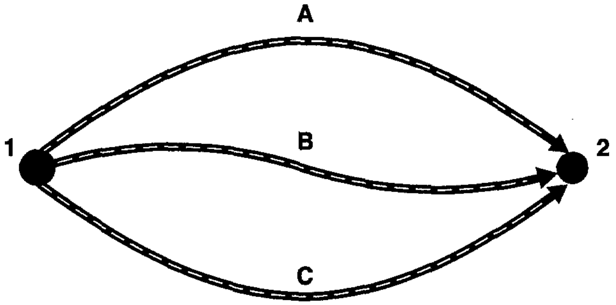
A simple example of dynamic assignment

A simple example serves to illustrate the motivation for dynamic traffic assignment and the dangers of the temporal aggregation now practiced in modeling. The example indicates that considering the temporal distribution of demand can dramatically change the flows that are predicted for the utilization of alternative routes. In fact, in the example, a road that is not used at all in a static assignment turns out to be heavily utilized during the peak period under a dynamic assignment model.

Consider the extremely simple network illustrated in Fig. 4 with two nodes – 1 and 2 and three links (A, B, and C) that connect the nodes. The links are all two-lane roads with lengths, free flow speeds, and capacities indicated in the Figure. Volume-delay relationships are derived from the BPR volume-delay curve with standard parameter values. Note that roads B and C have lower travel speeds and capacities than road A.

Assume for the purposes of analysis that the peak period is three hours long and that total demand for travel between node 1 and node 2 is 25,000 vehicles or 8,333 vehicles per hour. Demand is not uniform across the peak period, however. Rather, demand is 6000 vehicle trips in the first hour, 11,000 in the second hour, and 8,000 in the third hour.

Figure 5 shows the (user) equilibrium flows calculated for each route during each hour of the peak period, as well as the flows calculated for the static, one period model. We assume for simplicity that the flows during each hour are independent of flows during other hours. Note that Road C is not utilized at all in the one period model, but carries nearly 1500 vehicles in the middle hour of the peak with the three period assignment. The travel speeds are



Route Characteristics	Road A	Road B	Road C
Length (Miles)	21.93	19.75	18.52
Free-Flow Speed (miles/hour)	60	50	35
Free-Flow Time (minutes)	21.93	23.70	31.75
Flow Capacity (cars/hour)	4000	3400	3000

Fig. 4. A simple network example.

quite different from the multi-period calculation, so clearly mode choice behavior would be expect to vary. Also, computation of air quality impacts of flows on this network would certainly be different.

With this simple example, we have not even begun to explore the errors associated with static travel demand models. However, until such time as significant empirical research is performed with dynamic models, we are not likely to understand the magnitude of the various forms of aggregation error. Since traffic levels and network performance vary enormously by time period, it would appear that this aspect of travel demand modeling should not be ignored any longer.

The dynamic traffic assignment problem

In order to capture route choice behavior and its aggregate effects, a dynamic assignment procedure will need to treat relatively small time intervals. The simplest way to think about this is to assume that there is an origin-destination matrix for every 5, 10 or 15 minute interval throughout the peak period as shown in Fig. 6. If one were to begin the assignment computation before the beginning of the peak, the first travelers would see uncongested links. As time went on, travelers departing from home in later time periods would face route choices in which travel times had increased to the congested levels at least on some network links.

As a thought experiment, but one perhaps which is computable these days,

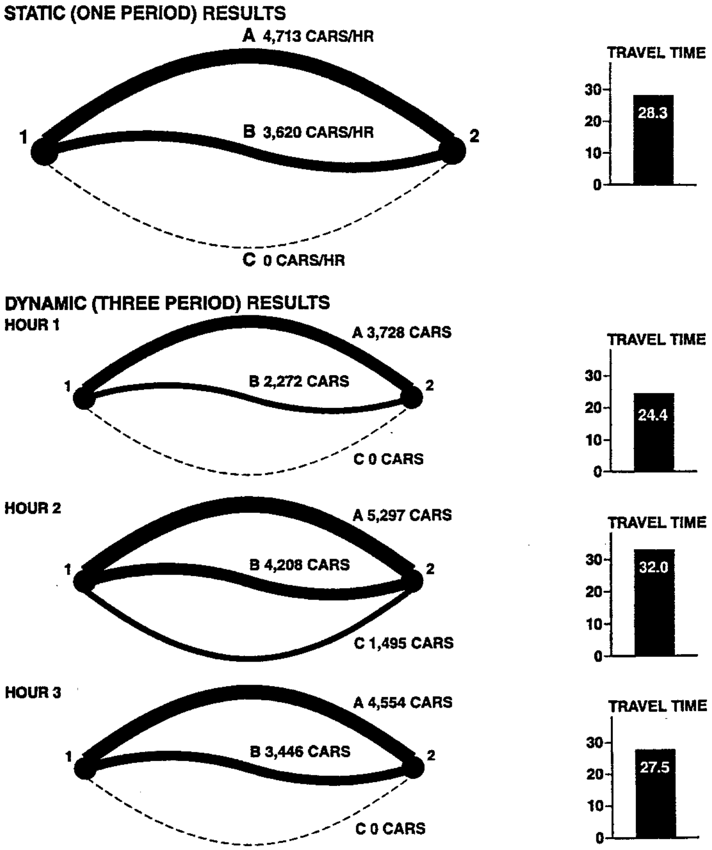


Fig. 5. Comparison of a static and dynamic assignment.

we could assign each traveler separately to the network based upon level of service computed taking into account the trips already occupying network links. This "one-at-a-time" dynamic assignment model could be done assuming random link travel times and using choice models for the evaluation of a large number of possible routes. The process would assign travelers in the sequence of their departure times, but otherwise picked at random from each equivalent departure time cohort.

From a behavioral perspective, there are many factors that unquestionably influence route choice. These would include knowledge about alternatives, adaptive behavior in the face of unanticipated delay, and preferences for specific characteristics of routes such as travel time consistency, avoidance of traffic lights, a preference for controlled access roads, or many other route attributes (Antonisse et al. 1989). Incorporating these factors requires behavioral research of considerable depth and extent.

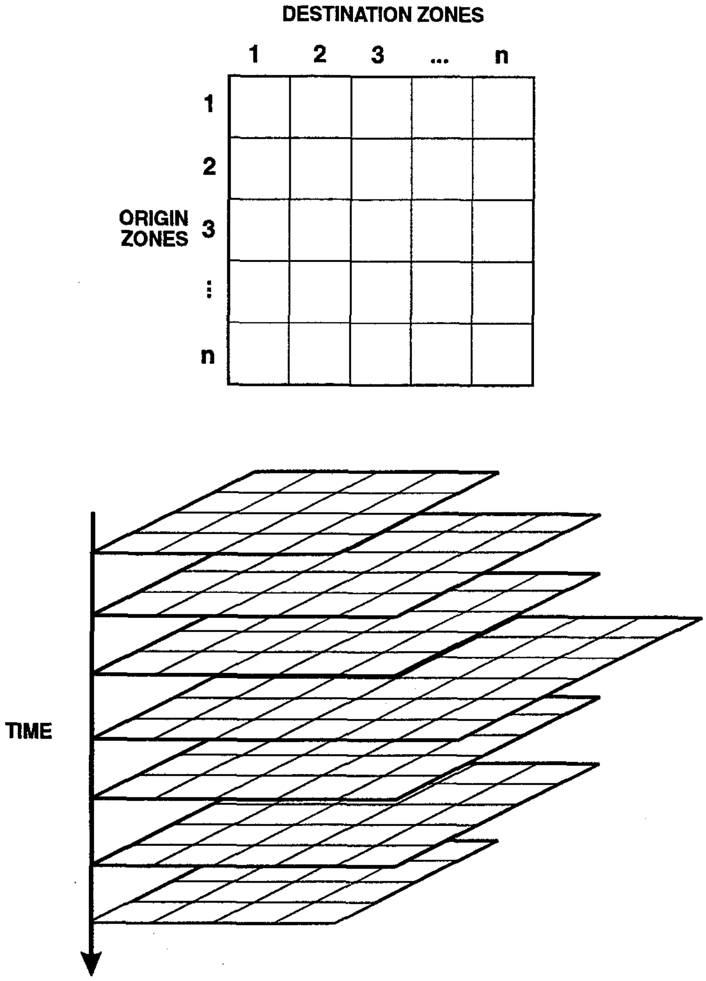


Fig. 6. Typical input to traffic assignment.

In our thought experiment, we would need to store the path of every traveler who had left home so that we could recompute his location for the next iteration. This would be a substantial, perhaps prohibitively large amount of information to track.

If we attempt a computationally more efficient assignment procedure with aggregation of travelers, there is still substantial bookkeeping with regard to the links on which traffic for each O-D pair is to be found in each time interval based upon its departure time interval. Also, we must confront the issue of contention among travelers and O-D pairs for use of network links and the issue of equilibrium flow characteristics as in the static case. Here there are advantages to the formulation of dynamic traffic assignment as a mathematical programming model.

Algorithmic solution of the dynamic traffic equilibrium assignment model
Dynamic models as discussed previously have adopted UE-style objective functions and recently been formulated including models that incorporate departure time issues. Janson developed a convergent dynamic equilibrium algorithm formulated as a bi-level problem in which the upper problem is a static assignment in which it is assumed which nodes are crossed by flows with specific destinations in each relevant time period (Janson 1991). In the lower level problem, the node time intervals are updated based upon new node-to-destination zone, dynamic shortest path calculations assuming the impedances derived from the flows from the upper level problem solution at the prior iteration. Iteration back and forth between the upper and lower level problems continues until the node time intervals do not change significantly. Experiments reported in (Janson 1992) indicate that the method converges and gives reasonable results. A further extension developed subsequent to the report upon which this paper is based (Janson & Robles 1994) extended the model to treat time in a more continuous fashion such that fractions of trips are more appropriately assigned to the correct links in any time period and congestion effects can be calculated more accurately.

In Fig. 7, the results are shown for a dynamic user equilibrium assignment that was computed for a simple network with three routes, each of which is comprised of many short links. The method utilized was a version of the algorithm discussed above. Traffic was assigned over 15 time intervals of 10 minutes duration each. Three thousand vehicles were assigned overall with a variable percentage departure rate by interval. All departures were in the first ten intervals, and the results are depicted in Fig. 7 for the first six intervals. A standard Bureau of Public Roads (BPR) function was used for computing travel time, except that alpha was set equal to 4.5 for route B as might be appropriate for a older facility more susceptible to traffic congestion. In the Figure, congestion is seen to grow through time as more traffic departs from the origin. Congestion levels then decline as the departure rate falls and the network begins to clear. The location of congestion on the network changes through time and congested links can be clearly identified by time period with a dynamic model.

This dynamic assignment approach appears to be workable and, in an extended form, best suited for use as part of the proposed model formulation described in this paper. This method assumes that route choices are made at the time that travel is initiated. This can be regarded as precursor formulation to variations in which travelers change routes enroute based upon conditions encountered.

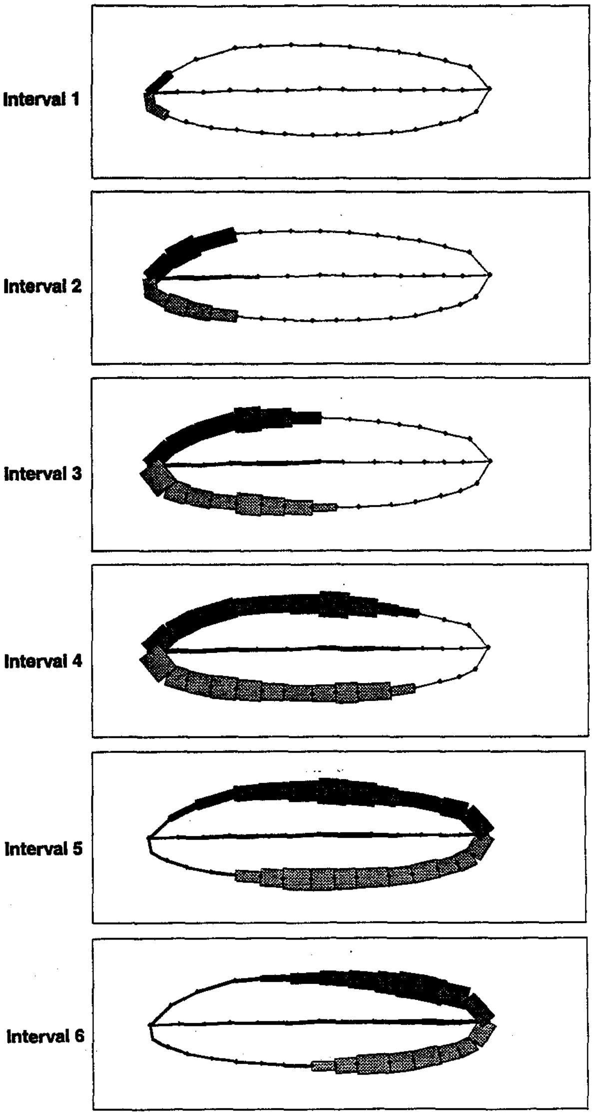


Fig. 7. A dynamic user equilibrium assignment example.

Extension to stochastic, dynamic models on supernetworks'

A key aspect of the proposed approach is the development of a stochastic, dynamic equilibrium solution for supernetworks. The extension of the supernetwork concept to the dynamic or time-dependent case is feasible for user-equilibrium based upon the work cited above.

A dynamic assignment based upon stochastic user equilibrium for traffic assignment has been implemented in an experimental code for TransCAD. Consequently, it should be possible to implement a dynamic, stochastic supernetwork model. Since we do not presume that dynamic models are without the need for further theoretical development, it is possible that this will be a major research activity. Also, the development of a computable model for large scale networks may be difficult. Due to the lack of practical experience with alternative dynamic models, this should not simply be a theoretical exercise. Rather, it must entail consideration of the validity of different formulations of dynamic models.

Integration of traffic engineering models

Many of the factors that determine network link travel times performance and congestion either are not represented or are represented poorly in traffic assignment models. This is particularly the case for roadway geometry and traffic control signals. While it is possible to include intersection performance in equilibrium assignment models, there are significant restrictions on the way this can be done without destroying the equilibrium model formulation.

In particular, equilibrium assignment models require that volume-delay functions be continuous, twice differentiable, and defined for oversaturated volumes (Regueros 1992). By itself, this may make it impossible to use assignment models to analyze the effects of transportation management strategies.

In contrast, simulation models are an effective way to model intersections, corridors and small networks. Simulation can be utilized iteratively with an assignment model (as in SATURN), as can analytic models for queues (as in an CONTRAM), but iteration back and forth does not necessarily lead to convergence or convergence to the correct equilibrium solution.

An important area of research is, therefore, to make it more practical and attractive to incorporate traffic engineering models of various sorts into static and dynamic equilibrium models. One appealing approach has been developed by (Regueros 1992). This method approximates the output of a simulation or analytic model at every iteration of an UE assignment with a linear cost function. The proposed Linear Approximation Model (LAM) requires only that a flow-delay model can be evaluated for every flow vector, but does not have restrictions on continuity of the cost function. As a result, it can be applied to a wide range of traffic engineering models. Limited experience has shown that the LAM model can improve the accuracy of assignment results (Regueros et al. 1994).

Techniques for improving the convergence of combined assignment-simulation models are an important topic. Extension of the LAM method or an alternative for the stochastic case would clearly be of interest. This poses additional complexity since the direction finding step in the stochastic assignment is not guaranteed to move in the right direction.

Also needed are better analytic approximations for the flow-delay functions that are relevant for traffic flow modeling. Traffic networks are heterogeneous and it may be critical for planning models to utilize different volume-delay models and relationships for different types of network links.

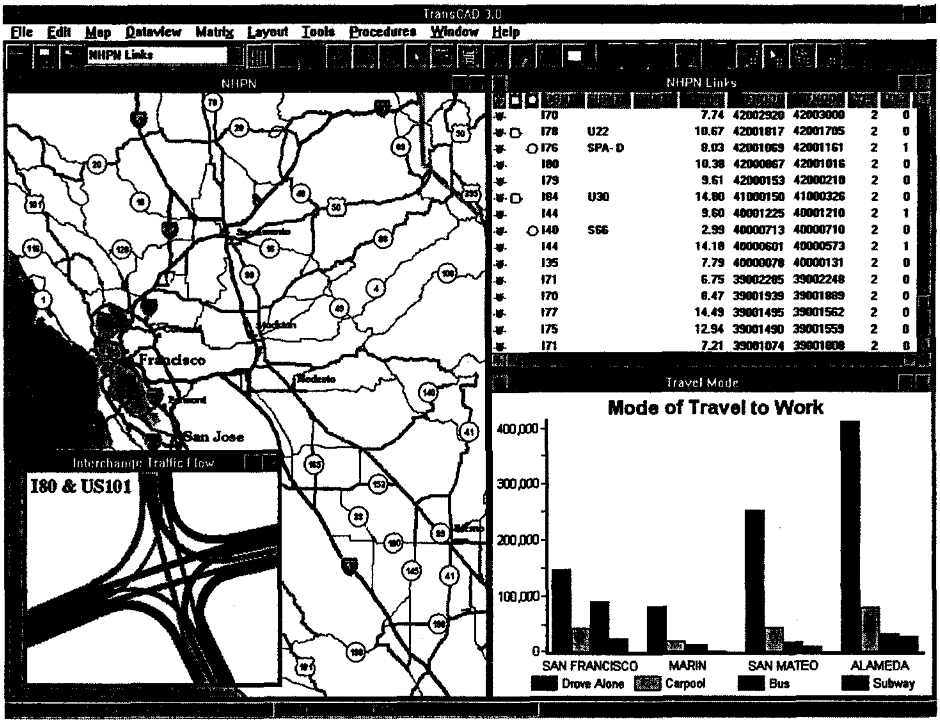
Integrating traffic engineering and forecasting models is intended to strengthen both sets of tools. The linkages that can be made will also facilitate modeling of impacts such as those on air quality.

Use of GIS software technology

Rapid advances in software technology and computer hardware hold considerable promise for transportation modeling. Apart from sheer speed or capacity improvements, GIS is one of the software technologies that appears to hold considerable promise for advancing demand forecasting. A GIS is a spatial database manager system that facilitates the development, storage, and manipulation of geographic and related attribute data. GIS systems store data in layers that are traditionally associated with points, arcs (for linear features), and polygons (for areal features or zones).

GIS systems feature powerful graphic display functions, of which map displays of the type shown in Fig. 8 are the most notable. A GIS makes it possible for analysts to produce onscreen and printed map graphics that convey a wealth of information about transportation models and forecasts. Some GIS systems have significant capabilities for accessing and manipulating tabular data associated with transportation entities, a feature notably lacking in most planning software. Powerful GIS systems now run on low cost computer hardware, and will be widely available to transportation planners and modelers in the future.

There is little controversy about the fact that GIS systems have particular value in data preparation, particularly when the GIS data already exist. It also seems clear that the digitizing and data editing capabilities of GIS can greatly reduce the time and cost of assembling inputs for demand models. Some GIS software is particularly useful in making use of Census data including TIGER, Census, and Census Transportation Planning Package, CTPP (Fleck & Simkowitz 1989; Simkowitz 1993). GIS software is being used exten-



I70		7.74	42002920	42003000	2	0
I78	U22	10.67	42001817	42001705	2	0
I76	SPA- D	8.03	42001069	42001161	2	1
I80		10.38	42000867	42001016	2	0
I79		9.61	42000153	42000210	2	0
I84	U30	14.80	41000150	41000326	2	0
I44		9.60	40001225	40001210	2	1
I40	S66	2.99	40000713	40000710	2	0
I44		14.18	40000601	40000573	2	1
I35		7.79	40000078	40000131	2	0
I71		6.75	39002285	39002248	2	0
I70		8.47	39001939	39001889	2	0
I77		14.49	39001495	39001562	2	0
I75		12.94	39001490	39001559	2	0
I71		7.21	39001074	39001808	2	0

Fig. 8. GIS Graphics display.

sively for defining traffic analysis zones and developing zonal attribute data prior to modeling. The polygon overlay capabilities and spatial aggregation functions make it possible to convert data from one zoning system to another.

It is not appreciated the degree to which the networks that are used in planning lack sufficient detail for the purposes to which they are put or to which they ought to be put in the future. GIS offers a particularly effective means of improving network representations and properly reflecting capacities and intersection characteristics.

Beyond aiding data preparation and visualization, why should GIS technology be important in improving travel demand models? One reason is that GIS technology directly supports much of the manipulation inherent in forecasting packages and, in fact, is more efficient than the existing generation of UTPS software for many of the requisite data manipulations (Slavin et al. 1991). A more important reason is that GIS opens up some new territory for travel demand models as well, although this has barely been recognized in the published literature (Ferguson et al. 1992).

Use of GIS in planning enhances the empirical content of the modeling process. This can be vital in circumstances where conceptual formalism may obscure flaws in forecast accuracy and model validity. Clearly, a GIS can assist planners in making more use of pertinent data in model building. Perhaps the most striking example is the opportunity to perform analysis at various spatial scales. For example, trip generation can be examined at the household, parcel or land use level within zones rather than just for aggregate units. As Replogle points out, a GIS "may make it possible to overcome many problems inherent in aggregate zone-based model structures where the variance in the data within zones exceeds the variance between zones. Highly disaggregate analysis of origin and destination characteristics can be accomplished in the GIS environment . . ." (Replogle 1989). A GIS framework also provides a means of enhancing disaggregate modeling through more effective identification of choice sets and spatial alternatives (Patterson & Ferguson 1990). In these and in other ways, a GIS can resolve some of the difficulties with planning models by reducing undesirable aggregation and aggregation bias (Prastacos 1990).

When necessary, GIS technology makes it easy to aggregate spatial data with minimal effort. The aggregation capabilities can be utilized to generate outputs from demand models that are inputs to other models. For example, a GIS can easily aggregate network characteristics for grid cells of selected dimensions to prepare inputs to air quality models.

A GIS can also perform valuable model integration functions that would otherwise be prohibitively cumbersome. With respect to model integration and traffic engineering models specifically (Hatton 1991) linked TransCAD and TRANSYT-7F, one of the most widely used macroscopic models for optimizing traffic signals. Advantages cited by Hatton included more rapid data preparation and more efficient data management. From a practical point of view, it has been demonstrated that GIS is a valuable mechanism for integrating travel demand, traffic engineering, and environmental models and this form of model integration is expected to be commonplace in the future. Tools to support model integration will include extensions to the basic GIS architecture. The one GIS designed specifically for transportation applications, TransCAD (Caliper 1990) has an extended data model with direct support for the storage and manipulation of transportation "objects" (i.e. data structures). As shown in Fig. 9, these are familiar constructs to demand modelers. Further extensions for managing temporal data will be required to support dynamic models of the type described in this paper.

Networks **Routes** **Tours** **Flows** **Zones**

Fig. 9. Some common transportation objects.

Advantages of the modeling approach in addressing travel demand and air quality requirements

The principal aim of the approach outlined is to achieve accurate predictions of traffic levels in response to the types of capital improvement and traffic management projects that are likely to be undertaken in the next decade. The approach that has been outlined above is a logical outgrowth of previous research, yet would represent a substantial departure from and extension of the state-of-the-art. This approach can remove many of the untenable assumptions that currently plague travel demand modeling, yet offer constructive improvements in response to prevailing critiques of the modeling process.

The supernetwork approach adopts the more reasonable assumption that it is the utility of the entire trip and not just one subcomponent travel choice that is maximized. The supernetwork approach also significantly reduces bias associated with the independence from irrelevant alternatives property of the multinomial logit model. The reason is that the network structure incorporates a substantial amount of the interdependence of alternatives explicitly. For example, routes that have links in common have correlated travel impedances and utilities.

When the supernetwork is solved to equilibrium, the model guarantees that the level-of-service assumed to determine mode split is identical to that which determines path choice and results from the collective choices of travelers. This removes the assumption that there is no significant interaction between mode and path choice or between individual and aggregate route choice behavior.

One attractive aspect of this approach is that the approach is workable for both transit and highway modeling. In fact, the method has been shown to provide superior results to conventional models for tackling some of the most complicated interdependencies in transit modeling (Caliper 1987).

We believe that incorporation of the time element and provision for utilization of very detailed micro scale spatial data will foster progress toward the valued goals of increasing the accuracy and improving the sensitivity of planning models for operational planning and analysis.

Dynamic models with fine grain network and spatial resolution appear to be the only reasonable means of accurately evaluating congestion management and mitigation strategies and identifying the extent to which changes in land use, work schedules, and network characteristics can be helpful in meeting planning objectives. By implementing the capability to predict flows at specific locations and points in time, the validity of demand models can be more directly assessed. Also, traffic management measures can perhaps play a greater role in the model development and calibration process.

The proposed approach does not exhaust the a number of other possible reformulations of the travel demand process and does not solve all modeling problems. However, it is important to recognize that the approach should be able to benefit from and complement significant advances in disaggregate models, activity analysis, traffic simulations or land use modeling.

The finer spatial and temporal granularity will also greatly enhance the use of models for predicting air quality impacts. Here too, the aim of the combined travel and air quality models should be to replicate air quality measurements. The GIS framework provides a direct means of storing air quality data and also for calculating air quality impacts for buffers and grids of any type that could be utilized in emissions modeling from mobile sources. The GIS also will facilitate integration of travel demand and air quality models and visualization of results.

There is also reason to believe that a GIS will facilitate more detailed and accurate modeling of emissions (Bruckman & Dickson 1993). In particular, the GIS makes it possible to model vehicle mix and vehicle use geographically as well as handle climatic variations, natural boundaries and the spatial dispersion of pollutants. Finally, a GIS provides a flexible means of calculating a wide variety of measures of effectiveness for user-defined spatial areas and time periods. Report writing and graphic output devices further enhance the comprehensibility and usefulness of output in communicating results.

IV. Research recommendations

A substantial research program is necessary to implement the approach that has been outlined. New theoretical development is required to extend the model formulations into a unified framework, to solve outstanding mathematical issues, and to demonstrate viable solution methods. Alternative model formulations need to be researched and evaluated. Considerable empirical research is also required to further both conceptual understanding and practical application of the proposed methodology. Much of the requisite research has value to the ongoing work of modelers and also may be of benefit for other approaches to reformulating demand models.

Formulation and implementation of unified supernetwork models

A general approach needs to be developed for the formulation of supernetwork models. By this we mean that conceptual and practical guidance is necessary for constructing supernetworks to represent the types of scenarios for which demand must be forecast. In the case of highway networks, this entails treatment of HOV lanes and ride sharing alternatives, whereas for transit it must include access and egress modes as well as possibly multiple transit modes. Truck traffic cannot be ignored in highway networks.

A general issue to be investigated is the degree of aggregation that is appropriate. Here it should be noted that there is a tradeoff between the realism of the most disaggregate network representations and the very large potential size of the supernetworks to be solved. Data requirements must also be considered as they often dictate a more aggregate formulation.

Estimation of link utility functions

For both route choice, and in the case of joint models, there is a need to quantify the disutility or generalized cost of each link in the network or supernetwork. Because of the objective to model human behavior, rather than simply identify the least cost route for travel from an origin to a destination, it becomes imperative to estimate the magnitude of the importance of the various choice determinants. This includes the value placed upon travel time components, the disutility of transit transfers, and the importance of all other factors influencing the choice to travel, the destination, mode, or route utilized. As indicated previously, stated preference models are a viable means of obtaining the necessary information in any specific empirical setting.

Improved solution methods for SUE

The current solution method for SUE is computationally demanding, and development of faster convergence methods would be a big step forward in making

SUE easier to use and to calibrate. It would be particularly useful to find a fast method for recalculating SUE after a small perturbation is made to the network.

A version of SUE with capacity constraints would also be extremely useful for general application. Caliper implemented SUE with upper bounds on links, but only for a network with one destination (Caliper 1987). As Hearn has indicated, bounded flow methods would be an extremely useful extension for traffic assignment models generally (Hearn 1979). Research is needed to develop a practical means of computing the bounded UE assignment problem, and also to generalize the formulation, if possible to SUE. An approach suggested by (Daganzo 1977) is attractive for further investigation.

Calibration methods for unified models

The problem of calibrating traffic assignment models represents one of the most significant omissions in transportation modeling. One must struggle to find even a discussion of this problem in the literature, let alone meaningful research for use as guidance. The one exception is (Fricker 1989) who notes that it is typically assumed that calibration is done, presumably manually through trial and error. Fricker notes the dubious practice of adjusting speeds to calibrate assignment models. Of course, this can lead to significant biases in other models or analyses that make use of these data.

The calibration problem for SUE is more formidable than for UE and is more difficult still for supernetworks which involve multidimensional choice. Experience with calibrating a supernetwork model for the Long Island Rail Road suggests that the problem is difficult, but solvable (Caliper 1987). However, rather more evidence is needed before general claims can be made for calibration methods.

Calibration and evaluation of supernetwork models requires that a system portrait be available for the base case. In practice, this requires measurements that are not always readily available. This engenders a need for practical and conceptually consistent means of estimating O-D matrices from counts and other available information. Estimation should be done with a method that is consistent with the traffic assignment model that is being utilized. Janson & Southworth (1992) developed a method for estimating departure times from traffic counts using dynamic assignment. Nielsen developed an approach for O-D table estimation which works with any traffic assignment method including SUE and should work with dynamic models as well (Nielsen 1993).

Research on dynamic assignment models

Research is needed to understand the basic properties of dynamic assignment models and methods on realistic networks with multiple O-D pairs and tens of thousands of links. An important aspect of the research is investigation of alternative formulations of the dynamic assignment problem and alternative solution algorithms for specific formulations. Comparisons with simulation should also be useful in developing an understanding of the behavior of the models.

A major focus for theoretical investigation is the necessary criteria for dynamic assignment models. The literature now offers a wide array of models with widely varying assumptions and application domains. For alternative formulations, there are fundamental issues about convexity (Carey 1992), existence and uniqueness of equilibria, and the suitability of model assumptions. There are also many empirical alternatives for formulating dynamic models in terms of network representation, link length, time granularity, and assumptions about temporal flow precedence constraints. Operationalizing dynamic equilibrium assignment in a realistic setting entails testing the model and calibration with empirical data from typical environments.

We have previously identified the extension of SUE on supernetworks to the dynamic case as a major research goal. This will require extensions to the formulation for the dynamic assignment model as well as the development of a workable solution approach.

Traffic and pollution model integration research

Integration of traffic engineering and air pollution models with the travel demand models is another important research program element. By integration, we refer here to implementation of modifications of the demand forecasting models and the other models that make it possible to perform forecasting and impact analysis in a more accurate way. The aim is specifically to go beyond mere sequential iteration between or among models. Rather, it should be possible to reconcile the logical and empirical requirements of relevant models through greater geographic and temporal decomposition and through unification of overall data inputs and outputs. Numerous theoretical difficulties make this a nontrivial area for research.

In the case of traffic engineering models, the specific integration of intersection models with assignment methods is compelling. The main reason is that the amount of delay associated with intersections is potentially substantial relative to overall travel times for trips made in urban areas (Al-Habbal 1988). For this reason, traffic control strategies should influence route choice, and having a means of predicting these impacts would be desirable in developing effective strategies.

Currently, there are substantial difficulties with potential solution methods for assignment models with general link interactions, i.e. where the flows on links are related to flows on other links. With the network representation of intersections implied above, the assumption of no link interactions is expressly violated. Another difficulty is treatment of saturated conditions. Neither existing assignment methods nor conventional simulations model these situations.

Results developed by (Al-Habbal 1988) suggest that there is promise for extending assignment models to treat junction delay. A new assignment model combining volume-dependent turning movement delays and signal optimization has been developed and is being tested (Caliper 1993). Research with realistic intersection models and a wide variety of traffic models is seen as a practical means of examining possible further developments as well as surfacing additional theoretical difficulties. Since planners and engineers already use these more detailed tools, some guidance for consistent demand forecasting may also result from this line of inquiry.

With respect to air pollution modeling, the ability to calculate speed profiles by link would significantly improve accuracy. Distinguishing the fleet mix by link would also apparently have a substantial impact on accuracy. Naghavi & Stopher (1993) found that a substantial amount of pollutant emissions were associated with a rather small number of vehicles. If the fleet mix could be characterized by link and time period, a considerable improvement in pollutant emission estimates would result. Innovations in license plate recognition from video and geocoding of automobile registrations may make this a reality in the future as part of a data collection protocol for dynamic modeling.

Computational support for research

The feasibility of the research outlined in this paper depends fundamentally upon the development and advancement of computer-based methods for travel demand modeling. Even if the theoretical advantages of the approach can be justified, it will have to be established that the models can be implemented with empirical data and that computationally tractable solution methods are available.

Advances in computers have now brought computation costs down to the level approaching the cost of electricity. For this reason, it is efficient to make extensive use of computation as an integral part of any long term effort to revamp travel demand models.

Accordingly, we believe that a computational laboratory or toolset should be implemented in software to facilitate travel demand research. This laboratory should be the result of a concerted software engineering effort to enable the rapid implementation, testing, and evaluation of new travel demand modeling approaches.

The laboratory should be portable in that it should be accessible to a wide range of potential users. It should also be portable across operating systems and machine environments so that it has a life expectancy of sufficient duration. It is important that this testing facility and prototype software run on extremely high performance computers. This may be required for the research and would otherwise anticipate the resources that will appear on the desktops of the future.

Two types of testing and evaluation are envisioned. One is synthetic and substantially computer-based. Computers can rapidly generate test problems, and subject models and algorithms to a wide variety of stress tests that one or two empirical data sets would never pose. Extensive testing with empirical data representing small-scale and large-scale modeling problems is also essential. The computer-based laboratory would therefore also contain empirical datasets assembled for research purposes.

Previously, we have argued that GIS technology is an essential element of future travel demand modeling systems and we envision that an advanced GIS system would provide the foundation for the development of prototypes for new travel demand models. Even if not fully realized in the manner described above, we would expect that GIS extensions for travel demand modeling will be researched and implemented. The extensions that seem the most appropriate in light of current research thrusts would involve extension to the temporal dimension and the development of object-oriented methods for model management. It is further assumed that research prototypes would feature improved interactive graphic displays and interfaces for modeling.

Implementation of the types of models proposed in this paper involve network building and editing tasks that are an order of magnitude more involved than for current models. GIS support for extensive manipulation of networks is therefore envisioned as a necessary step. This will go beyond mere manipulation of geographic entities, however. The main reason is that network building has always entailed a significant amount of abstraction from geographic networks. Indeed, part of the art of network analysis has usually been the development of an appropriate network representation that is suitable for both the empirical problem at hand and the algorithmic solution envisioned. With the advent of advanced computer graphic environments, object-oriented software technology, and GIS, there are opportunities for developing improved methods, guidelines, and tools for network development and maintenance. This would include support for conflation, aggregation, disaggregation, and network algebra of various sorts. Support for a high degree of human-machine interaction in network design may also be warranted.

Data collection

As with any method for travel demand forecasting, some amount of data collection will be essential. In the approach we recommend, the temporal currency of data is important. In this regard, it must be noted that many demand modeling efforts have been out of date by the time that they have been completed. The 1990 journey-to-work urban level data have recently become available. These data constitute an invaluable resource for travel demand modeling in the next few years. It is important that travel demand research to exploit it begin immediately. Otherwise, research may be fatally comprised by changes in travel patterns that have occurred since 1990.

The data collection required for implementation of the unified supernetwork approach is not necessarily more onerous than that which would typically be implemented. There is reliance upon surveys and counts of a fairly traditional sort, but perhaps with slightly different content. For example, there would be greater emphasis on route choice and trip timing than might otherwise be the case. Also, stated preference experiments would be included in the survey research.

For research purposes, several datasets should be developed. At least one should be from a large metropolitan area in which there is rapid rail transit. Another should be from a locality in which traffic control for highways is the only significant issue. One of the virtues of the supernetwork approach is that it can be used in projects that are more narrowly focused than regional planning. As a result, this methodology can be used by a transit company or in a traffic management project. Research datasets for these types of applications should also be gathered. Data sets from a variety of different settings should be utilized. This is a necessary means of developing a methodology that is empirically valid, robust and generally useful.

Long term research makes demands upon data that may not always be fulfilled by modeling activities that are pursued by MPOs and other agencies. For this reason, government organizations should contemplate funding the development of datasets for research purposes that can be utilized by a broad array of researchers. While this may be a complex undertaking, the development of a comprehensive travel demand dataset to accompany the 1990 CTPP may help advance the state-of-the-art more than any other single endeavor.

Various new methods for collecting the necessary data should also be explored and encouraged. We are in an exciting era in which the digital revolution and other new technologies are continuously challenging us to make better use of our resources. Various means of passive data collection including use of video imagery can be expected to provide new and valuable sources of information for demand modeling.

There is also a strong case to be made for the use of data from natural occurring experiments and quasi-experimental design techniques for advancing and validating travel demand models. There are many places in the world where significant changes are being made to highway and transit systems. With adequate preparation and the collection of before and after data, the raw material for testing the predictive validity of new approaches to travel demand modeling can be available.

V. Concluding remarks

This paper indicates that there are many difficulties associated with the current generation of transportation planning models. It is commonly recognized that there are inconsistencies among the model components, but it may be less appreciated how poorly the conventional models perform as predictive tools. When one considers the simplifications traditionally employed in modeling traffic flows, it would be foolhardy to underestimate the difficulty of producing successful demand forecasting tools.

Nevertheless, there have been many important advances in demand research that can provide the basis for improved forecasting methods. This is most certainly the case with disaggregate choice models and advanced network analysis methods.

In this paper, we have outlined research that will test what we believe to be the most promising means of revamping the travel demand forecasting process and placing it upon a sound theoretical foundation. The unified approach utilizing supernetworks solved with stochastic user equilibrium methods has sufficient advantages that we believe it should be the approach of choice until a better alternative can be demonstrated. This opinion rests to a degree on a belief that the user equilibrium flow condition is a bad assumption for traffic assignment and that it leads to unrealistic predictions of network utilization.

The treatment of the time dimension with respect to travel behavior and network performance looms as an obvious focal point for future research. The simplification imposed by one-period static modeling is easily shown to lead to incorrect and biased forecast results.

Many of the research problems discussed in this paper are core problems that will have to be solved before travel demand models become useful for air quality or IVHS analysis. A deeper understanding of travel behavior with respect to route choice as well as accurate modeling of traffic systems performance seems essential for these applications.

A major objective in reformulating travel demand models should be to produce models that generate forecasts with acceptable error levels (e.g. within 10–20 percent) with respect to predicting system changes. This requires that the models replicate current behavior even more accurately and makes calibration to the base case a feasibility test for an improved methodology.

The importance of empirical testing and model validation cannot be overemphasized. Prediction is inherently an empirical matter. Moreover, most of the important theoretical insights and conjectures about travel demand, in general, and traffic assignment, in particular, have not been tested on large scale, realistic networks (Mahmassani & Mouskos 1988). This should be an important research priority.

A scientific approach to improved travel demand modeling must be carried within a rigorous framework that provides for evaluation of model error. Because travel demand modeling inevitably must predict human behavior, it cannot be assumed that useful accurate prediction is feasible or, even if feasible, that errors in data, model component error, calibration error, or error propagation do not render our efforts senseless. The burden remains with model builders to establish the validity of results and that errors fall within acceptable bounds.

Finally, Federal agencies should encourage the use of new and improved approaches to modeling and to data collection. No one should underestimate the conservatism that accompanies the use of conventional planning models and the obstacles this conservatism presents for the introduction of improved forecasting methods.

Acknowledgment

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