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Integrated Transportation and Land Use Forecasting: Sensitivity Tests of Alternative Model Systems Configuration

June 2001

TMIP

Travel Model Improvement Program

U.S. Department of Transportation
Federal Highway Administration
Federal Transit Administration
Assistant Secretary for Transportation Policy

U.S. Environmental Protection Agency

Travel Model Improvement Program

The Department of Transportation, in cooperation with the Environmental Protection Agency and the Department of Energy, has embarked on a research program to respond to the requirements of the Clean Air Act Amendments of 1990 and the Intermodal Surface Transportation Efficiency Act of 1991. This program addresses the linkage of transportation to air quality, energy, economic growth, land use and the overall quality of life. The program addresses both analytic tools and the integration of these tools into the planning process to better support decision makers. The program has the following objectives:

1. To increase the ability of existing travel forecasting procedures to respond to emerging issues including; environmental concerns, growth management, and lifestyles along with traditional transportation issues,

2. To redesign the travel forecasting process to reflect changes in behavior, to respond to greater information needs placed on the forecasting process and to take advantage of changes in data collection technology, and

3. To integrate the forecasting techniques into the decision making process, providing better understanding of the effects of transportation improvements and allowing decision makers in state governments, local governments, transit operators, metropolitan planning organizations and environmental agencies the capability of making improved transportation decisions.

This program was funded through the Travel Model Improvement Program.

Further information about the Travel Model Improvement Program may be obtained by writing to:

TMIP Information
Metropolitan Planning Branch (HEPM-30)
Federal Highway Administration
U.S. Department of Transportation
400 Seventh Street, SW
Washington, D.C. 20590

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S.H.Putman Associates, Inc.

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Acknowledgments

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SHP - 14 August 1998

1 - Executive Summary

1.1 Background

With the passage of the Clean Air Act Amendments of 1990 (CAAA) and the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), and now the Transportation Equity Act for the 21st Century (TEA21), the questions asked of the traditional travel forecasting process have increased in complexity and impact. In particular the process now must answer questions regarding air quality, land use, demand management and the impact of new infrastructure. Many of the questions now being posed to the process had not been previously asked.

The consistency requirements of both acts explicitly recognize the inter-relatedness of transportation and land use. As such, the acts assume the need for a proper representation of those linkages between land use and transportation phenomena which can significantly alter long range forecast results. The need for a representation of transportation land use interactions in forecasting has long been discussed in the profession. Much of the discussion in transportation and land use planning practice, when it does acknowledge the potential importance of these interactions, addresses this issue in terms of requirements for equilibrium solutions. What is not clearly known, is: a) whether such solutions are computationally practical; b) whether they will differ significantly from solutions achieved in the absence of formal linkages between the two forecasting activities; and c) whether they will actually be better forecasts of the future land use and transportation reality.

In order to address these issues, the Federal Highway Administration sponsored this study to perform a comprehensive series of tests, within the context of the forecasting process, to determine the criticality of the consistency issue, identify conditions under which it must be addressed, and make technical recommendations for methods to modify existing procedures.

1.2 The Questions to be Investigated

In brief, the purpose of this project was to answer the following ***four questions:***

> ***1. Does a linked transportation and land use model system produce results, forecasts, which are different from those which would be produced by an unlinked system?***
>
> ***2. Is the implementation of such linked model systems practical in a planning agency context?***
>
> ***3. If the results from a linked model system are different from those produced by an unlinked system, and if it is practical for planning agencies to produce these consistent forecasts, then are the results sufficiently different to warrant the additional cost of obtaining them?***
>
> ***4. If the forecast results are sufficiently different and may be practically obtained in agency practice, is there a way in which an agency could determine, without actually***

4. If the forecast results are sufficiently different and may be practically obtained in agency practice, is there a way in which an agency could determine, without actually having to do all the work of implementing an integrated model system, whether it will be worth the effort, in terms of the significance of the forecast differences, in their particular region?

1.3 The Answers We Found

With regard to Question 1 we found:

- *It is virtually certain that systematic errors in transportation and/or land use forecasts will result from any attempt to produce forecasts of the one without some form of direct connection to the other. The more difficult question is to determine what sorts of connections between transportation and land use forecast methods should be made.*

- *When, in this study, the comparisons between alternative integrated transportation and land use models were made in terms of changes in employment and household levels, there were, for at least some variables in all regions, significant differences in the results produced by the sequential model configuration runs when compared to the results produced by the equilibrium model configuration runs.*

With regard to Question 2 we found:

- *These model system configurations can be, and have already been, implemented within a regional planning agency (MPO) context.*

With regard to Question 3 we found:

- *Only under the most unusual of circumstances would we not expect significant systematic errors in forecasts made without any feedback between transportation and land use. By unusual circumstances, we refer to a region where there is no traffic congestion, nor is there expected to be any during the entire forecast period, and where no significant alterations to the transportation system are expected to take place, and where there will be no significant changes in regional totals or geographic distributions of population and/or employment.*

- *Once having taken the step of deciding to implement either form of model system configuration with feedback, the difference in "cost" between system configurations such as those examined here is minimal.*

- *The final decision as to the need for the full equilibrium system can be deferred until the completion of the sequential system implementation.*

With regard to Question 4 we found:

- *Again, only under the most unusual of circumstances would it be possible to justify transportation forecasts made without any input (or feedback) from land use.*

- *Each of the two sets of models, transportation, and land use, requires inputs from the other in order to make reliable forecasts. In order to accomplish this, the minimum workable degree of connection between the models is embodied in the sequential model system configuration. The use of unconnected transportation or land use models to make forecasts, most especially long term forecasts, in regions of 250,000 or more population simply is not likely to produce consistent and reliable results.*

- *The responsiveness of the land use models to changes in travel times (i.e., "feedback" from the transportation models) is primarily determined by the travel time elasticities of the employment and household location models and by the travel time aggregation procedure(s) necessary to link the models. The responsiveness of the transportation models to changes in employment and household locations (i.e., "feedback" from the land use models) is primarily determined by the level of congestion on individual network links.*

- *If the particular household and employment location models being used, or considered for use, provide for the calculation of these elasticities as part of the process of calibration, or the statistical estimation of their equation coefficients, then it will be possible to have some advance indication of the likely responsiveness of the land use models to changes in travel times or costs.*

- *Errors are introduced into the forecasts in both the disaggregation and the aggregation procedures. The tension here is because, it is currently impossible to get the data necessary to operate the land use models at the same fine geography that the travel models use. Similarly, the more one aggregates the travel model geography the less reliable are the estimates of network link flows and congestion. This is the main cause of the poor results to be had from sketch level network analysis.*

- *By examining the frequency distributions of the link volume/capacity ratios for the modeled network, along with knowing the functional forms of the volume/delay functions, it will be possible to estimate the likely sensitivity of the combined model system forecast to changes in travel patterns and link flows.*

- *The use of the equilibrium model system configuration can compensate for errors in the application of specific models or submodels in the overall system.*

- *When used for policy comparison, the equilibrium model system configuration will provide more reliable forecasts of the differences between policy alternatives.*

1.4 Conclusions

For nearly half a century transportation planners have been making use of increasingly complex computer models for forecasting the consequences of construction of, and modifications to, transportation systems. For most of that time, and in the majority of instances, the inputs, especially the employment, household, and land use inputs, to their forecasting models have been considered only as an afterthought. For at least two decades there has been ample evidence that transportation and land use do affect one another. To be sure, there continues to be scholarly discussion, not to mention heated debate in which some of the vocabulary is not at all scholarly, on the strength of the interaction between transportation and land use. Even so, transportation modeling has received several orders of magnitude more funding than land use modeling. The reasons for this funding imbalance could be debated endlessly, but the facts of the amounts are indisputable. Yet, withal, it is more than a little difficult to accept the proposition that transportation planners could estimate the travel demands which are likely to be placed on their networks in, say, the year 2020, with out doing some rather sophisticated forecasting of the inputs to the travel demand processes. These inputs, inevitably, are employment and residence location and land use. Over such long time periods, the location of employment and residences will be affected by transportation facility attributes, as well, for that matter, as interaction with each other. It makes no sense to do forecasting of travel demand or of employment and household location in isolation one from the other.

This study examines the alternative configurations which are currently and readily available to allow integrated transportation and land use forecasting. We demonstrate that such forecasts can be implemented in regional planning agencies, MPO's, in various sizes of region. We then go on to demonstrate the effects of alternative model system configurations, and provide some guidelines which will allow an agency's technical staff to make informed decisions as to how to modify their own transportation and land use modeling processes in order to produce more reliable forecasts and policy evaluations.

2 - Introduction and Study Purpose

2.1 Introduction

There are relationships between transportation and land use. Transportation affects land use. Land use affects transportation. These statements have been made by planners, economists, engineers, legislators, and politicians, not to mention business persons and the population at large, for decades, perhaps for centuries. Since the middle of the twentieth century attempts have been made to quantify this relationship with respect to the specific effects that changes in transportation systems might have on residential and/or commercial location, and vice versa (e.g. Mitchell and Rapkin, 1954). Highway impact studies were done repeatedly, in numerous cities and towns across the United States, as a part of the federally required assessment of the impacts of new roadway construction[1]. Taken all together, for the most part, these studies were not definitive, and were conducted in the absence of the well defined corpus of theory which would have been necessary for their more satisfactory preparation. Over the years since mid-century there have been numerous attempts to legislate the integration of transportation and land use planning in order to produce more reliable, and at the very least more consistent forecasts of the consequences of proposed plans, both for transportation and for land use. Many, if not most, of these legislative initiatives have been honored more in the breach than in the respecting of their goals.

Through all of this the use of computer models of transportation, demand as well as route choice, for example, have been in continuous use by regional and metropolitan transportation planning agencies. Their counterpart models of employment and household location and land use have not enjoyed anywhere near so universal an acceptance of their practice. In fits and starts, there have been periods when many agencies were attempting to make use of some form of land use model to provide projections, policy analysis, and simple inputs to the transportation models. Even so, far more agencies today, within a few years of the end of the century, still rely on various simplistic and non-systematic means to do this work.

What has been different over the past five years or so, at least for the larger urban areas, and most especially for those with air quality problems, has been the combined requirements of the Clean Air Act Amendments of 1990 (CAAA), and the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Taken together these acts require, in urban areas above a population of 250,000 and where air quality standards are being violated, that the inputs to the air quality models used to evaluate transportation proposals be consistent. This is generally taken to mean that there must be an appropriate connection between the transportation and the land use models which are used to prepare the inputs for air quality forecasts[2]. In response to this, many agencies are

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[1] For an excellent overview of the history of these and other aspects of transportation planning in the United States, see Weiner (1992).

[2] A very fine discussion of these issues may be found in the Transportation Research Board's Special Report 245 (1995)

the need to integrate their transportation modeling procedures with some form of land use model (or model package). While there had been research done in this area prior to the late 1980's there had been no actual agency application of such a linked, or integrated, transportation and land use model system (Putman, 1983, 1991, Webster, et. al., 1988). As such, there was some consternation amongst agency practitioners as to whether these integrated model systems were a practical proposition for application. The idea for conducting this study arose at the same time that the first practical applications of these integrated model systems were being implemented in U.S. planning agencies.

The purpose of the study has been to explore the consequences of implementing these more complex systems of computer models. In particular it was hoped that we could establish first, whether use of a linked, or integrated, transportation and land use model system would produce results, forecasts, which were different from forecasts that might be produced in the traditional way, where the transportation and land use forecasts were not connected one with the other. Then, second, we were to determine the extent to which the implementation of such model systems was practical in the operating, planning, agency environment. Third, if the systems were practical, and if they gave different results, were the results sufficiently different to warrant the expense of obtaining them? Finally, were there means by which an agency could determine, in advance of actually implementing the full fledged model system, whether it would be worth, in the sense of the above questions, the effort?

2.2 What is an Integrated Transportation and Land Use Model System?

Beginning with Federal Highway Administration sponsorship in 1971, Professor Stephen H. Putman, Principal of S.H.Putman Associates began the development of what is now known as the Integrated Transportation and Land Use Package (ITLUP). The specific intent of the development of that package was to attempt to capture the interrelationships of transportation and land use. The original research performed using this model package, developed in a university setting, clearly demonstrated the general importance of these linkages, previously overlooked in transportation policy analyses (Putman, 1973). Another output of this work was the inclusion, in the early 1980's, of the land use model portion, the models EMPAL and DRAM, of this package in a preliminary form, as part of the final release of the Urban Transportation Planning System (UTPS) package distributed by the US Department of Transportation. Shortly thereafter the USDOT discontinued support of the UTPS package. Even so, since that time extensive revisions and modifications to all portions of the Integrated Transportation and Land Use Package have been made. All or portions of it, principally the EMPAL and DRAM models, have been applied in more than fifteen different metropolitan areas in the United States, as well as in cities overseas.

The overall integrated transportation and land use approach, as embodied in a linked system of computer programs and procedures, involves several major components. These are: (1) a set of procedures for forecasting the spatial location of employment and households in a metropolitan region, (2) a procedure for using these location forecasts to produce a set of origin destination trip matrices, (3) a procedure, when appropriate, for doing mode split analysis, (4) a procedure for assigning highway and transit (in most cases only highway) trips to a capacity-constrained highway network and (5) a set of procedures for linking the congested travel times back to the employment and household forecasting procedures in order to complete the feedback loop. Such an integrated process, overall, is the only approach which allows for the explicit representation, analyses, and evaluation of the effects on traffic congestion and transportation efficiency of changes in urban design and land development patterns in combination with socio-economic changes in the region. Decades of transportation and land use studies of every sort have shown us that there clearly are relationships between transportation and land use or land development. However, if we look over all these many studies, it is sometimes very difficult to understand how the varying results that were obtained can all be considered as being logically consistent.

One of the important results which followed from the development of an integrated transportation and land use model package was that it's overall construct provided a way in which it could be seen that the apparently conflicting results from transportation and land use studies were in fact conflicting only because of the ways in which they were being viewed. The most obvious example is in some of the traditional approaches to solving local congestion problems. In such cases, a study will be done of a physical transportation facility and need will be defined for increased capacity of one sort or another on the network. Such capacity will be constructed and will result, in the *short-term*, in an improvement of vehicle flow and a reduction in the observed congestion. Unfortunately, in the *long-term*, such strategies often have just the opposite result. The increased network capacity is used by trip makers to make more trips and/or longer trips. Thus, in the long-run, it has often been the case that an improvement in a transportation system, most frequently in terms of highway construction, while having a short-term effect of improving the situation for travelers, has a long-term effect of doing just the opposite. Indeed, one of the consequences of highway construction in the absence of demand management or urban design, in an attempt to in some way regulate land use and land development, has been to spread greater network congestion over a larger number of links in the network. The traditional transportation planning approach makes it very difficult to anticipate these kinds of system responses to particular policy implementations. In this traditional sort of analysis, a series of exogenously produced estimates of trip demands, usually in the form of origin destination trip matrices, is calculated using exogenously estimated sets of socio-economic data.

Let us consider, for example, an agency preparing, in 1990 or 1995, long-term transportation plans for the year 2010 or 2020 or beyond. In such a case, typically, a series of socio-economic forecasts, in terms of employment locations and household locations spatially distributed over a large region, would be prepared first. These would in some way be based upon information about the highway system that the region was expected to have, though in fact, there would be even at this stage in the process an inconsistency, because the system that the region would be expected to have would show different characteristics to users as a function of what the users were doing about using the system. In any case, a set of forecasts would be developed and then, based on the forecasts of the location of employment and households, a set of estimates would be made of numbers of trips originating from each zone and terminating in each zone. Next some form of trips distribution procedure would be invoked, which would calculate the number of trips going from each particular origin zone to each particular destination zone in the region. These trips, or some portion of them that were expected to be highway trips, would then be assigned to the links of the proposed highway network. Any of a variety of trip assignment algorithms might be used. The intention of any of them would be to calculate how many trips would travel across each of the individual links in the highway network. Then, based on the number of trips using each link, an estimate would be made of the congestion, the increased time and/or cost, that would be experienced by each of the users of that particular link in the network.

Once these congestion levels had been calculated for all of the links in the network, it would then be possible to trace through the network the minimum cost paths from each zone to each other zone over the congested network. Looking at these minimum cost paths, as well as at the congestion levels on individual links of the system, the conventional analysis procedure would then identify links which should have capacity increases which normally would be accomplished by construction or modification of one sort or another. Once these links had been identified, construction projects could be described and budgeted and the analysis would be completed in the form of a set of recommendations as to places where the network could be improved.

The principal failing of this procedure is that the congestion which results from the initial estimates of trip makers, and thereby from the initial estimates of the locations of employment and households would, in and of itself result, over a span of years such as that with which the forecasts traditionally are concerned, in a rearrangement of the locations of employment and households. This means that in order to properly estimate the congestion, it is in effect necessary to know the congestion. And in order to properly know the congestion, it is necessary to know the location of employment and population and the resulting demand for trip flow on the network and so on and so forth. The system which the traditional transportation modeling process is attempting to describe is a classic example of a complex system containing a mix of both fast and slow disequilibrium adjustment mechanisms. Such systems can only be properly analyzed by use of some form of interactive (integrated) technique which explicitly represents both the direct and the indirect connections or, as it is sometimes described, both the feed-forward and the feed-back connections amongst the system elements.

A complementary system to this one is the system of traditional land use analysis, or traditional urban design analysis. In such a case, what is normally done is that descriptions of the transportation system, which may include highway as well as transit, are taken from exogenous (to the model system) sources. That is to say, somewhere someone will provide an estimate of the zone to zone travel time and travel cost on various modes that a user might experience, let us say again in the year 2010 or 2020[3]. Based on these estimates of the transportation system attributes, and on a set of regional forecasts of employment and households, as well as on initial

[3] Though, in fact, even as we enter the twenty-first century, some major planning agencies continue to make use of land use forecasting procedures which entirely overlook transportation system characteristics as a determining factor in employment and household location.

data describing the locations of employment and households, a calculation can be made which will estimate the location of employment and households in the various zones of a large region. Often, a whole series of such forecasts will be made, done at five or ten year intervals from some base year, out to some long-term planning horizon.

The difficulty with this approach, which is analogous to the difficulty with the traditional transportation planning approach, is that no cognizance is given to the fact that these locations of employees and households will, by virtue of the trips necessary to interconnect them, themselves result in network congestion. The congested network times will in most cases be somewhat, if not significantly different, from the initial estimates of the network times. And again, clearly, that what is needed is some kind of interactive forecasting procedure which combines both the effects of the location of employees and households on the transportation system as well as the effects of changes in the transportation system characteristics due to congestion on the location of employees and households.

It is precisely this interactive process that the integrated transportation and land use package was designed in to represent. As such, this process properly reflects the transportation and land use consistency which is required as input to the air quality estimates now required by the CAA and ISTEA. Even the earliest test of the integrated transportation and land use package, done more than twenty five years ago, shows that the interrelationships between transportation and land use can be just as important and in some cases more important than the individual direct consequences of either set of phenomena (Putman, 1973). Having articulated a framework for examining, or analyzing, or understanding the transportation and land use interactions, it then becomes possible to consider the consequences of a wide assortment of different kinds of policies. Policies which attempt to achieve their aims by changes on the demand side, in terms of urban design policies, land use control policies, and such like, as well as policies which attempt to achieve their aims by acting on the supply side in terms of various kinds of transportation improvements, either in highways or transit or combinations thereof, as well as in access and increases in utilization efficiency of existing facilities.

2.3 The Plan of the Study

The major focus of this study has been on comparison of the results from a substantial set of numerical experiments (computer runs) of integrated transportation and land use model packages. The purpose of these runs was to provide sets of forecasts derived from common data sets and models, with the difference from one computer run to another being solely du to the configuration of the linkages, if any, amongst the models. In order that the bulk of the project's resources be devoted strictly to making the model system configuration comparisons, it was necessary to make use of existing location and land use models in combination with existing transportation models, and that the work be done in cooperation with an MPO (later with several MPO's) where the necessary models had already been installed and calibrated. While all MPO's had fully operational transportation model systems, rather few of them had operational land use model systems. Of those agencies doing formal (computer based) land use modeling, at the time of this study, the overwhelming majority were making use of EMPAL and DRAM. In order that this study could focus on the differences in model system outputs which were due solely to differences in the transportation to land use linkages, it was desirable to have all the test regions making use of identical model systems. As this was not possible on the transportation model side, it was hoped that at least the land use side could be kept "constant". We are of the opinion that most of the conclusions from this work would also apply to transportation models linked to other employment and household location models, provided that those model were, themselves, properly sensitive to travel times and/or costs. For application purposes, agencies with existing transportation modeling capabilities already adjusted, adapted, and properly installed for agency use, had found it quite convenient to connect their existing transportation models to the EMPAL and DRAM models for the forecasting of employment and household locations. What is important however, in terms of an integrated analysis, is that having made the connection from the network analysis in terms of congested travel times as input to EMPAL and DRAM to calculate the relocation of activities, that the process then be connected at the other end, with the outputs from EMPAL and DRAM becoming inputs to the trip generation, mode split and distribution procedures. Then, following the trip assignment, the congested network times and/or cost become input to a subsequent recalculation of the EMPAL and DRAM procedures to estimate employment and household changes which might take place as a result of the network congestion.

In this way, for example, one could take the outputs of EMPAL, which are the forecasts of employment by zone in the region, and link them to DRAM to calculate the forecasts of households by income and of land use by zone for the region. One could then use these as input to the trip generation and distribution components of some standard transportation planning model package such as EMME2, MINUTP, or TRANPLAN, and then having completed the assignment of trips to the network using this package, calculate the minimum paths through the networks. If multiple modes are being analyzed then the minimum times through the networks via these different modes would all be calculated. They would be combined in a composite cost calculation and the composite cost estimates of zone to zone composite travel times or travel costs would then be taken and used as inputs to recalculation of employment and household location by the EMPAL and DRAM models. This was the procedure followed in this study.

The initial computer experiments were performed using the data and models developed at or by the Metropolitan Service District (METRO) for the Portland, Oregon region. METRO already had operational versions of EMPAL and DRAM which had previously been calibrated for the region's data. METRO was making use of their own suite of travel demand models, and was a licensed user of the EMME2 transportation model software, which they were using for their trip assignment work, amongst other things[4]. Work on this project began with our work at METRO.

Prior to the start of work on this project **S.H.Putman Associates** were working with the

[4] EMME2 is a proprietary software package developed and distributed by INRO Consultants Inc., Montreal (Quebec), Canada

Southern California Association of Governments (SCAG) to first implement EMPAL and DRAM for the southern California (Los Angeles) area and second, to assist SCAG in connecting these models to their existing travel model system. With the calibration of EMPAL and DRAM having been completed initial work had begun on the linking of these models to SCAG's transportation models. SCAG was making use of the TRANPLAN transportation model software for both travel demand and trip assignment[5]. In the summer of 1993, the first runs were completed of a linked, equilibrium seeking, transportation and land use model system using the data and models implemented at SCAG. By the start of this project it had thus been demonstrated that linked model systems of this sort could be made operational in a planning agency setting.

Several months were spent working with METRO to do the improvements to EMPAL and DRAM, involving both model development, and on the part of METRO, of data development to support some of the computer experiments. In addition, it was decided that the forecasts developed (produced) for this study should, at least in the first instance, not be radically different from those in current use at METRO. The reason for this was NOT that these model studies were to be used for any of METRO's purposes, but rather that it made sense not to cloud the issue of the model system comparisons with wide differences from METRO's accepted forecast future. This goal proved much more elusive than we originally expected. Each time it seemed that the desired results had been obtained, there were changes in the data from METRO, or revisions in METRO's opinion as to which were their best forecasts. Eventually, with METRO staff agreement, we arbitrarily selected a particular set of forecasts, known as Base Case IIA, to be the "target" for our own baseline forecast runs. Adjustments were made to the zonal attractiveness measures in both EMPAL and DRAM, and our own baseline (BLN) run was thus made to conform relatively closely to METRO's Base Case IIA[6].

It soon became clear that there was sufficient interest in the possible outcomes of this study that it made good sense to extend it to examine more than just one metropolitan area. **S.H.Putman Associates** offered to include, at no additional cost to the study sponsors, comparable model run examinations of the SCAG integrated model system[7]. At an even later date, FHWA suggested that the generality of the study results would be greatly enhanced by the inclusion of additional cities of different sizes and/or types. This resulted in the provision of supplementary funding to cover the eventual inclusion of computer model system examinations of the Pikes Peak Area Council of Governments (PPACoG) in Colorado Springs, CO, the Mid-America Regional Council (MARC) in Kansas City, and the Southeast Michigan Council of Governments (SEMCoG) in Detroit. At an even later date, with separate funding, a similar set of tests were conducted for the Sacramento

[5] TRANPLAN is a proprietary software package developed and distributed by The Urban Analysis Group, Danville, CA.

[6] It is important to note that this effort has NO effect on the subsequent model system comparisons.

[7] This was made possible by SCAG's offering us access, at no charge, off business hours, to their computer system for remote log-in and model execution.

Area Council of Governments (SACoG) in Sacramento, CA. These results were consistent with the previous ones, and were also used to develop our conclusions. Overall, then, six different metropolitan regions were eventually studied as part of this work.

For each region, all of whom had their own implemented versions of EMPAL and DRAM, and a travel demand and trip assignment model package, either EMME2, MINUTP[8], or TRANPLAN, the first step was to develop an initial model run for a single five year period, from 1990 to 1995. Actually, even before models runs could be contemplated, it was necessary to install the hardware and software necessary to implement some form of remote connection to each agency's computers. In some cases this was a rather straightforward matter, while in others there were numerous arcane complexities to be overcome before an operational remote link was established. Once we were able to link into each agency's computers, we could begin to attempt a first set of trial model runs. In the preparation of this first model system run for each region, there were many steps which had to be taken, as myriads of small details needed resolution. A list of these "details"includes such matters as 1) checking the consistency of data files, 2) determining the compatibility of the impedance (travel time) matrices used in the EMPAL and DRAM calibrations with the impedances used to start the combined model system runs, 3) developing the procedures to do both geographical and variable specific disaggregation from the land use model level of geography to the transportation model level of geography, 4) working out the necessary consistency in the travel models themselves with respect to peak-hour, daily, or whatever, trip factors, 5) developing the procedures to aggregate the congested travel times back up to the land use model geography from the transportation geography, 6) where necessary, developing the means for calculating the convex combinations of link volumes necessary for the operation of the algorithm (MSA) which ensures the convergence of the equilibrium seeking model system configurations. There were other matters as well. What we were doing in this initial process was getting the integrated model system configurations worked out and operational for each of the regions.

Once a preliminary run of the set of integrated models had been completed for a particular region, the next step was to do a formal baseline run. In each case, the runs were made by using the agency's existing implementation (sometimes with necessary simplifications) of their transportation models and their EMPAL and DRAM models. As a consequence we assumed that the 1995 forecasts produced would be relatively close to those being used by the agency. In each case the baseline run (BLN) was done using what we refer to as a sequential model system configuration, which is defined fully in Chapter 3. The successful completion of the baseline run was then followed by an equilibrium (EQL) run, in which an equilibrium procedure was included. At that point it became possible to compare, in each region and, as each succeeding region's runs were completed, from one region to another, the results obtained from the two different model system configurations.

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[8] A sixth region, Sacramento, CA, was analyzed for the purposes of another research project after the completion of the computer work for this project. That regional agency, the Sacramento Area Council of Governments (SACoG), made use of the MINUTP travel model software. The results of that project, as they pertain here, were similar with respect to tests of integrated model system configurations.

Following the successful running of both the sequential and the equilibrium system configuration runs from 1990 to 1995, the models, for each region, were run on out to the forecast horizon year of 2010. Again, comparisons were done between the results from the baseline runs made using the sequential model system configuration, and the equilibrium runs made using the linked, equilibrium, configuration.

2.4 Overview of this Report

This report contains eight chapters. The first chapter was an executive summary of the project. Following this second, and introductory chapter, is the third chapter, which contains a description of the different model system configurations that were examined and for which computer test runs were performed. The fourth chapter presents a description of each of the five regions whose data and models were used for this study. The fifth chapter reviews the method followed in the performance of this study, and the transportation model system configurations in use by each of the five regional agencies with which we worked. The sixth chapter presents empirical results from the computer runs which were done, with a particular focus on a comparison, within study regions, between the results obtained from the two principal model system configurations tested. The seventh chapter is a continuation of the presentation of empirical results, but in this case with an emphasis on region-to-region comparison in an effort to develop general conclusions. The eighth and final chapter contains our conclusions and recommendations regarding the use of integrated transportation and land use models in agency application.

3 - Definitions of Alternative Model System Configurations

3.1 Introduction

All the various ways in which an agency might (or might not) link their transportation models to their land use models, if they are using land use models, can be considered as being of three major types. We refer to them here as: 1 - No-Feedback, 2 - Sequential, and 3 - Equilibrium. Within each of these types there are many possible variations and elaborations, but the general structures are the same. The point of specifying this typology is to provide a structure within which to consider the many possibilities.

The purpose of linking models of complex phenomena is to provide a means by which the results of the models can affect each other and thus represent relationships between the modeled phenomena. In the case of transportation models, quite apart from the possibility of their being linked to land use models, there are usually a variety of links between trip generation models, trip distribution models, mode split models, and trip assignment models. Amongst these there may be different configurations of direct and indirect connection, each of which is intended to add greater accuracy and reliability to the model outputs. Similarly, if the modeling of employment and household location and land use is done by separate models, they too may be linked in various ways. Here the point of linking the models is to provide for the interaction between various categories of locator such as households and employment. In this report we are principally concerned with land use - transportation interactions, but recognize, and in some cases analyze land use - land use interactions as well as transportation - transportation interactions.

Taken together, the possibility of linking transportation and land use models is entertained specifically for the purpose of improving the accuracy and reliability of forecasts from both components. Transportation models may produce better forecasts, and thus be of greater use in planning, when they are linked to land use models. In the same vein, land use models may also produce better forecasts if they are linked to transportation models. Thus there is the potential for both activities, transportation planning and land use planning, to benefit from such linkages between their analysis techniques. In the following discussion we will present the major possible model system configurations along with comments on some of their advantages and disadvantages.

The chapter is arranged into four sections following this introduction. The first section briefly describes the No-Feedback model configuration, and is followed by a discussion of the Sequential configuration. The third section contains a description of the Equilibrium model system configuration, and is followed by a brief set of conclusions.

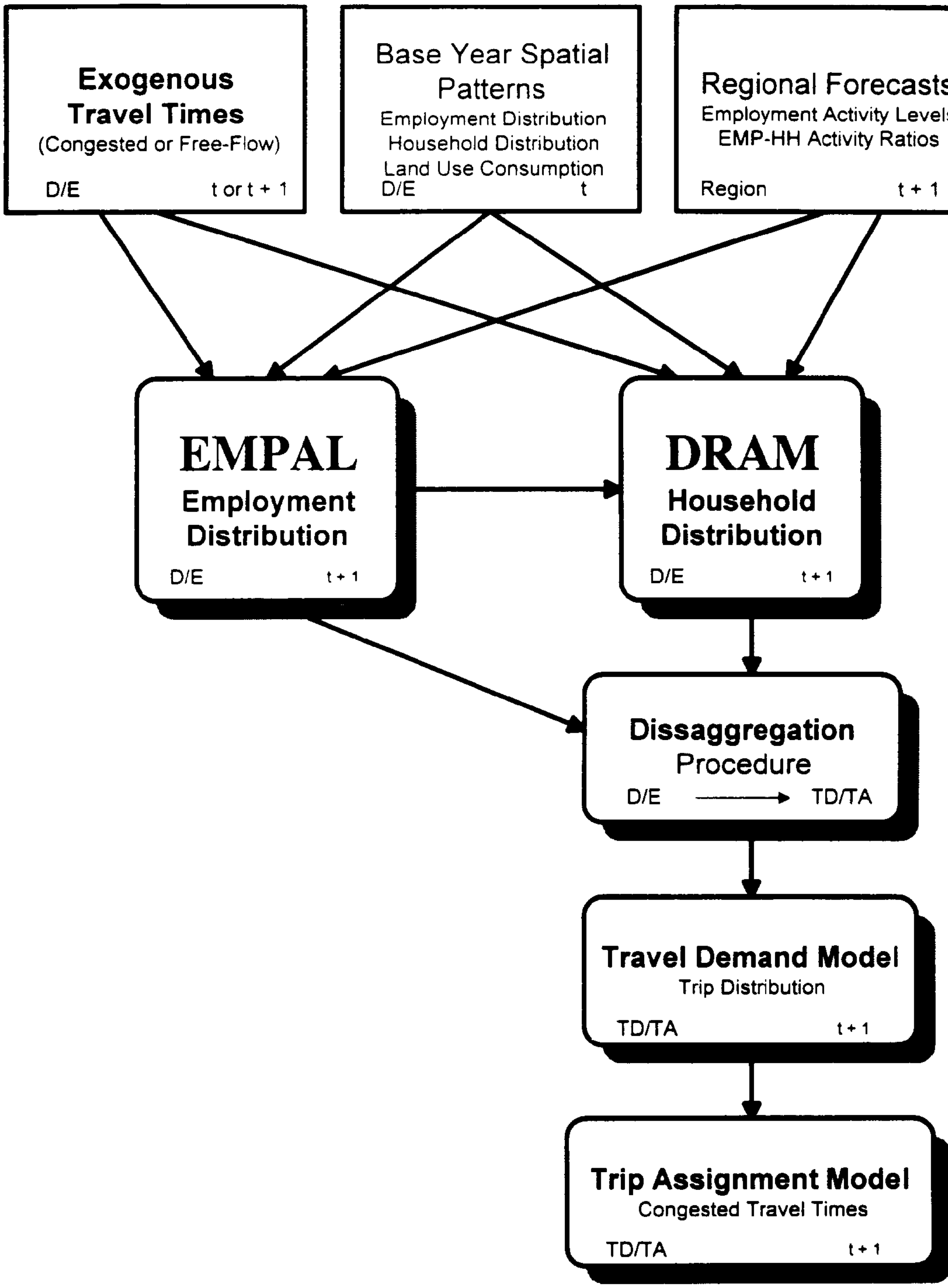
3.2 The No-Feedback Model Configuration.

If it weren't for the fact of its being a rather commonly used model system configuration, this could almost be called a "straw man" configuration. It is important to note that some agencies have no formal modeling procedure for the development of land use forecasts, and other agencies that may have such procedures make no attempt to use the resulting forecasts as input to their transportation modeling process. In some cases the land use, or socio-economic forecasting activities of a regional agency are carried out in a manner which is entirely independent of the transportation planning activities. Similarly, the transportation planning and forecasting work is done in a manner entirely separate from land use planning efforts. This complete lack of connection is, in part, responsible for many unpleasant surprises in planning, where, for example, roads are highly congested long before they were expected to be, or employment and household developments "pop-up" in places where they were not expected. The use of modeling (or non-modeling) approaches where there is a total lack of connection between the two forecasting and analysis efforts, while still found to be the state-of-practice in some agencies, is beyond the scope of the "model configurations" examined in this study.

Next up from a no land use modeling approach and/or no procedural connection to transportation modeling is the configuration which we refer to as the No-Feedback configuration. It is likely that this approach will lead to incorrect forecasts as well, but here at least the two planning activities are cognizant of each other, even though the work is done independently. In this study we define the No-Feedback configuration to be the least connected model configuration that would be worth considering, and that we do only by mention. Even so, many planning agencies, today, at the close of the twentieth century, are making forecasts of location and land use, and forecasts of transportation network loadings and congestion, without any formal connection between the two processes. ***Only in the case where it could properly (correctly) be said that the transportation network(s) in a particular region were both, 1) adequate to accommodate all future traffic with absolutely no increase in travel times and/or costs due to congestion, and 2) never going to be modified by the addition of new links, would it be possible to justify not connecting the travel models to some form of land use model.*** Even in such a case, the land use forecasts would undoubtedly benefit from being prepared in a recursive fashion, with the models for, say, employment and residence being linked together, and running in five year steps. In this way the effects of changes in residential location and employment location would affect each other in subsequent time periods. Even if the transportation system were never going to be changed or get congested, it is still likely that there would be moving about of places-of-work and places-of-residence in the region.

Perhaps the most succinct way of pointing out the problem with a No-Feedback model configuration is that in such cases it would be possible to prepare the forecasts for the year 2020 before having prepared the forecasts for the year 2010. Since it is virtually certain that the location of activities and the trip patterns of 2010 have some effect on the patterns of employment and household location and on the patterns of trip making in 2020, it is clear that a model system configuration which ignores even this simple temporal sequence in the model structure is likely to give unreliable forecasts.

For purposes of illustration and comparison with the other model system structures, the No-Feedback structure is given in Figure 3.1. Notice that the forecast procedure begins with exogenous travel times between the zones which are defined for the "land use" models EMPAL



"No-Feedback" Model Configuration

Figure 3.1

and DRAM. The geography (level of geographic disaggregation) for the data or process defined in each box is shown by the small letters in the lower left corner of each box. D/E refers to the geography for the employment and household location - land use modeling work, and TD/TA means the geography for the travel demand - trip assignment modeling work. In the lower right corner of each box is an indication of the time period of the data or process, with t for current year, and t+1 for future year.[9] The other inputs to the model process are the base year data which describe the spatial patterns of employment, households, and land use, and the forecast year data which describe the regional totals as well as the regional activity ratios such as population-per-household, employees-per-household, rates of unemployment, and others. All these items comprise the input to the two land use location models.

The location/land use models are then executed. EMPAL is run first, to produce forecasts of the time t+1 location of employment at place-of-work. Next, DRAM is run to produce forecasts of the time t+1 location of households at place-of-residence. This is followed by a Disaggregation Procedure which converts the outputs of the two models at the D/E level of geographic detail to the appropriate set of travel model input variables at the TD/TA level of geographic detail. It is important to note that for some agency's model structures the Disaggregation Procedure may be required to accomplish both a geographic transformation as well as conversion and/or estimation of additional variables. As an example, some travel demand models require, as input, future year estimates (forecasts) of automobile ownership rates per household. These are not forecasted by DRAM and EMPAL and so must be calculated (forecasted) by a post-processing model which could be embedded in the Disaggregation Procedure. There is currently no standard way of accomplishing these tasks. In some cases the geographic disaggregation is done first, and is followed by conversion of variables. In other agencies the process is reversed, with additional variables being generated at the D/E geography and then being disaggregated to the TD/TA geography. Finally, some agencies use a mix of processes, with some variable conversion and/or estimation both before and after the geographic conversion.

Noting again that in many agencies' practice, there is no such connection, if there were such a connection then this structure would continue with the running of the Travel Demand and Trip Assignment models. What would happen to the outputs of this process depends upon the local circumstances. There may or may not be a review process to determine whether models should be rerun with modified inputs. Most important is the fact that there is no formal means for connecting the congested travel times[10] back to the employment and household location and land use forecast, and they will in all likelihood have been produced in the absence of any travel time/cost data at all, or with

[9]Note that even though the convention of t and t+1 are used here, the normal case is for the time periods to be five years in length, meaning that the time points referred to here will be five years apart. Thus if t was 1990, then t+1 would indicate the next time point, or 1995.

[10]In some agencies transportation models there is no congestion, as the transportation models are run for twenty-four hour link volumes and capacities, and virtually no congestion is manifested.

network free-flow times. As stated above, only in very rare circumstances would we expect that following this approach to the transportation and land use forecasting and planning needs of a metropolitan region could yield reliable results. These circumstances are so rare as to make it a virtual certainty that the use of a No-Feedback model configuration will never be adequate for any metropolitan planning agency's operational planning and forecasting needs.

3.3 The Sequential Model Configuration

The first model system configuration to be seriously considered in this study is what we call the Sequential configuration. Here the output of the employment and household location and land use model forecasts becomes input to the travel models which, in turn, produce forecasts of the congested network travel times or costs. In the subsequent time period the congested network travel times become input to the employment and household location and land use models. This step, here again, assuming that the travel models are being run in such a way as to permit whatever congestion may exist in the region to become manifest on the modeled networks. In diagrammatic form, the Sequential model structure is shown in Figure 3.2. ***This structure is the least sophisticated model configuration that any transportation and/or land use planning agency could expect to produce reliable forecast results in practice***. As mentioned above, even though there may not be much network congestion in a particular region, network additions to previously unserved areas will have observable and analyzable effects. Further, the simple process of proceeding through the forecasting effort in a recursive[11] fashion is likely to improve the accuracy and reliability of the forecasts produced. There also are links between the locations of employment and households that the Sequential configuration captures. Consider, for example, the suburbanization of employment which followed the initial suburbanization of population in most metropolitan areas. The employment relocated, at least in part, in response to the new locations of the population which served as both market for retail trade, and labor supply for skilled occupations. A forecast procedure which did not make use of recursive linkages would be incapable of capturing this employment suburbanization phenomenon.

The diagram of the structure can be seen to differ from the No-Feedback form by the addition of three boxes. First, note that there is a separate indication of input of travel times to the travel demand models. This is to show that these times may differ from the times which are used as input to subsequent recursions of the entire system, starting with the EMPAL and DRAM forecasts. In virtually all cases, these times would at least differ from the times used as input to EMPAL and DRAM by virtue of the fact that the travel demand modeling is done at a finer level of geography. Further, while most agencies use loaded network, or congested, times as input to the travel demand models, there are some agencies where only unloaded or design, or policy, times are used. There are also issues, as mentioned above, regarding the use of daily link volumes and link capacities, versus using peak hour volumes and capacities.

[11]By recursive, we mean a simple passing of the outputs of one model to the next. There is no attempt to represent any sort of equilibrating process, only a sequence of one model's outputs becoming inputs to the next.

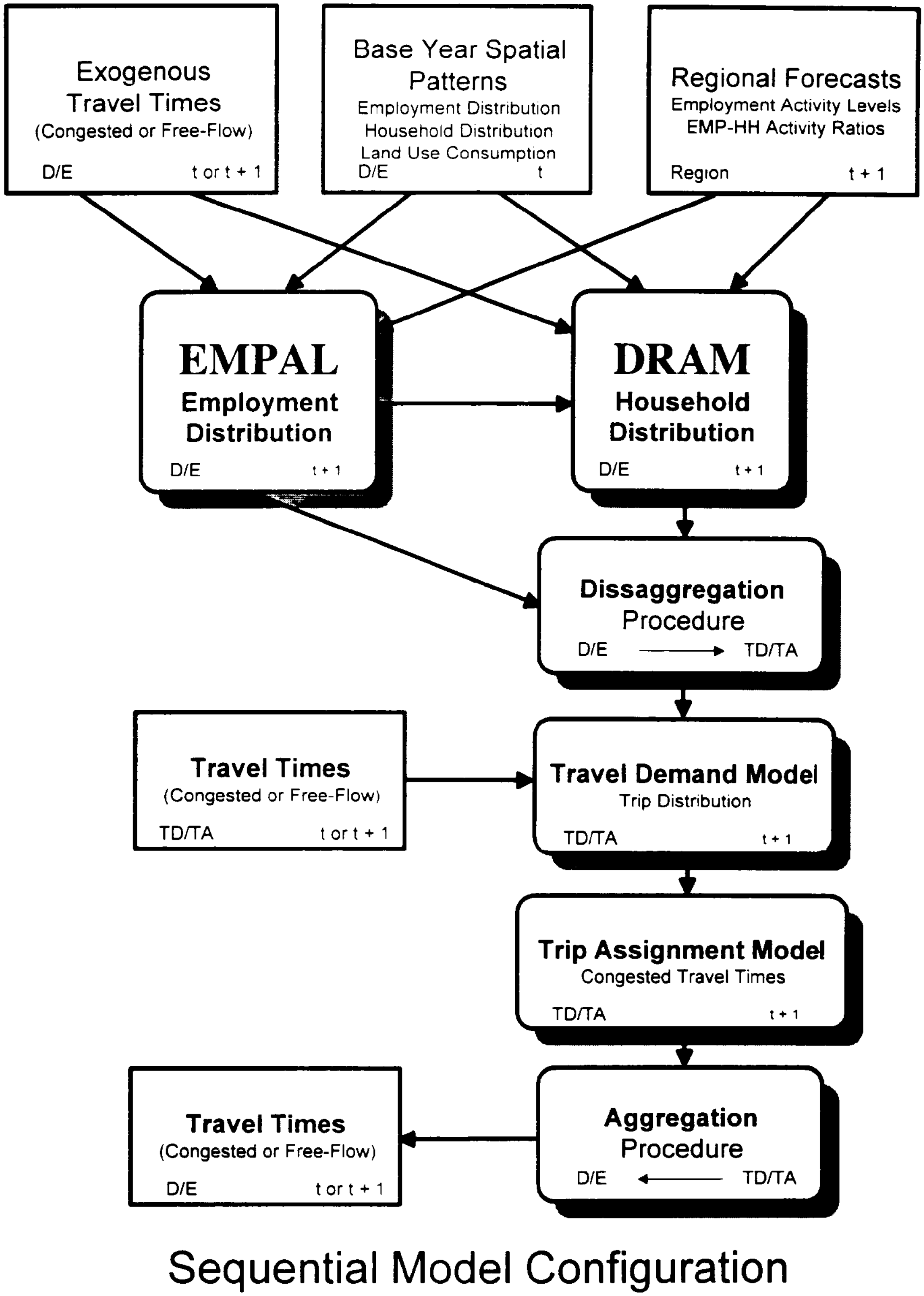

Exogenous
Travel Times
(Congested or Free-Flow)
D/E t or t + 1
Base Year Spatial
Patterns
Employment Distribution
Household Distribution
Land Use Consumption
D/E t
Regional Forecasts
Employment Activity Levels
EMP-HH Activity Ratios
Region t + 1
EMPAL
Employment
Distribution
D/E t + 1
DRAM
Household
Distribution
D/E t + 1
Dissaggregation
Procedure
D/E → TD/TA
Travel Times
(Congested or Free-Flow)
TD/TA t or t + 1
Travel Demand Model
Trip Distribution
TD/TA t + 1
Trip Assignment Model
Congested Travel Times
TD/TA t + 1
Travel Times
(Congested or Free-Flow)
D/E t or t + 1
Aggregation
Procedure
D/E ← TD/TA
Sequential Model Configuration

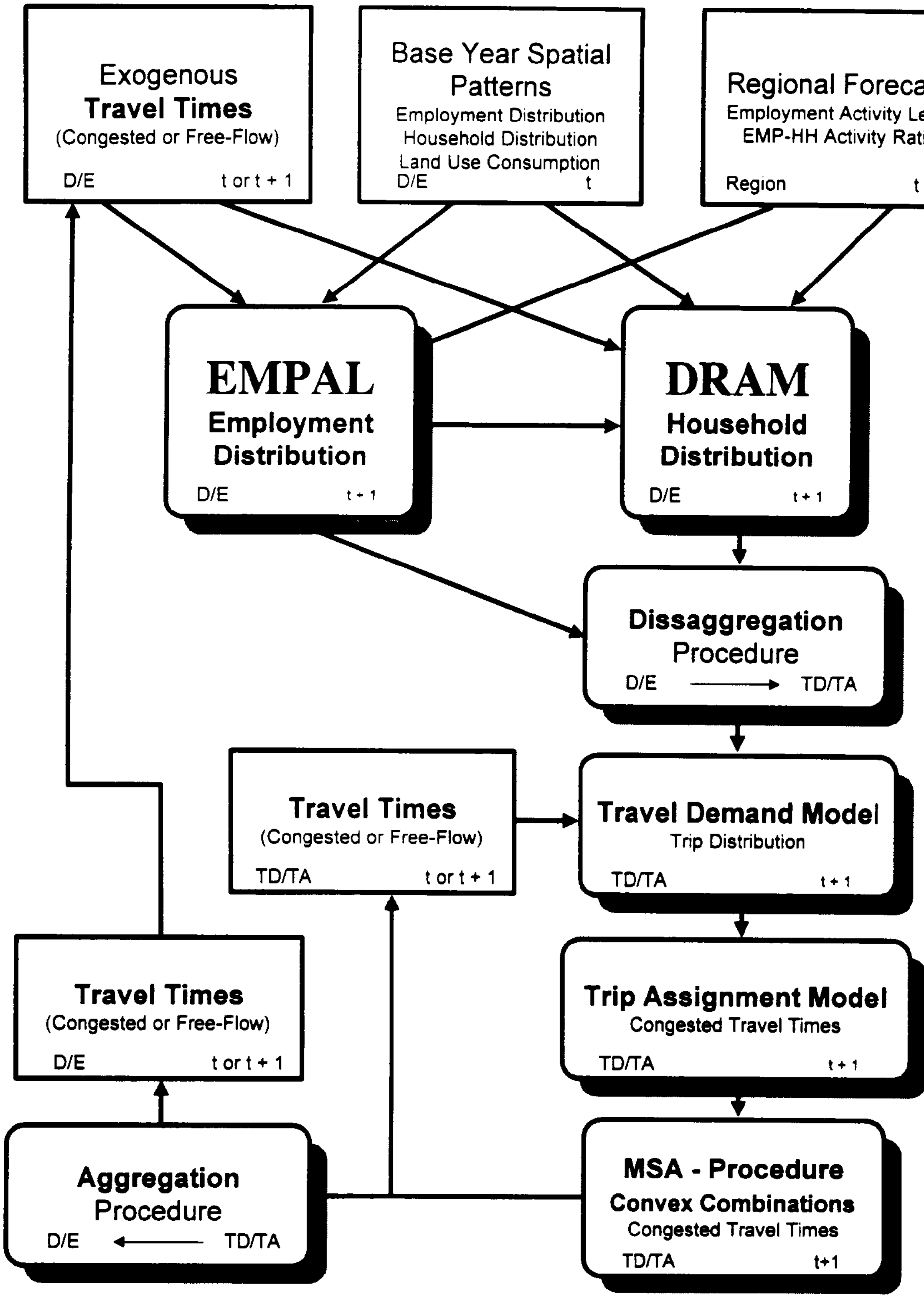
Figure 3.2

Second, there is an aggregation process shown taking place after the Trip Assignment model run is completed. This serves the purpose of converting the travel times used in the travel demand models, at the TD/TA geography, to travel times in the D/E geography for use in the next recursion of the model system, beginning with their use as input to EMPAL and DRAM. The procedure followed in the performance of this aggregation must be carefully considered. One typical approach is to select a TD/TA geography zone to represent each D/E zone, and then to calculate the travel time skim trees[12] for the representative zones. Another approach is to take the TD/TA geography zone-to-zone travel time matrix and, using a representative zone for each of the D/E zones, simply "compress" the matrix by discarding the unneeded rows and columns. Another approach, somewhat more complex, is to calculate average times between each of the TD/TA level zones that make up a D/E zone, and each of the TD/TA zones which make up the "destination" D/E zone. In addition to these, various other approaches have been used, but these are the most common. Particular attention must be paid, regardless of which aggregation approach is taken, to how the intrazonal times are calculated for the D/E geography. Most land use models will be sensitive to these times, the diagonals of the zone-to-zone travel time matrix, and it is therefore quite important to see to it that they are as reliable as possible. The third additional box on the Sequential configuration is simply the D/E geography travel times at time t+1, which are used as input to the next recursion, that is the next five year step, in the model forecasting sequence.

3.4 The Equilibrium Model Configuration

This is the most comprehensive structure examined in this work, consisting of all the parts of the Sequential configuration, plus the additional steps necessary to run the entire system to an equilibrium solution within each time period, before moving on to the next time period. The system structure has been augmented by the addition of the MSA Procedure, which serves to implement the equilibrium solution. This procedure, which follows Trip Assignment, involves a particular form of averaging of the link volumes on the networks. This averaging can take several different forms, but the form used here, the Method of Successive Averages (MSA), has been shown to be both reliable and computationally efficient (Putman, 1991). Following the MSA Procedure, which will be described in somewhat more detail in the following paragraph, the "combined" travel times must be aggregated from the TD/TA geography to the D/E geography. Note, too, in the diagram, that there may be use of the combined times to feedback to the travel demand models for one or more iterations before proceeding on to the full system iteration involving the use of EMPAL and DRAM as well. If there is to be a feedback to travel demand, it will be done at the TD/TA geography using the combined times prior to their aggregation to the D/E geography. Once the combined times at the D/E geography are calculated, they are used as input to a next iteration run of EMPAL and DRAM. This run is followed by runs of the travel

[12]Skim tree is the transportation modeling term for zone-to-zone travel times over the minimum paths through the network.



Equilibrium Model Configuration

Figure 3.3

models (either with or without possible iterations within the travel models) and the generation of a new set of congested travel times. The individual link flows (volumes) which produce these new times are then averaged, by use of the MSA Procedure, with the prior combined link volumes, and the congested travel times are then recalculated. Minimum path trees through the network are then traced to calculate to get a new set of congested times. These, in turn, are passed on to a subsequent iteration of EMPAL and DRAM. The process continues until a prespecified convergence criterion has been met, or until a maximum permitted number of iterations has been reached. In practice a substantial degree of convergence is usually reached by the third iteration, and the algorithm never has required more that six or seven iterations for any practical convergence tolerance to be reached. Note that these iterations are ***intra-*** time period iterations. Thus we are describing several iterations to be calculated in producing the forecast, say, of the year 2000 starting from 1995. Following these iterations, the recursive structure of the model system comes into play as the year 2000 outputs become input to the forecasts for 2005.

The MSA procedure is only one of several ways in which the congested travel times from one iteration of the models could be combined with the congested travel times from succeeding iterations. Tests have, however, shown that it is a very robust procedure for accomplishing this task, and it requires rather little computational effort (Putman, 1991). The procedure is, in effect, a weighted average of successive estimates of congested travel times, with each successive estimate having less weight than the prior ones. Consider the following equation:

$$X_a^{n+1} = X_a^n + \alpha (Y_a - X_a^n) \qquad (3.1)$$

where X_a are the flows on link a at iteration n, Y_a are the flows on link a at the current iteration, and α is a weighting parameter. In the MSA procedure, α is simply 1/n where n is the number of the iteration being calculated. If one begins with some trial estimate of link flows then each additional estimate of link flows is added to the weighted sum of the prior flows, as can be seen by rearranging the terms of the equation:

$$X_a^{n+1} = (1.0 - \alpha) X_a^n + \alpha (Y_a) \qquad (3.2)$$

The initial set of travel times coming from the Trip Assignment model are calculated by tracing the shortest paths through the network, given that the link travel times represent the congested link times. In earlier attempts to solve combined employment and household location, land use, and travel models the convergence was attempted by use of averages of the travel times (Putman, 1983). This approach does not work. What must be done is to average the link trip volumes and then trace the shortest paths through the network with the links congested by the properly (MSA) averaged link volumes. Thus the MSA procedure as used here does this particular form of averaging the link volumes in order to then calculate the revised skim trees, and produce the "averaged" link times. This procedure is guaranteed to converge to a unique solution, and is the approach used throughout this study for the Equilibrium model system configuration.

Finally, it should be noted that the calculation of an equilibrium amongst locating activities and trips on the transportation network(s) may or may not produce the best forecast for each time point. It is close to certain that some intra-time period iterations will improve the forecast. What is uncertain is how many of these iterations should be conducted. The issue may be thought of in terms of rate of adjustment, on the part of various activities in the system, to disequilibrium conditions. In the case of trip flows on networks, these adjustments will take place quite rapidly - often within minutes or hours of a "change" in the network such as an accident or a closing of a link in the network. The case of the Olympic games in Los Angeles comes to mind, where vast numbers of travelers made temporary changes in their usual work trip travel paths. The construction of a new link on the network will result in trip flows changing quite rapidly. This same construction may also have some effect on the location of activities, depending to a significant extent on the "size" and location of the link. To the extent that such relocation is induced, it will occur over a much longer period of time, often a matter of several years. Households, for example, will not pick up and change place of residence the very day that the new facility becomes available, but, both before construction is complete, and after, those households who are making relocation decisions will likely be influenced by the expectation and/or existence of the new facility. At present it is impossible to specify how many iterations is the precisely correct number to be performed. It is clear, however, that ***some iterations***, by virtue of introducing feedback into the model system calculations, ***will always give better forecasts than no iterations***. Additional research into the performance of these systems, and into collection and use of data to test them statistically, would be of considerable benefit in providing agency guidance as to the optimal numbers of iterations, which might differ for various of the submodels in the system, as well as for different regions with different characteristics, to be conducted in the implementation of these systems.

Having now defined the three model system configurations which will be referred to throughout this report, we may move on to the next chapter, containing a description of the overall approach taken in conducting this study.

4 - Descriptions of the Regions Studied

4.1 Introduction

The initial plan for this study had the computer experiments being performed only on the Portland data using the DRAM and EMPAL models in conjunction with METRO's travel model system. It soon became clear to us that the test would have to be extended to cover other metropolitan areas in order to have some assurance that the results from this study would be generalizable. First Los Angeles, and later Colorado Springs, Detroit, and Kansas City were added in order to have a modest dispersion of types of regions. In this chapter we describe some of the attributes of these regions. We cover demographic and economic data as well as geography and land use. We also give here a set of descriptions of the transportation networks for the regions, as used in these analyses.

Transportation and land use modeling requires that each region be divided into subareas or zones for analysis purposes. The zones defined for use in the employment and household location and land use models are, as is universally the case in transportation and land use modeling practice, different in size from the zones defined for use in the travel demand and trip assignment, et al, models. A principal reason for this is the lack of uniform employment, household, and land use data at the fine geography used in the travel models. A useful way in which to present the differences both within and between the various study region is in terms of both the numbers of zones as well as the amount of activity, on average, which each zone represents. This information is given in Table 4.1. Note the very substantial range in numbers of land use model zones and the mean population per zone, ranging from 85 to 772 zones, and from 4,155 persons per zone in Kansas City, where the land use models are implemented at the census tract level of detail, to 26,812 persons per zone in the Detroit models where the zones are census tract aggregations. For the travel model work, the range is from 1555 traffic analysis zones for Los Angeles, to 350 traffic analysis zones (TAZ) for Colorado Springs. Interestingly, due to the overall sizes of the regions populations, and therefore of trips, the Los Angeles models, even with their greater number of TAZ's have a mean of 4,510 trips per TAZ, nearly four times greater than the 1,177 trips per TAZ in Colorado Springs. Finally, note the ratios of TAZ's to land use model zones. The highest ratio is found in the Portland modeling scheme where there are 100 land use model zones and 1189 TAZ's. This is the scale at which it was necessary to do the model runs. The tests of a 100 TAZ network analysis clearly showed the inadequacy of the use of sketch networks, and the tests of the land use models at a finer level of detail, 328 census tracts, were made impossible due to serious data quality problems. The lowest TAZ to land use model ratio is 2:1, which was the level for both Los Angeles and Kansas City, principally because the Los Angeles work is being done at too great a level of aggregation for a region of such considerable size.

4.2 The Sizes of the Regions: Regional Totals

The five regions which were included in this study cover a broad spectrum of city, or metropolitan region, types and sizes. The smallest region included in this study is Colorado Springs, which in

Geographic Scale of Land Use and Transportation Models		Portland METRO	Los Angeles SCAG
Land Use Models	Number of Land Use Zones	100	772
	Total Land Area in Acres	2,378,185	6,131,786
	Total Population[13]	1,477,895	14,531,529
	Population per Land Use Zone	14,779	18,823
	Population Growth (1990 - 2000)[14]	16.1%	19.1%
Travel Demand Models	Number of Traffic Analysis Zones (TAZ)	100/1189	1555
	TAZs per Activity Zone	1:1/12:1	2:1
	Total Trips (1995)[15]	744,004	7,013,106
	Trips per TAZ	7,440/626	4,510
	Growth in Trips (1995 - 2000)[16]	10.0%	6.6%
Network Model	Links[16]	18,495	27,071
	Links per TAZ	185:1/16:1	17:1

Table 4.1

terms of the 1990 population ranked as the ninety-first metropolitan area. The largest of the regions included in this study was the southern California, Los Angeles, region, which ranked second in the 1990 census. Of the other three study regions, Detroit was sixth, Kansas City was twenty-fifth, and Portland was twenty-seventh. In addition to population size, the city "types" are also quite varied, ranging from the very slow growth of Kansas city and Detroit to the very rapid growth of Colorado Springs. Table 4.2, shows the populations of the five study regions beginning

[13] 1990 U.S. Census.

[14] MPO estimates.

[15] Travel demand model estimates for P.M. peak period.

[16] 1995 network models.

Geographic Scale of Land Use and Transportation Models		Colorado Springs PPACoG	Detroit SEMCoG	Kansas City MARC
Land Use Models	Number of Land Use Zones	85	174	377
	Total Land Area in Acres	312,506	3,169,084	1,272,673
	Total Population	397,014	4,665,236	1,566,280
	Population per Land Use Zone	4,671	26,812	4,155
	Population Growth (1990 - 2000)	24.3%	4.7%	7.6%
Travel Demand Models	Number of Traffic Analysis Zones	350	1548	789
	TAZs per Activity Zone	4:1	9:1	2:1
	Total Trips (1995)	411,786	2,729,414	912,013
	Trips per TAZ	1,177	1,763	1,156
	Growth in Trips (1995 - 2000)	8.0%	-4.3%	5.3%
Network Model	Links	5,444	24,593	10,514
	Links per TAZ	16:1	16:1	13:1

Table 4.1 (continued)

with 1980, and continuing to a forecast horizon year of 2010. The 1980 and 1990 values are adjusted numbers from the decennial census data, with the adjustments being made to match the size of the study region which, in most cases, does not precisely match a census SMSA or CMSA definition. The values for the years beyond 1990 are the regional control totals prepared by the agency for each region, and used in the forecasting experiments described in this report.

The growth in population can also be seen in the light of a graph of the normalized growth for each of the study regions. In this graph, for each of the regions, the total population for each year beyond 1980 is divided by the population for 1980. This gives a set of lines which show the relative rates of growth of each of the regions which can be visually compared to each of the other regions. From this it is clear that the Colorado Springs region has the greatest rate of increase of population from 1980 to the 2010 horizon year, while the Detroit region has the least. If the employment figures for the regions are examined, some differences can be seen. Here, as seen in Table 4.3, it is Portland which shows the greatest rate of increase, though the Colorado Springs

Year	Colo Springs	Detroit	Kansas City	Los Angeles	Portland
1980	310,615	4,604,053	1,306,450	11,496,463	1,239,986
1990	395,510	4,521,180	1,427,950	14,531,529	1,412,344
1995	463,356	4,666.450	1,484,386	15,054,000	1,526,465
2000	491,633	4,735,101	1,536,947	16,299,000	1,639,969
2005	526,828	4,808,145	1,587,215	17,445,000	1,756,220
2010	560,645	4,893,315	1,635,370	18,830,000	1,877,687

Table 4.2: Study Region Base Year and Forecast Populations

region is a close second. It must be recalled, however, that these numbers, with the exception of the 1980 and 1990 values which are *data*, are all *forecasts* for each region prepared by the agency (MPO) for the region. As such, they represent the current best estimate of what will happen over the next fifteen years, and are obviously subject to change. Here, too, a graph of

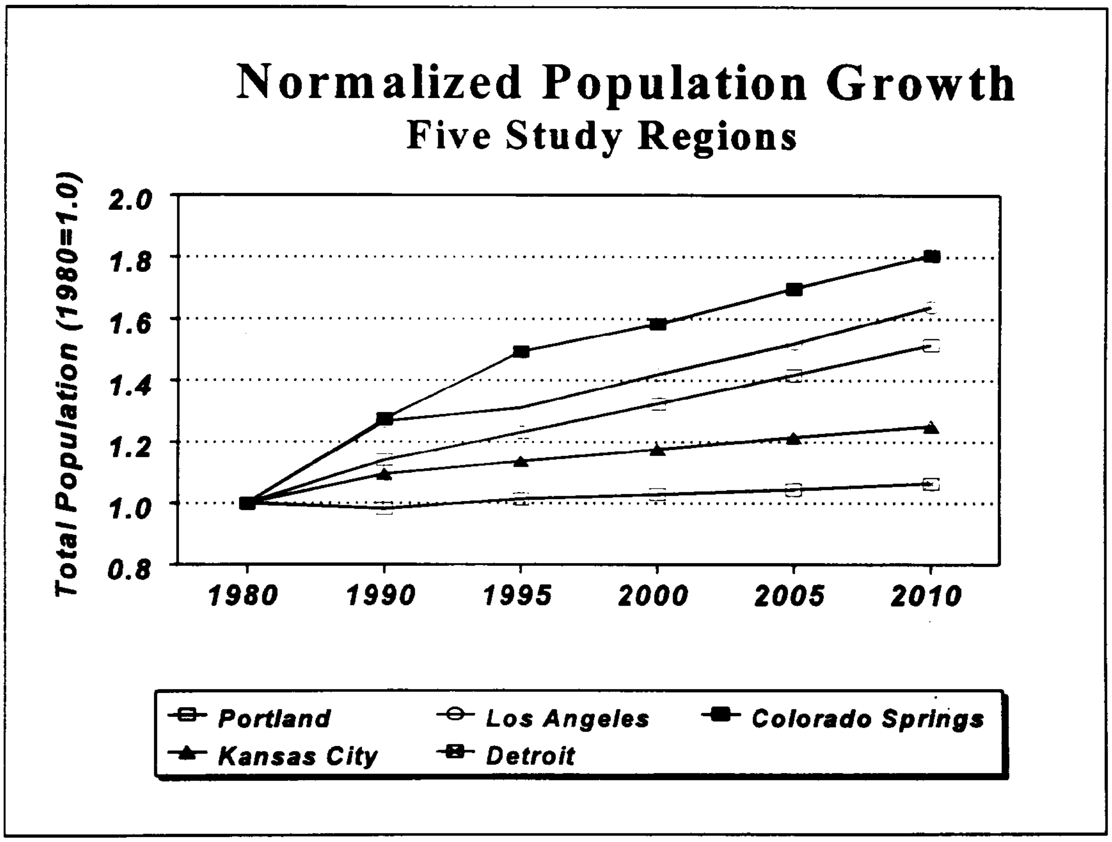


Figure 4.1: Population Growth Comparison

the normalized employment growth provides a sense of what has been happening in these regions. Note the considerable employment increases in both Colorado Springs and Portland. At the same time note the much smaller growth rates experienced by Detroit, Kansas City and Los Angeles.

Year	Colo Springs	Detroit	Kansas City	Los Angeles	Portland
1980	141,715	2,032.638	664,076	5,445,400	722,310
1990	193,772	2,350.238	757,624	6,359,700	846,783
1995	214,271	2,476.842	792,874	6,875,165	938,862
2000	231,449	2,614,310	848,873	7,927,362	1,040,955
2005	250,215	2,723.698	910,934	8,461,860	1,154,148
2010	265,456	2,775.960	939,202	9,268,840	1,279,651

Table 4.3: Study Region Base Year and Forecast Employment

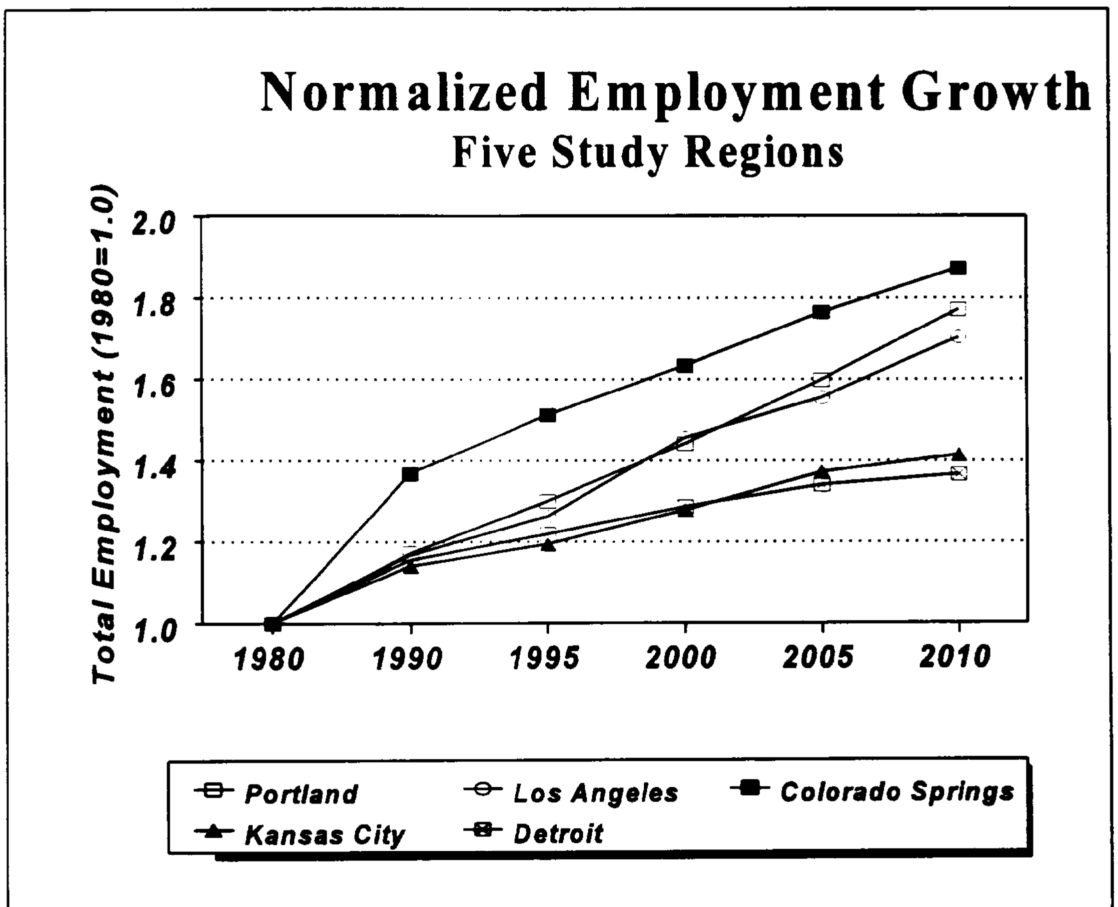


Figure 4.2: Employment Growth Comparison

It is also important to note that even though these regions grew considerably slower than the first two, they still showed increases, for each entire metropolitan region, of more than 10%. Again, it is important to note that forecasting regional employment growth is even more difficult than forecasting the regional population growth. As such, all of these forecasts must be taken for what they are. These are agency (MPO) forecasts, which were either prepared for this project, or prepared for other agency forecasting work, and adapted for use in this project. As such, these are, at the time of this study, the the best available forecasts or estimates produced by the regional planning agency for each of the study regions, of their regional employment totals for the next fifteen years. If, or where, the agencies were directly involved in the use of these types of models for their normal forecasting and policy analysis, then they would, as a matter of course, regularly review and update these forecasts. In addition to these forecasts, the agency would also be responsible for estimating various regional rates or ratios, such as unemployment, net commutation, persons per household, and the like.

4.3 The Forms of the Regions: Regional Spatial Patterns

In addition to the regional totals and forecasts, the spatial patterns of activities in the five study regions are of considerable importance. The best way of encompassing these is to examine maps of their locations. There is also a summary statistic of spatial dispersion known as the Gini Coefficient (Shryock, et al, 1976) for which a value of 1.00 represents the highest concentration, and 0.00 the greatest dispersion[17]. The Gini coefficients for total employment and for total households in the 1990 base year for all the study regions are given in Table 4.4, below. It may

	Colo. Springs	Detroit	Kans. City	Los Angeles	Portland
Employment	0.788	0.783	0.836	0.853	0.913
Households	0.749	0.714	0.735	0.797	0.854

Table 4.4: Gini Coefficients for 1990 for Study Areas

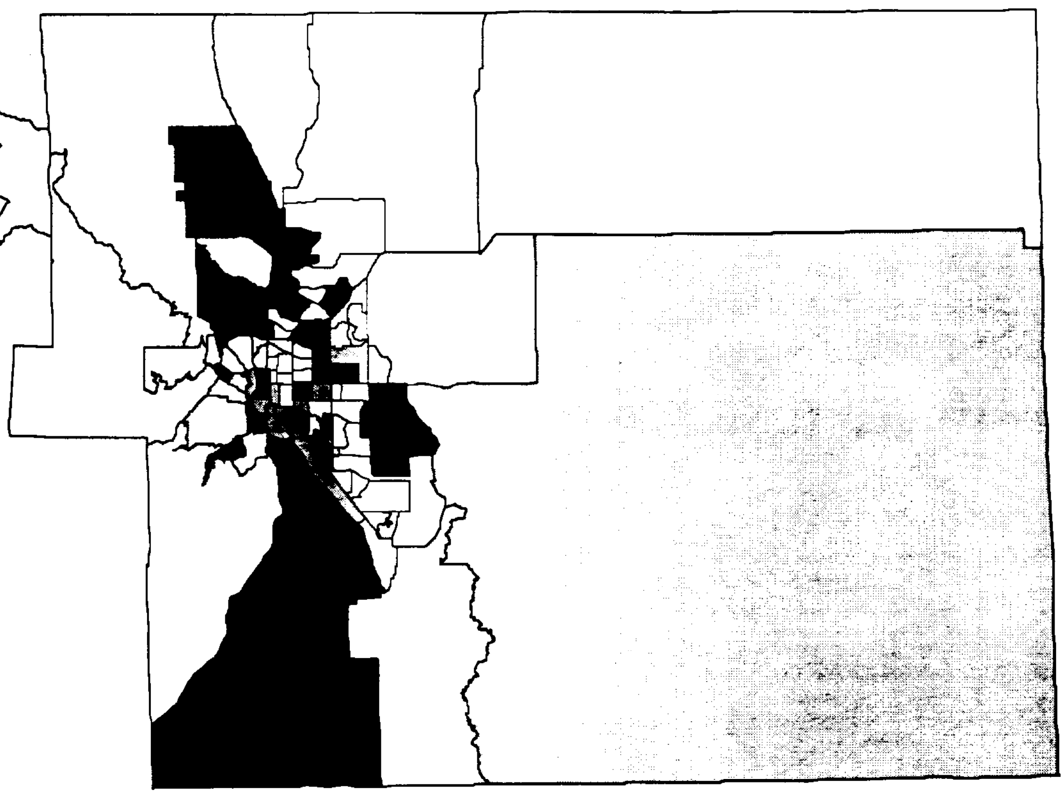
be seen that for both total employment and total household dispersion the Portland region is the most concentrated. It is interesting to note that, based on this measure, both the Kansas City and the Colorado Springs regions are more dispersed than is the southern California region included in the Los Angeles (SCAG) study area. This, however, is due at least in part to the specific "design" of the regions' zone systems. The Gini Coefficient is somewhat less sensitive to a uniform dispersion of activities than to one with sharper maxima (peaks). Employment and households in the SCAG region are more uniformly dispersed than they are in the other regions. This more uniform dispersion shows up more on the maps, but results in a slight bias in the Gini Coefficient.

Maps showing the land use model zone definitions and the base year spatial distributions of employment and households in all five study regions are given in the next several pages. Note, in reviewing these maps, that the legend scales vary from map to map. It would have been useful to keep all the legends identical, except that there is such a wide range of region size and therefore of zone (population or employment) size, that a set of uniform legends would have resulted in some maps having all empty zones, or in some maps having all black (highest scale) zones.

[17]The maximum concentration would be when all activities were concentrated in the single "center" zone of the region. The most dispersed situation would be when each zone had the mean value of zonal population, or the uniform dispersion case. The uniform dispersion case is also used to define the lower boundary, or the worst possible fit of employment or household data in the calibration of EMPAL and DRAM.

Colorado Springs (PPACoG) Region

Location of Total Employment - 1990

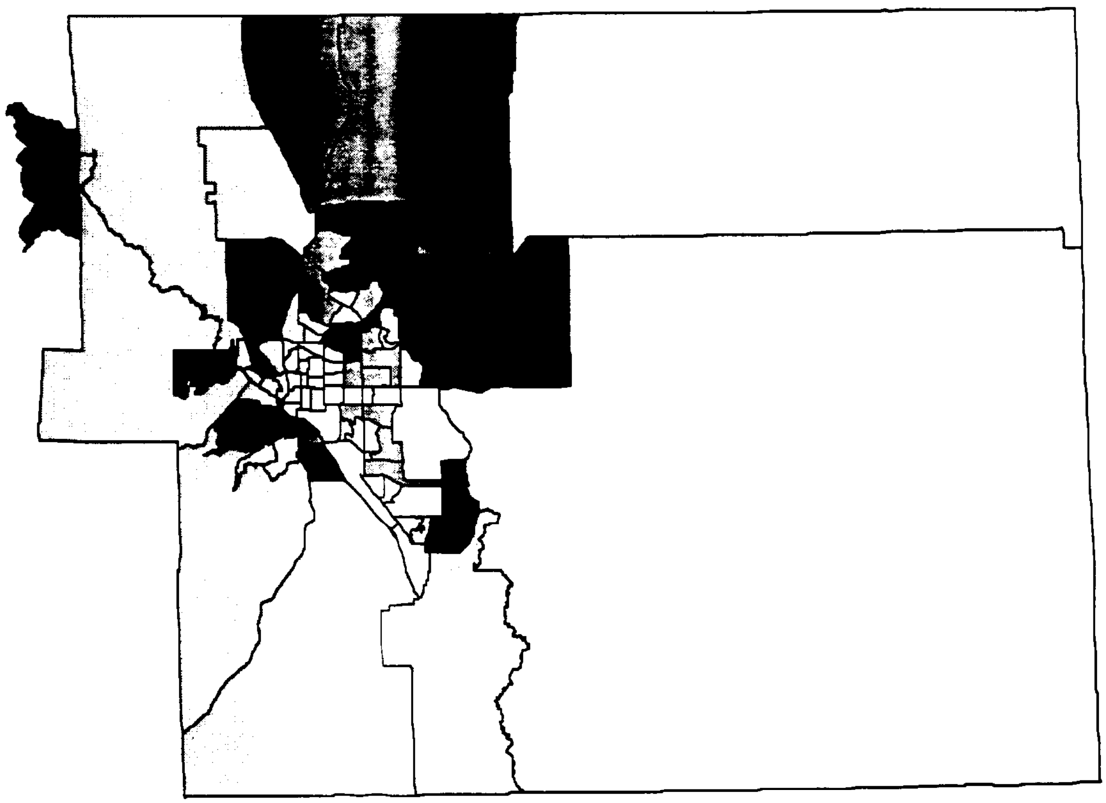


Employment
- 0 - 1000
- 1001 - 2000
- 2001 - 3000
- 3001 and up

Total regional employment:
187,570

Colorado Springs (PPACoG) Region

Location of Total Households - 1990



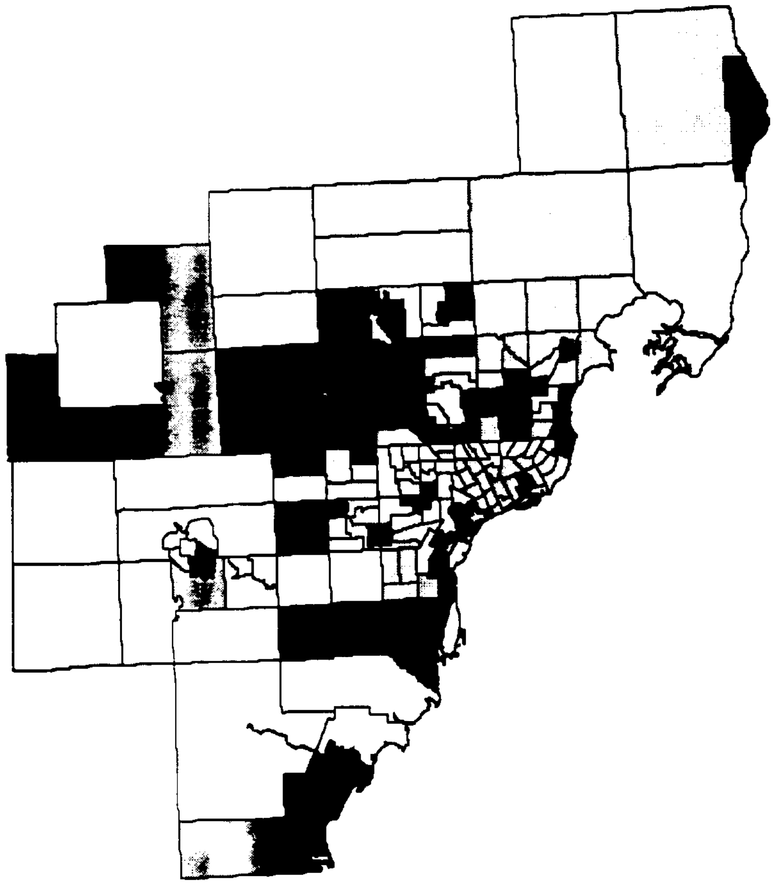
Households

- 0 - 1000
- 1001 - 2000
- 2001 - 3000
- 3001 and up

Total regional households: 152,749

Detroit (SEMCoG) Region

Location of Total Employment - 1990



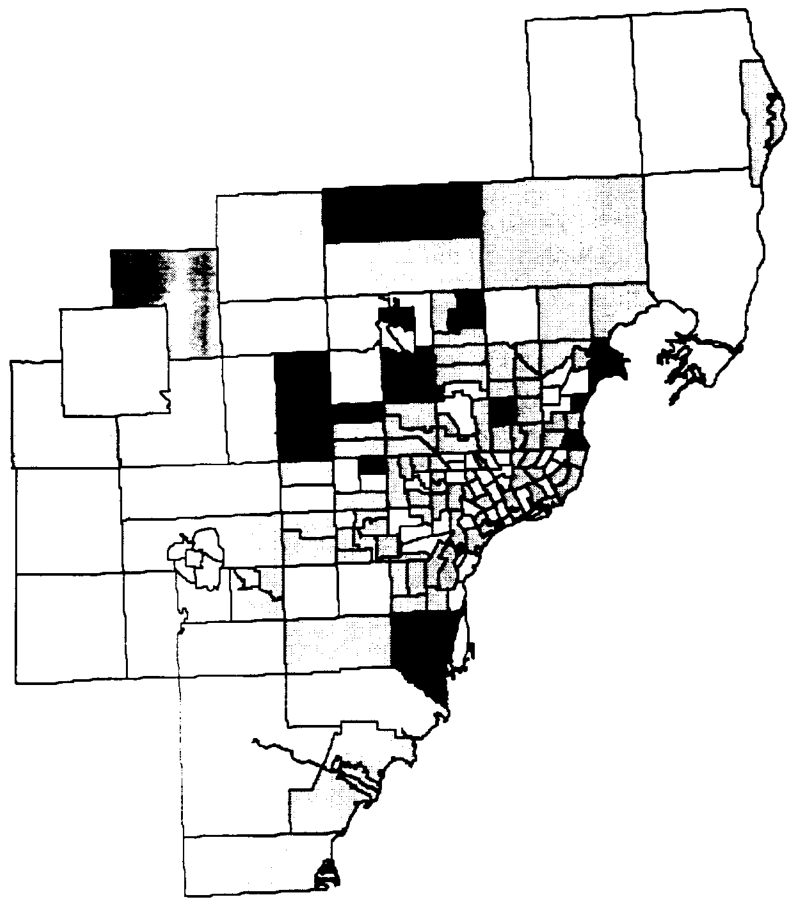
Employment

- 0 - 8000
- 8001 - 16000
- 16001 - 24000
- 24001 and up

Total regional employment: 2,542,667

Detroit (SEMCoG) Region

Location of Total Households - 1990



Households

0 - 8000

8001 - 16000

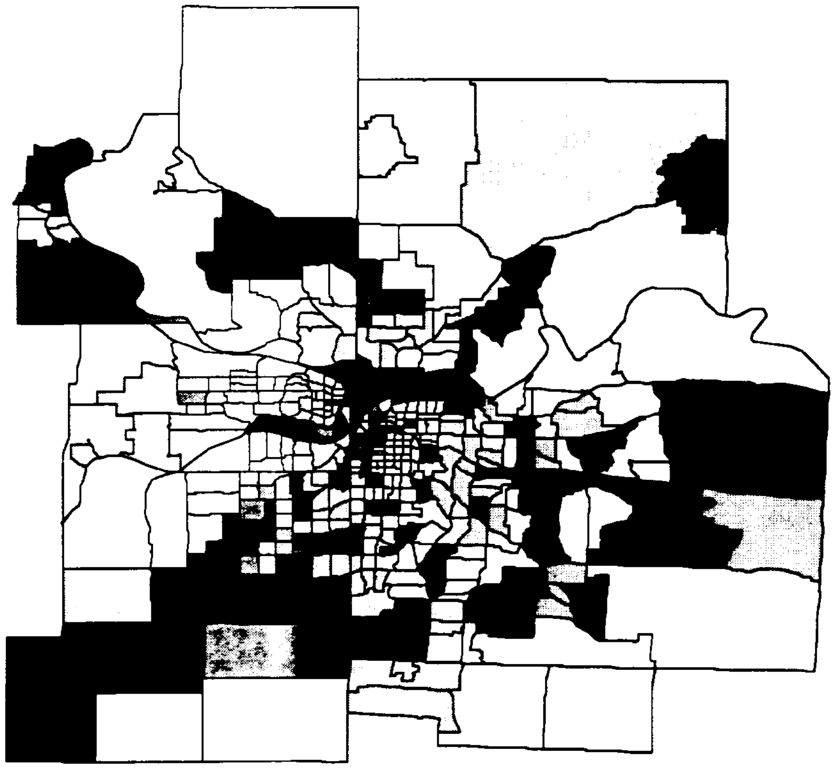
16001 - 24000

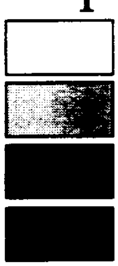
24001 and up

Total regional households: 1,779,413

Kansas City (MARC) Region

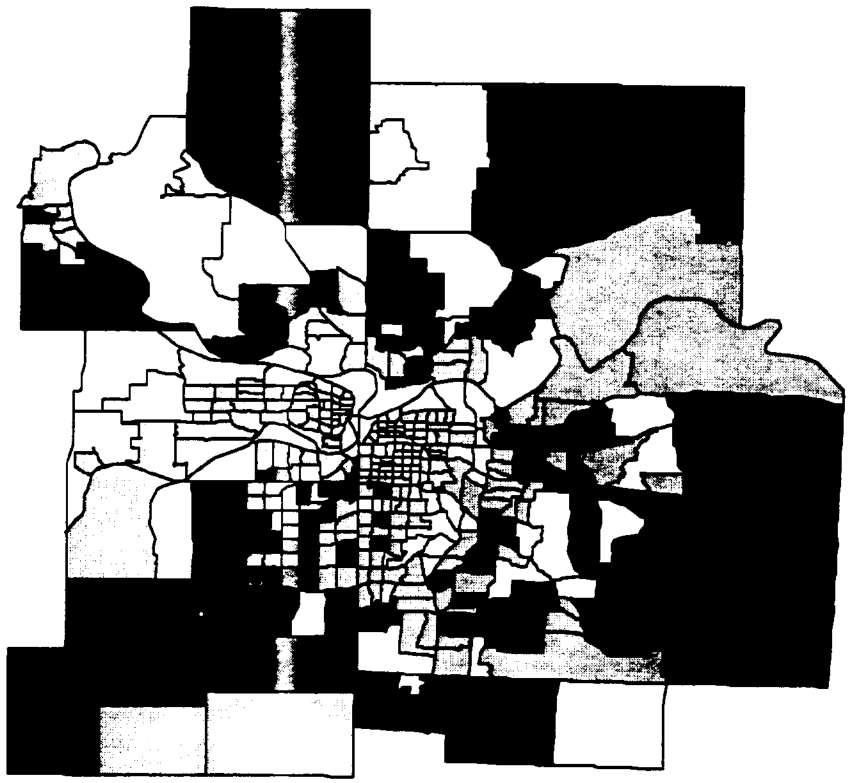
Location of Total Employment - 1990



Employment

0 - 1000
1001 - 2000
2001 - 3000
3001 and up

Total regional employment:
758,727

Kansas City (MARC) Region
Location of Total Households - 1990

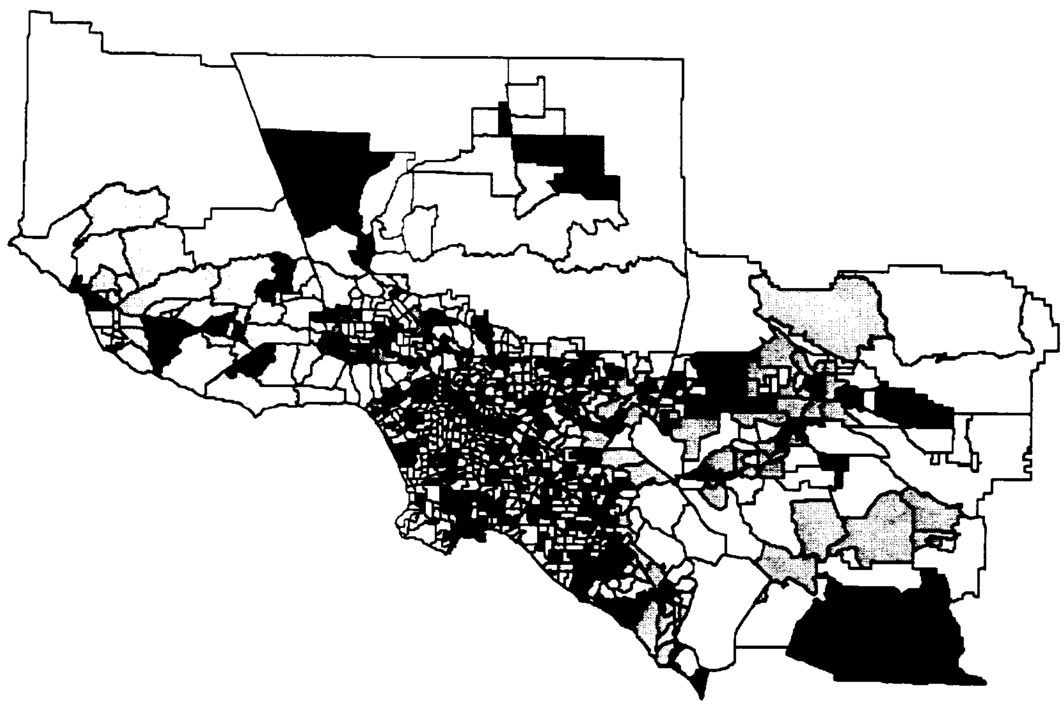


Households
- 0 - 1000
- 1001 - 2000
- 2001 - 3000
- 3001 and up

Total regional households:
552,203

Los Angeles (SCAG) Region

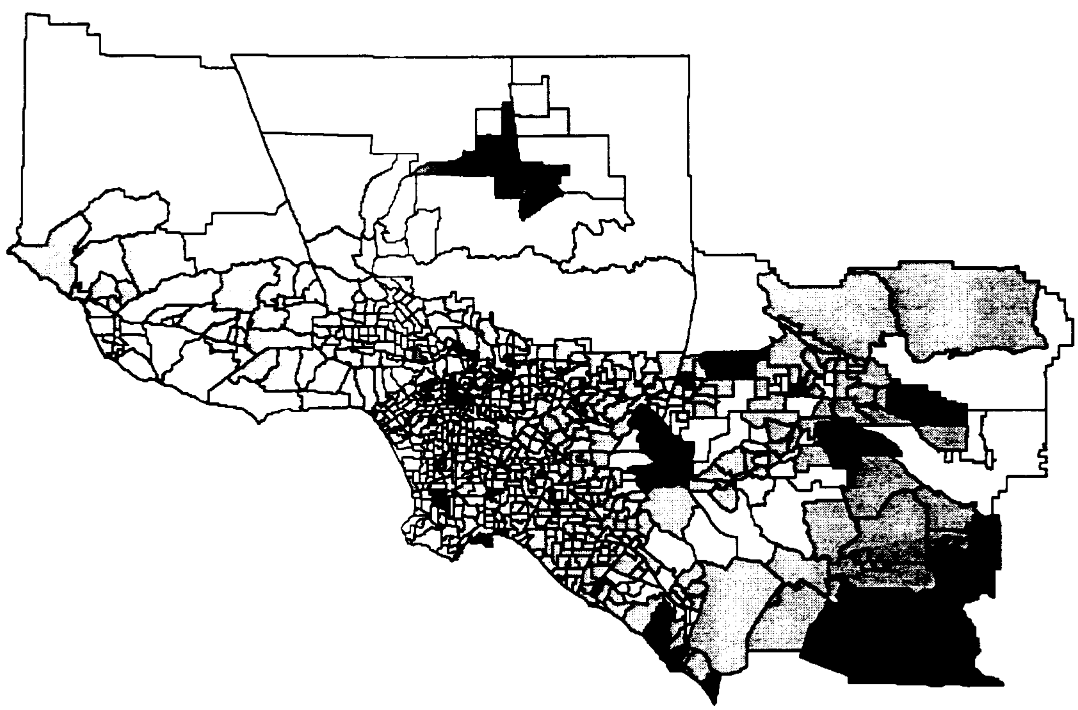
Location of Total Employment - 1990



Employment
- 0 - 5000
- 5001 - 10000
- 10001 - 15000
- 15001 and up

Total regional employment:
6,843,111

Los Angeles (SCAG) Region
Location of Total Households- 1990



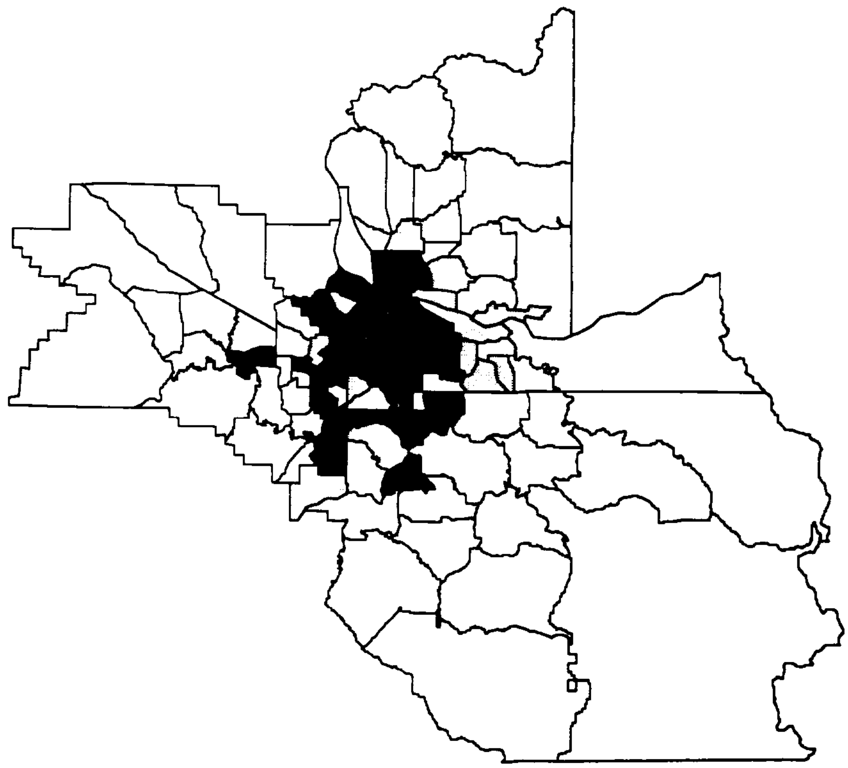
Households

- 0 - 5000
- 5001 - 10000
- 10001 - 15000
- 15001 and up

Total regional households:
4,704,636

Portland (METRO) Region

Location of Total Employment - 1990

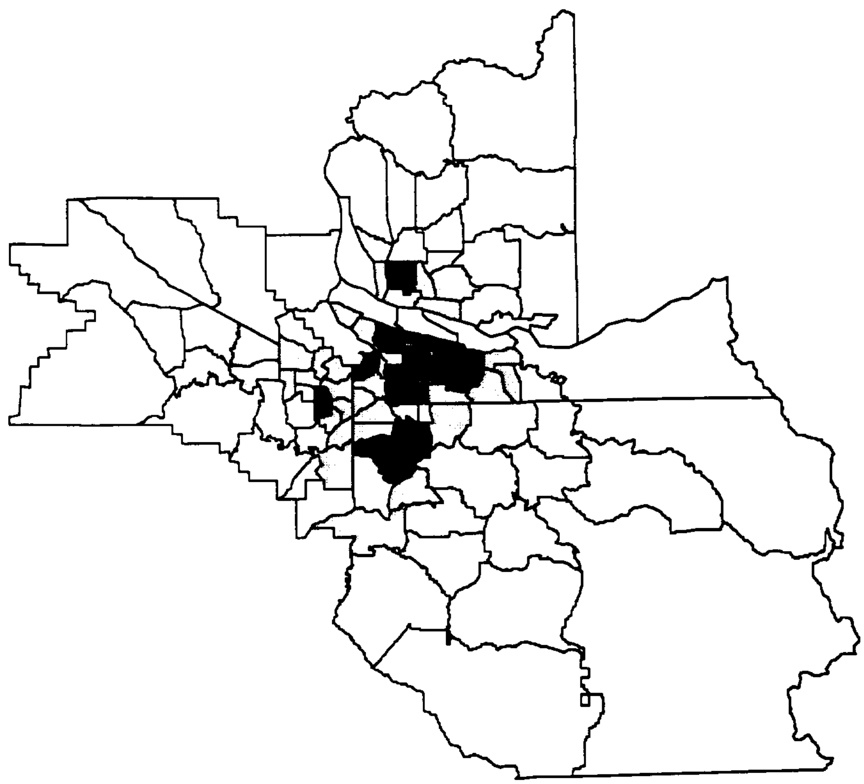


Employment
- 0 - 5000
- 5001 - 10000
- 10001 - 15000
- 15001 and up

Total regional employment: 846,762

Portland (METRO) Region

Location of Total Households - 1990



Households

☐	0 - 5000
▒	5001 - 10000
■	10001 - 15000
■	15001 and up

Total regional households:
553,684

4.4 The Connectivity of the Regions: Model Highway Networks

The representation of the physical highway network is particularly important for an integrated land use and transportation model. The responsiveness of estimated travel times to changes in land use activities depends on the relationship between travel demand (highway trips) and network coverage and capacity. If the design capacity of the model highway network exceeds estimated traffic volumes on all routes, then travel times are completely determined by the design speeds of the network links. This means that travel times will be independent of traffic volumes throughout the region and over the entire forecast horizon. However, for most metropolitan regions, on a significant number of network links, estimated traffic volumes exceed design capacity. When parts of a model highway network are already congested, then changes in the distribution of land use activities, through changes in traffic volumes, lead to changes in travel times. When trip-makers chose different locations and routes, traffic volumes on congested network links increase or decrease, and the minimum travel time paths through the model highway network become longer or shorter. Therefore, the attributes of the model highway network (i.e., network coverage, network capacity, network connectivity, link volume-delay functions) are an important determinant of the responsiveness of estimated travel times to changes in modeled land use activities. The coverage of the model highway networks (i.e., the density and geographic location of the network links) differs significantly from region to region. The differences in network coverage are mainly due to dissimilarities in the geographic regions, but are also the result of differences in transportation modeling practices.

The Los Angeles study region is the largest (61,107,348 acres) of the FHWA study regions. As a consequence, the model highway network for Los Angeles has extremely high vehicular (29,743,237 capacity-miles[18]) capacity. In practice, the Los Angeles model highway network consists of four "sub-networks" (i.e., Los Angeles and Orange County, San Bernardino and Riverside County, Ventura County, and Palmdale/Lancaster.) These four areas are separated by mountains, and are connected by only a few network links.

The Portland model highway network is also divided into "sub-networks", in this case, due to the presence of the Columbia and Willamette Rivers. The "sub-networks" represent the actual highway networks of Clark County, Washington (north of the Columbia River); Portland City, Multnomah and Clackamas Counties (east of the Willamette River); and Portland City, Multnomah and Clackamas Counties (west of the Willamette River).

The Kansas City region is located at the confluence of the Kansas and Missouri Rivers. Because of this, the Kansas City highway network, like that of Portland, appears in the models to have several distinct "sub-networks".

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[18] Capacity-miles is defined as the product of link capacity (vehicles per hour) and link length (miles) summed for all network links.

If a model highway network is divided into distinct sub-networks, then the attributes of the network links that connect the sub-networks are especially important in determining the balance between modeled network capacity and estimated travel demand.[19] Since these links are likely to experience significant traffic congestion, the representation of their actual capacities can have a disproportionate effect on the responsiveness of travel times to changes in land use activities.

The Colorado Springs and Detroit model highway networks are less constrained by geography. The majority of the Colorado Springs model highway network lies to the east of the outer edge of the Rocky Mountains, and most areas of the region are connected by many network links. The eastern area of the Colorado Springs study region is sparsely populated, so the density of network links in this area is low. The Detroit study region is bounded on the east by Lake Saint Claire, but otherwise is mostly free of geographic constraints on the location of streets and highways. The grid structure of streets and highways in the Detroit region is pervasive, and network connectivity is nearly uniform throughout the region.

The total capacities of the model highway networks reflect the geography (e.g., total land area) of the study regions, but are also determined by socio-economic characteristics (e.g., population). Table 4.5 lists summary statistics of network capacity (number of links, capacity miles, freeway-expressway capacity miles) and network density (capacity-miles/population, capacity-miles/area) for each of the study regions.

Of course, the Los Angeles model highway network has the largest capacity, since the Los Angeles study region is the largest in terms of population and land area. Nearly, 50% of the total capacity-miles of the Los Angeles network are classified as freeway or expressway, a much larger proportion than for any other region except Kansas City. However, because of its large extent, the density (with respect to land area) of the Los Angeles network is lower than the densities of all of the other networks examined in this study. The Detroit highway network, which is unimpeded by any significant barriers (except Lake Michigan on the east) and which follows a well connected grid pattern, has a greater density (with respect to land area) than all of the other highway networks examined in this study. The Portland model highway network is much more sparse than the Detroit network, mostly due to geographic constraints (rivers, national forests, and mountains) and by restrictions on development beyond the urban fringe. As a consequence, the density of the Portland network (with respect to both population and land area) is significantly less than the density of the Detroit network.

4.5 Network Congestion Levels

All of the factors described above -- network coverage, network capacity, link volume-delay functions -- along with estimates of travel demand, determine the level and distribution of

[19] The MPO for the Portland region (METRO) uses special procedures to adjust estimates of the demand for travel between their three sub-networks in order to more accurately represent observed trip-making patterns.

Network Capacity, Summary Statistics					
	Portland (1990)	Los Angeles (1990)	Colorado Springs (1995)	Detroit (1990)	Kansas City (1990)
Number of Links	18,495	27,071	5,444	24,593	11,081
Capacity-Miles	4,409,263	29,743,237	2,186,152	15,860,620	5,003,101
Freeway Capacity- Miles	891,246	13,661,939	644,420	5,890,660	2,352,283
Population	1,477,895	14,531,529	397,014	4,665,236	1,566,280
Area (acres)	2,382,790	61,107,348	487,882	2,881,187	1,271,560
Capacity-Miles/Population	2.98	2.05	5.51	3.40	3.19
Capacity-Miles/Area	1.85	0.49	4.48	5.50	3.93
Freeway Capacity-Miles/Population	0.60	0.94	1.62	1.26	1.50
Freeway Capacity-Miles/Area	0.37	0.22	1.32	2.04	1.85

Table 4.5: Summary Statistics on Networks[20]

congestion (i.e., links where volume exceeds design capacity, increasing travel times for all trip-makers that use those links) on the model highway network. In general, the sensitivity of travel times to the locations of land use activities increases as congestion increases on the model highway network.

Table 4.6, presents summary statistics of network congestion for the 1995 baseline equilibrium network assignments, including average volume/capacity ratios for all network links, average volume/capacity ratios for freeway links, and the percentage of total travel time due to congestion.

It is important to note here that the average volume/capacity ratio statistics are not independent of network geography or the distribution of vehicle trips across the model highway network. (The percentage of travel time due to congestion statistics are comparable across the FHWA study regions.) If a large number of network links are unused or lightly used, then the average V/C

[20] Due to differences in the functional classifications of network links, the freeway capacity statistics may not be strictly comparable across regions.

Network Congestion, Baseline Traffic Assignment					
	Portland (1990)	Los Angeles (1990)	Colorado Springs (1995)	Detroit (1990)	Kansas City (1990)
Average V/C Ratio	0.75	0.67	1.20	1.14	1.00
Average V/C Ratio (Freeways)	1.10	0.79	1.37	ˉ1.14	0.99
% of Travel Time Due to Congestion	20.59%	45.36%	39.14%	13.88%	11.88%

Table 4.6: Summary Baseline Network Congestion Statistics

ratio statistics will be biased downward, even if a large proportion of trips are subject to congestion. This is particularly true for model highway networks that extend into sparsely populated, rural areas. Figure 4.5 shows the distribution of volume/capacity ratios for two 1995 Portland forecasts -- a baseline, sequential forecast and an MSA, linked model forecast. This graph shows that 30.0% of the volume-capacity ratios are less than 0.25. Approximately 10% of the links on the Portland model highway network are unused.

Average volume-capacity ratios can also be biased upward, when a few network links are extremely congested. For example, approximately 1% of the links on the loaded network for the 1995 Colorado Springs baseline traffic assignment have V/C ratios in excess of 5.0, and five links have V/C ratios greater than 20.0, as shown in the frequency distributions of v/c ratios in Figure 4.6. The effects of just these few extremely congested links are to give an unwarranted upward shift in the average V/C ratio statistics. For this reason *it is generally a good idea to look at the frequency distribution of V/C ratios as well as at the average values when reviewing transportation model results.*

Having presented here the general descriptions of the five regions which were studied, we turn next to a description of the approach taken in this study to answer the questions posed.

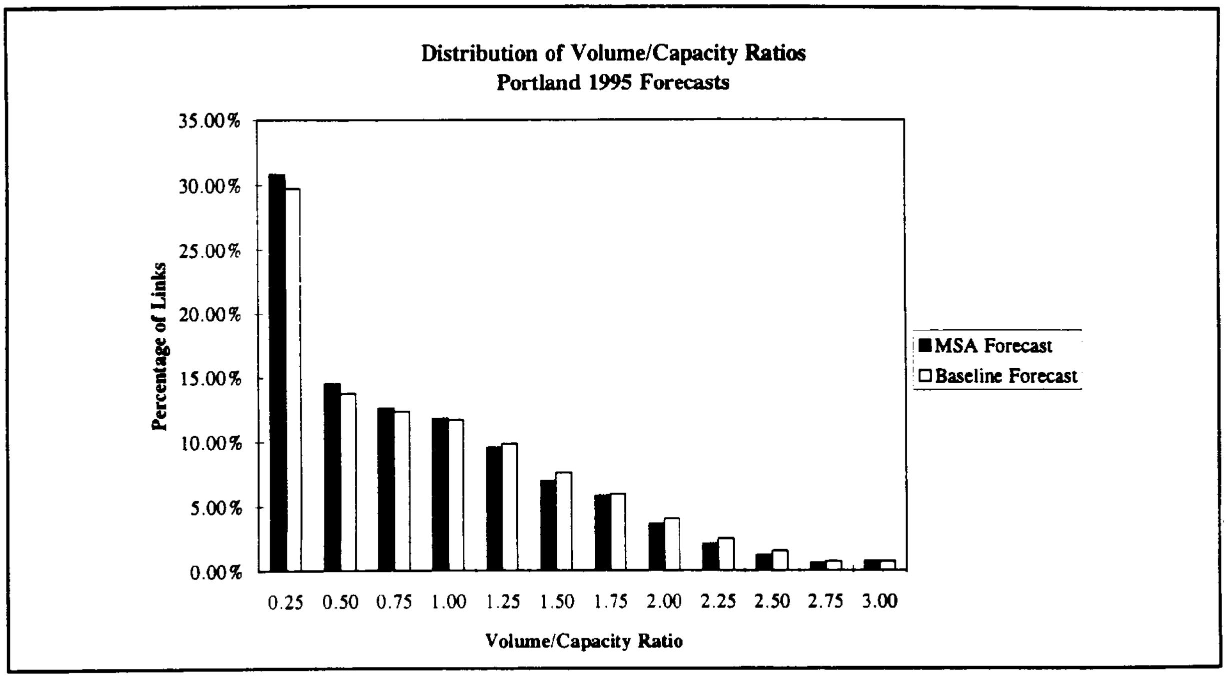

Figure 4.5: Portland Network V/C Ratio Distribution

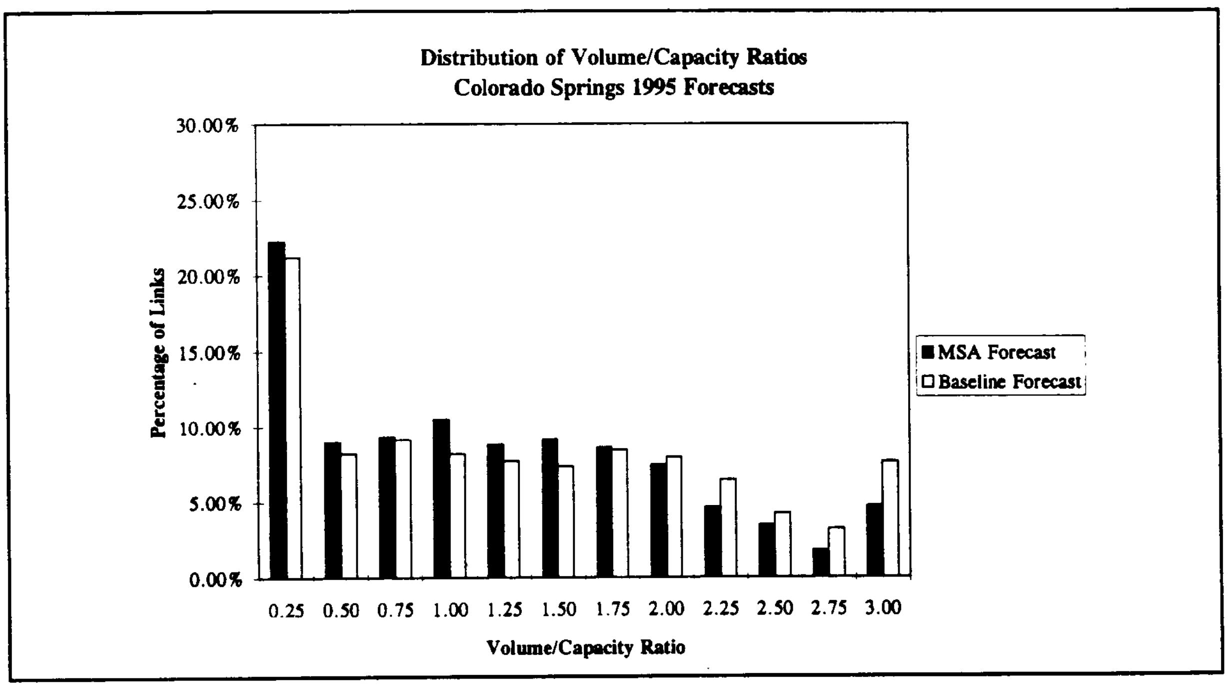

Figure 4.6: Colorado Springs Network V/C Ratio Distribution

5 - The Method Followed for this Study

5.1 Introduction

Performing a full set of integrated transportation and land use forecast model runs for five metropolitan regions involved a considerable amount of organization of procedures. Each of the regions studied has its own particular implementation of their travel model software. Two different transportation model packages were involved, two regions were making use of EMME2 and three regions were making use of TRANPLAN, there were numerous differences amongst the regions as to how they implemented their travel model structure. Add to this the additional steps necessary for the integration of the travel models with the location and land use models, the procedures to disaggregate and aggregate the data between the different geographies used for land use models and transportation models, plus the algorithms to assure convergence of the equilibrium model system configuration, and the result is a very considerable mass of procedures and protocols.

The first step to be taken with each region was to discuss the agency's willingness to participate in the study and, given their commitment, to plan the logistics of accomplishing the work for this project. Following this, we attempted to obtain agency documentation[21] and/or engage in formal discussion with the agency's technical staff to learn the model configurations they were using. In every case **S.H.Putman Associates** had assisted, under previous contract arrangements that were not related to this project, the agency in the installation of the DRAM and EMPAL models, but had had no prior involvement with the agency's travel models. As a consequence, the running of the land use models presented no problems, but it was necessary to learn the operation of the transportation model software. This was not quite as complex a problem as it would be for an initial agency traffic modeling effort, as we did make use of existing agency models and were, in most cases, assisted by agency staff in learning to run their models. At the same time that we were discussing each agency's model systems we began the development of the procedures which would be used to enable remote access of the agency's computer system so that model runs could be made from off site.

Once these matters had been attended to, it was possible to begin the testing of the remote computing configurations, and then, to undertake the series model system configuration comparisons. In the next section of this chapter we describe, in general terms, the experimental design followed for the computer runs. This is followed by descriptions of the transportation model configurations used by the agencies, and of the modifications which we made for the purposes of these experiments.

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[21] As a side note, mention should be made of the fact that the considerable press of day-to-day activities on agency staff has, amongst its other consequences, the effect of making preparation of technical documentation a low priority matter. Thus in many agencies it is rather difficult to obtain complete and current documentation on travel model implementations.

5.2 Experimental Design for the Study's Model Runs

When first contemplating the design of this study we were immediately confronted by the enormous number of computer runs which one *could* conduct, and the obvious and pressing need for an experimental design which would reduce the task to feasible proportions. We also determined to try to develop a strategy which would allow us to learn, from the model runs done for one region, which runs must be included for each other region, which ones did not need repeating for other regions, and a set of runs which would be repeated once or twice in order to verify or refute some particular finding which was not made clear from the first runs, or to show how specific results might vary from region to region.

Before the various model testing steps could begin it was first necessary to do some "accounting" work with respect to input data and model parameters. For both the transportation models and the land use models, there are large sets of input data files, as well as equation coefficients and exogenously estimated numerical inputs such as employment and population totals, as well as travel parameters which include network descriptions and trip making rates, and all the various ratios for geographical aggregation and disaggregation . Taken all together, there are literally tens of thousands of numbers which are input to each set of model runs. There was no way that our results could be kept verifiable and replicable, both of which properties are essential for work such as this, unless there was a final clear specification for each and every one of the inputs to each of the many computer runs that was to be performed. Thus the first step in actual model test implementation for each agency was to establish, without any doubt, the specific data and parameter inputs to be used in the test runs. The ease with which this could be accomplished varied considerably from one agency to another. In some cases each and every input item was clearly defined and documented. In other cases, while it might be known that such and such a file was input to Run X, it was not known (often due to agency staff turnover) how that particular file had been created, or from where the data had been obtained. In each agency's case we developed an inventory of the necessary inputs, saved them in a special computer disk directory, and set up a small version control database to monitor these files and thus ensure that the inputs to all the test runs were standardized. It should be noted that this was no small task. Whenever large scale computational tasks are being done the establishment of procedures for ensuring the consistency of inputs is critical to the success of the work, and at the same time this consistency is often an elusive goal. More than once in the course of this project it was necessary to rerun substantial sets of steps in the model configurations because files were "lost" or misidentified. Even so, this first step was, to the extent possible[22], completed for each agency in turn as a precursor to the beginning of the actual model test runs.

[22] In some cases, even after there had been agency agreement on a set of inputs, the agency later revised or reversed its decision and new runs or reruns were necessary.

5.3 Perform a Single Time Period Model Run of All Model System Components

With the data and parameter inputs identified and "set", the next step was to do an actual test run of all the model system components. This was, for all regions, a single forecast run from the 1990 input database to a "forecast" year of 1995. Here, the final parameter values from calibration of DRAM and EMPAL, along with the various exogenous parameters such as regional control totals for employment and population, were used along with the 1990 data to calculate an initial forecast of employment and household location and land use for 1995. In the regions where the agency was actively involved in the work, this preliminary estimate of 1995, was compared with agency expectations and/or data and adjustments were made in the models' zonal attractiveness factors in order to compensate for significant over or under estimation. It is interesting to note that the simple task of reviewing a forecast is in fact, at least for some agencies, a political act. In some agencies no staff member felt comfortable and/or able to spare the time in evaluating the preliminary 1995 forecast, even though it had been clearly stated that it was not to be used for local agency purposes, and that the review was strictly to attempt to identify locators and/or zones in which there were forecasting problems. In other agencies there was full cooperation by the staff in attempting to add their own local knowledge to the model performance by use of the exogenous attractiveness adjustments. As an important aside, we note that amongst these agencies the extent to which the agency made an ongoing effort to include the input from knowledgeable local planners in producing their forecasts was an important determinant of their success in having the forecasts used in the region by planners, developers, or any other concerned parties.

From a technical perspective it is important to briefly describe the operation of these attractiveness adjustments. First consider that for DRAM and EMPAL, the world (more specifically, the region) is described by the two time periods' data inputs to calibration. In this study, for all regions, this was data for 1985 and 1990. To the extent that, a) the two time periods in a particular instance might be anomalous in the region's history, or b) the data were unreliable or inconsistent, the models are, in effect, misinformed as to what has been taking place. The models can't "know" this, and the anomalous behavior and/or the statistical interpretation of unreliable data are subsumed into the estimated equation parameters. Any errors in calibration, i.e. the calibration residuals, are used in the preparation of the initial set of exogenous attractiveness adjustments. If these are used without review there is a chance that after a few time periods of forecast, the errors will result in the "explosion" or "implosion" of specific activities in specific zones. It is quite unreasonable to expect that a any model of a complex system can simply be set running, allowed to continue on for thirty to fifty simulated years, and give "good" final results after a single attempt. The purpose of the review of the 1995 forecasts, called by **S.H.Putman Associates** the model *validation* process, is precisely to incorporate local planners' knowledge to dampen or counter the effects of the anomalous or unreliable input data on the forecasts. This is **not** a matter of constraining a set of model forecasts simply to get the results that are wanted, but rather it is a means for the systematic input of local information beyond that which was in the initial calibration data set.

It was, we thought, necessary to establish that the effects of this adjustment of attractiveness of specific zones to specific locators would not so constrain the model outputs as to override the actual performance of the model. Several model runs were done with the Portland (METRO) data which established that the results of attractiveness modifications simply shifted the forecast values for the baseline run. When other inputs were changed for the purpose of testing policy, the model responded without any complications being caused by the attractiveness adjustments.

Another important procedure which had to be developed, usually as part of this first single period model run, was a systematic way of aggregating the agency's travel time matrix, the output of their trip assignment procedure, from the traffic zone level of detail at which the travel models were run, to the D/E zone level at which the land use models were run. Usually, there was a procedure in place, which had been developed by the agency in order to prepare the travel time matrix which was used as input to the DRAM and EMPAL calibrations, but often this procedure was not fully standardized, nor was it in a form which could easily be included as an automatic step in a model run. For each of the study regions an aggregation procedure was standardized for this purpose.

Several technical points had to be addressed in this process. First, was the issue of how the aggregation was to be defined. In some cases the travel time matrix aggregation problem is "solved" simply by picking a traffic analysis zone whose centroid is geographically close to the centroid of the land use model zone. This representative zone approach often gives reasonably good results, but omits information about the differences in travel time between different of the traffic analysis zones that are included in the larger land use model zone. This approach, however, often suffers from the problem of how to properly estimate the intrazonal travel times for the land use model zone system. Here, too, various approaches are possible, ranging from "picking a representative time", to various sorts of weighted or unweighted averages of times between the traffic zones included within each land use zone. Another approach to the estimation of interzonal times for the land use zones is to take weighted averages of the times between all the traffic zone pairs for the traffic analysis zones included in each pair of land use zones. For each of the study regions, the method used for the travel time aggregation is basically that which the agency had in place for its other modeling activities.

5.4 Perform a *Sequential* Model Configuration Run to the Year 2010

Having put together all the "pieces" necessary to complete the initial test run of just one time period, the next step was to attempt a run of the sequential model system configuration for four successive five year time periods, out to a forecast horizon of 2010. This required the assembly of sets of regional forecasts for each time period, and the transportation networks which were to be used. These networks were, in no case, available for each of the five year time points 1995, 2000, 2005, and 2010. This meant that, for each region, it became necessary to decide which year's networks would be used for which time period. These determinations are set forth in the sections that follow later in this chapter, as part of the discussion of the network components of the model systems. In addition, it here became necessary to develop an automated procedure for disaggregating the outputs of DRAM and EMPAL to the traffic zone level of detail, and, where needed for travel model input, to develop any supplementary variables that might be required. In the cases of Portland and Los Angeles, where previous work with integrated model systems had already been done, these procedures were, for the most part, in place. In the three other regions, it was necessary to work with agency staff to develop these procedures from various prototypes which the agency had on hand. Once the initial versions of the disaggregation procedures were developed it was still necessary to put them in a form which could be included in the stream of model system components so that they could be run "automatically" as a part of the integrated system runs.

The development of these connections from the land use models to the travel models were the last tasks necessary before the sequential model configuration could be tested. This configuration, already described in more detail in Chapter 3, consists of a connection at the end of each time period from the land use models to the travel models. The travel models are then run to produce an estimate of congested travel times which is, in turn, used as input to the next time period's forecast of land use, etc. For each of the agencies the model runs began in 1990 and made use of a matrix of congested travel times which were estimated independently of these model runs. From this a forecast of 1995 employment location was calculated by EMPAL, and of 1995 household location and land use, by DRAM. These 1995 forecast of employment and household location and land use were then used as input to the disaggregation procedure, and then, properly disaggregated, were used as input to the travel models. The travel models then calculated the congestion consequences (if any) on the region's highway networks. These congested 1995 times were then passed to an aggregation process, and the aggregated (to land use zone geography) times became input to the next time period forecast of employment and household location and land use. This next forecast, for the year 2000, was then disaggregated (to travel model geography), and used as input to the travel models. This process was continued to a final forecast year of 2010. This entire process is what we call the sequential model configuration baseline run.

The sequential model configuration baseline run was subjected to different levels of scrutiny by the regional agencies. In the case of Portland, attractiveness modifications were implemented in order to guide the baseline forecasts along a temporal trajectory that fell within a roughly $\pm 10\%$ tolerance around the Base Case IIA forecast which was at the time the accepted forecast produced by METRO, though these results were not reviewed by METRO staff.[23] In other agencies, too, there was only cursory scrutiny of the baseline, though the regional control totals were always those provided by the agency. Again we emphasize, that the forecasts produced in this study have no connection to any official forecasts produced or in use by any of the agencies with whose data we worked. We did, as an entirely independent matter, attempt to correct any obvious

[23] During the course of this study METRO made numerous changes to Base Case IIA. Since the time that these numerical experiments were conducted METRO have dropped Base Case IIA, and are now supporting a different forecast.

exploding or imploding zones. Once this set of tasks was complete, we had, for each region, a "standard" baseline against which we could compare the outputs from all other model configurations.

5.5 Perform an Equilibrium Model Configuration Run to the Year 2010

With the baseline (referred to hereafter as BLN) run completed the next task was that of implementing what are called the equilibrium runs (referred to hereafter as EQL). All of the various input files and the aggregation/disaggregation procedures developed in the preparation of the BLN runs were kept intact for use in these new runs. The difference between the BLN runs and these EQL runs is that within each forecast time period there are several iterations of the model system[24]. Our first task was to add the additional software that enabled the calculation of the convex combinations (a kind of weighted average) of the network link volumes for successive iterations of the model system. There are several ways in which this averaging can be done, the particular form we selected is known as the Method of Successive Averages - MSA, and was described in Chapter 3. Versions of this procedure, had to be added to TRANPLAN and enabled in EMME2. Then we tested the performance of the algorithm, both in terms of whether it yielded an equilibrium solution, and how much computational effort was required. Suffice it to say here, that the procedures did function correctly, were not exorbitant in their computational requirements, and demonstrated the feasibility of the equilibrium solution. An discussion of the numerical results of the first set of full models tests done under this project, those for Portland, forecast from 1990 to a 1995 equilibrium, are given in the next Chapter.

After implementing the algorithms necessary to achieve the intra-temporal equilibrium, the joint solution of employment and household location, land use, travel demand, and trip assignment, in the first time period forecast from 1990 to 1995, the next step was to perform a full equilibrium model configuration run from 1990 out to the 2010 forecast horizon. The experience from our earlier work both in the laboratory (Putman, 1991) and in Los Angeles, at SCAG, provided a basis from which to begin the new work. Though there were various complications in getting all the model configurations operating for all the regions, the complications were more a matter of clearing up uncertainties about initial model operation, than they were about actually implementing the equilibrium procedures. Ultimately all five regions model systems were

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[24]It is important to recall the difference between iteration and recursion. In a recursive process the results (outputs) of one step become input to the next. The recursive process moves on from one step to the next with no concern for issues of equilibrium or any other stopping criterion. The ***sequential model configuration used to produce the baseline forecasts (BLN) is temporally recursive***, in that the outputs from one time period become inputs to the next. *It is also intra-temporally recursive* in that within each time period the outputs from one model, say DRAM, become input to the travel models with no consideration of equilibrium. ***The equilibrium model configuration is also temporally recursive***. The results of one time period become input to the next. ***The equilibrium model configuration, however, is intra-temporally iterative***, in that there are multiple iterations within each time period as the outputs of one model become input to another in an iterative cycle which has as its aim the reaching of an equilibrium solution to employment and household location, land use, travel demand, and trip assignment within each forecast time period.

extended to being capable of functioning in either of the BLN or the EQL model run configurations.

Finally, it should be noted that numerous other runs, "side runs" were done as the work progressed and various other sorts of question arose. The included the runs done to test the effects of attractiveness modifications, to test differences in convergence rates in the presence of very high levels of network congestion, to test the effects of doing single step forecasts of twenty years' duration rather than the five year recursive steps, etc. These runs and their results will be discussed as the questions appear through the remained of this report. In the next section of this chapter we present descriptions of the transportation model configurations used in each region, including noting how the configurations used for these test had to be modified (when necessary) from what was the agencies standard practice.

5.6 Summary of Transportation Model Configurations for the Five Study Regions

It was not the purpose of this study to evaluate the transportation modeling practice of the study region agencies. As such, we attempted to make use of the exact transportation model configurations in current use at each agency. It was, however, necessary to make some changes in each of the regions, sometimes for simplification purposes, sometimes to enhance comparability of results, and sometimes because the agency's standard practice was, at least in some specifics, inconsistent with integrated model system configuration tests. In Table 5.1 we present a brief overview of the transportation model components used in each of the five study regions. In the table we also present, in boldface type, the model components which it was necessary to modify for the purposes of this study. These modifications do not represent changes made by the agency in their standard practice at the time of the study[25]. These modifications do not necessarily represent recommendations of **S.H.Putman Associates** as to changes in the way that the agency does its transportation modeling, nor do they represent recommendations on the part of the study sponsors. The modifications made here were solely for the purposes of accomplishing the goals of this study and do not necessarily represent comments on their appropriateness for achieving agency forecasting objectives.

5.7 Transportation Model Components and Disaggregation/ Aggregation Procedures

As can be seen in Tables 5.1a and 5.1b, a number of modifications were necessary in the various agencies' travel models for the purposes of this FHWA land use/transportation model integration project. The Pike's Peak Area Council of Governments (PPACoG), for example, provided a BASIC program for estimating trip productions and attractions, a file of node coordinates and link descriptions for building a TRANPLAN highway network file, and a TRANPLAN control file for trip distribution, peak-hour trip factoring, mode split, equilibrium network assignment, calculation of minimum travel time paths, and estimation of intrazonal travel times. PPACoG

[25]This does not mean that an agency might not change its practice at some later date. Some have.

Table 5.1a: Summary of **Transportation Model** Components by Agency[26]

Component	Colorado Springs PPACoG	Detroit SEMCoG	Kansas City MARC
Trip Generation	Linear regression model, seven trip purposes.	Linear regression model, six trip purposes.	Linear regression model, seven trip purposes.
Trip Distribution	*Travel deterrence based on uncongested travel times for all trip purposes.* **Travel deterrence based on congested travel times for all trip purposes.**	Travel deterrence based on congested travel times for all trip purposes.	*Travel deterrence based on uncongested travel times for all trip purposes.* **Travel deterrence based on congested travel times for home-to-work trips.**
Mode Split	Zone-specific ratios applied to home-to-work trips only.	Zone-specific ratios applied to all trip purposes.	Zone-specific ratios applied to all trip purposes.
Peak-Hour Factoring	Three hour P.M. peak- period trips and capacities factored to one hour P.M. peak.	*Twenty-four hour daily trips and capacities.* **From one hour PM peak-period trips and capacities.**	*Twenty-four hour daily trips and capacities.* **Two hour P.M. peak-period trips and capacities.**
Volume-Delay Functions	*Customized link-delay functions.* **BPR link-delay functions.**	*Customized link-delay functions.* **BPR link-delay functions.**	BPR link-delay functions.
Integration of "Four-Step" Model	*Unintegrated, individual model components.* **Completely integrated.**	*Unintegrated, individual model components.* **Completely integrated.**	*Unintegrated, individual model components.* **Completely integrated.**

also provided an EXCEL spreadsheet for disaggregating DRAM/EMPAL activity forecasts by socioeconomic characteristics and geographic zones. All of these had to be combined into a single model operation stream in order that the many required model test runs could be performed in a timely fashion.

With respect to land/use transportation model integration, the transportation model components provided by PPACoG required only minor modifications. These modifications, as well as those

[26] Model components that were not substantively modified for the project are shown in normal type.

Model components that reduce the "feedback" between the land use and transportation models, or are incompatible with an integrated land use/transportation model, are shown in italics.

Model components that were substantively modified for the FHWA project are in bold.

Table 5.1b: Summary of **Transportation Model** Components		
Component	Portland METRO	Los Angeles SCAG
Trip Generation	Fixed ratio model, six trip purposes.	Linear regression model,
Trip Distribution	Travel deterrence based on congested travel times for all trip purposes.	*Travel deterrence based on uncongested travel times for first trip distribution iteration*, based on congested travel times for all other iterations.
Mode Split	Zone-specific ratios applied to all trip purposes.	Linear regression model applied to all trip purposes.
Peak-Hour Factoring	Two hour P.M. peak-period trips and capacities.	Three hour P.M. peak-period (a transposed A.M. peak) trips and capacities.
Volume-Delay Functions	Conical link-delay functions.	BPR link-delay functions.
Integration of "Four-Step" Model	Completely integrated.	Completely integrated.

made in the transportation model systems of the other agencies cooperating in this study had as their major purpose, that of ensuring a degree of consistency which would allow the comparisons of model system configuration to be done both within and across regions. For PPACoG they were as follows:

1) *The PPACoG trip distribution model was modified to use congested highway travel times to calculate the separation of origin and destination zones, instead of minimum travel time paths on an uncongested highway network.*

2) *PPACoG's customized volume-delay functions were replaced with BPR volume-delay functions to calculate link travel times for the equilibrium network assignment procedure. It is necessary to use BPR volume-delay functions to maintain consistency with the MSA link averaging procedure used with TRANPLAN.*

In order to simplify the disaggregation procedure, the disaggregation spreadsheet provided by PPACoG was converted into a FORTRAN program. This program converts a DRAM/EMPAL forecast of population, total households, total employment and retail employment by activity zone into a forecast of population, households by dwelling type (single family residential/multi-family residential), households by income group (low/middle/high), total employment and retail employment by internal traffic analysis zone. To calculate the disaggregate activity forecast, the disaggregation program multiplies the aggregate activity forecast by fixed, marginal distributions of activities stratified by socioeconomic characteristics and traffic analysis zones.

PPACoG's trip generation model (which is written in BASIC) was also converted into a FORTRAN program. The trip generation model estimates trip productions and attractions for the internal traffic analysis zones by applying linear regression equations to the disaggregate activity forecasts. Productions and attractions are estimated for seven trip purposes: home-based work, home-based other, non-home-based, home-based social/recreation, home-based shopping, trucks, and trips with external origins or destinations. The total number of external-internal trips is calculated as a constant proportion of internal trips and allocated to the external traffic analysis zones in fixed proportions.

The trip distribution model provided by PPACoG uses minimum travel time paths on an uncongested highway network to calculate the separation of origin and destination zones. For the FHWA project, the trip distribution model is modified, so that congested travel times are used to calculate the travel separation functions for all seven trip purposes. Trip origins and destinations, for each trip purpose, are calculated using simple gravity models that were calibrated against observations from PPACoG's 1992 travel survey.[27]

Daily person trips are factored into P.M. three-hour person trips by multiplying the origin-destination person trip matrices by constant, region wide peak-period trip factors for each trip purpose. Of the seven trip purposes, only home-based work trips are assumed to be split between automobile and transit modes. Before mode split, home-based work person trips are converted into vehicle trips by dividing the home-based work person trip table by a region wide vehicle occupancy rate. (For the other trip purposes, vehicle trips are assumed to be equal to person trips.) Home-based work automobile trips are found by removing transit trips from the home-based work vehicle trip table, using a region wide mode split factor. Before trip assignment, the home-based work vehicle trip table is combined with the P.M. three-hour person/vehicle trip tables for the non-work trip purposes and a table of external-external trips (i.e., trips without origins or destinations within the Colorado Springs region).

The trip assignment procedure for Colorado Springs uses a 1995 (existing and committed) model highway network for all forecast time periods. The model highway network has 4412 nodes and 5395 links, with link capacities defined for a one-hour period. The assignment procedure provided by PPACoG uses customized volume-delay functions to calculate link travel times. Since the MSA procedure used with TRANPLAN calculates average link volumes using a BPR volume-delay "look-up table", the Colorado Springs trip assignment procedure was modified to use BPR functions. Within the trip assignment procedure, the P.M. three-hour vehicle trip table is factored, so that one-hour traffic volumes are assigned to a one-hour model highway network.

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[27] Barton-Aschman Associates (1993) *Colorado Springs Area Travel Survey: Final Report*

After the trip assignment procedure, intrazonal travel times are added to the matrix of interzonal travel times produced by assignment. The intrazonal times are calculated using the "Build Intrazonal Impedances" TRANPLAN module. In this module, intrazonal travel times are calculated as one-half of the average travel time to the six nearest traffic analysis zones. The final disaggregate travel time matrix (350 x 350 TAZs) is found by adding zone specific terminal times to the matrix of intra- and interzonal travel times. Before the travel time matrix is aggregated, the travel times for the external traffic analysis zones are discarded. For each activity zone, aggregate travel time is calculated as the trip-weighted average of the travel times for all of the TAZs which are contained within the activity zone.

For the other study regions there were also modifications to be made for the purposes of this study to ensure that the region-to-region comparisons would be consistent, and also to be sure that there was some appropriate representation of network congestion in the model system.

The original SEMCOG transportation model for the Detroit region calculates, as another example, travel demand for a twenty-four hour period. *The use of daily vehicle trips and twenty-four network link capacities unrealistically reduces the responsiveness of SEMCOG's transportation model to changes in land use, since the effects of peaks in travel demand on network congestion and estimated travel times are ignored. For this reason, trip factoring procedures and a revised set of volume-delay functions were added to the SEMCOG transportation model to estimate travel demand for the P.M. one-hour peak- period.*

With respect to land/use transportation model integration, the transportation model components provided by MARC for the Kansas City region also required substantial modification:

> 1) *Trip factoring procedures and a revised set of volume-delay functions were added to the MARC transportation model to estimate travel demand for the P.M. two-hour peak-period. The original MARC transportation model estimates travel demand for a twenty-four hour period.*
>
> 2) *The MARC trip distribution model was modified to use congested highway travel times to calculate the separation of origin and destination zones for home-based work trips, instead minimum travel time paths on an uncongested highway network.*

The trip distribution model provided by MARC uses minimum travel time paths on an uncongested highway network to calculate the separation of origin and destination zones. For this project, the trip distribution model is modified, so that congested travel times are used to calculate the travel separation functions for home-based work trips. (Uncongested travel times are used to calculate the separation of origin and destination zones for the remaining trip purposes.)

The Southern California Association of Governments (SCAG) had a completely integrated land use and transportation model prior to the start of this project. This integrated system was prepared by SCAG staff with assistance from S.H.Putman Associates and the Urban Analysis Group in 1993. The components of the integrated model included a SAS program for disaggregating DRAM/EMPAL activity forecasts by geographic zone, a FORTRAN executable program for estimating trip productions and attractions, TRANPLAN programs for trip distribution, peak-hour trip factoring, equilibrium traffic assignment, estimation of intrazonal travel times, calculation of minimum travel time paths, and aggregation of travel times to activity zones. There was a major difference from all the other regions' models, which is important to note. *The first iteration of SCAG's land use and transportation model uses uncongested travel times to calculate the separation of origin and destination zones for all trip purposes. Therefore, baseline estimates of trip distribution are unresponsive to changes in disaggregate travel times.*

A simplified version of METRO's (Metropolitan Service District) highly detailed travel demand model for Portland was used for the purposes of the project. METRO provided transportation model components for *two* activity/traffic analysis zone systems. For the first system, activity forecasts are made for 100 activity zones, travel demand is estimated for 100 traffic analysis zones, and estimated trips are assigned to a model highway network with 100 "load" nodes. For the second system, activity forecasts are made for 100 activity zones, and trip generation/distribution/mode split is estimated for the 100 activity zones, but trips are disaggregated to 1189 traffic analysis zones before assignment on a model highway network with 1189 "load" nodes.

With respect to land use/transportation model integration, the disaggregate travel demand model produces more satisfactory estimates of vehicle trips and highway travel times. The aggregate travel demand model produces too many intrazonal vehicle trips (which are not assigned to the model highway network) and uneven distributions of highway trips on the modeled highway links.

For the DRAM/EMPAL activity forecasts, the Portland region is divided into 100 zones. A more detailed geography would have given better results, but METRO was unable to develop the data necessary for it. For the transportation demand model, two zone systems are used -- the first system of 100 traffic analysis zones (which correspond exactly to the DRAM/EMPAL activity zones), and the second system of 1189 traffic analysis zones. The trip distribution model provided by METRO uses congested highway travel times to calculate the separation of origin and destination zones. Trip origins and destinations, for each trip purpose, are calculated using simple gravity models that were calibrated against observations from METRO's travel survey.[28]

There are innumerable other details regarding the various travel models, their forms, and procedures for dealing with different issues. Our effort in this study was to make minimal alterations to these models and procedures in order to achieve comparability across regions. In

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[28] METRO (1994) *The Phase III Travel Demand Forecasting Model: A Summary of Inputs, Algorithms, and Coefficients*

METRO (1992) *North/South Transit Corridor Study: Travel Demand Forecasting Methodology* most cases there would have been more than one way to accomplish these ends. We believe that the specific resolution of most of these details would not materially affect our study results - with the exception that all regions' models had to make use of peak period networks and congestion in order that the overall integrated model systems would be responsive to their interconnections.

5.8 Remote Computing Configurations

All of the hundreds of test runs done for this project were initiated remotely. Each agency's transportation model was run on the agency's own computer, using the software and data which was their normal practice (except as modified for the purposes of this project, as detailed in Tables 5.1a and 5.1b above. In some cases the DRAM and EMPAL models were also run on the agency's computer, and in some cases they were run on an **S.H.Putman Associates** computer. At the beginning of the project it was obvious that in order to accomplish the study goals it would be necessary to have direct access to each agency's computer facilities. For one thing, we could not afford to learn how to run the travel model packages as well as the many individual customized submodels that made up the travel model configurations of the several planning agencies. For another, each agency had already invested substantial resources in preparation of these models and also had staff who were accustomed to running the models. We knew that in order for the project to succeed we would have to draw upon those resources and, to the extent possible make use of the existing model setups on each agency's computer. At the same time, it was clear that the work would have to proceed on the various agency systems in parallel, rather than sequentially, one agency after another. While in fact it turned out that the actual progress of the study was more sequential with overlap than it was fully parallel, it still would not have been possible for our staff to go to each agency and remain there while the computer runs were done. We began with some trepidation, not having had much prior experience in remote computing, but found that with minor exception it was rather straightforward. All of the study regions except Portland were accessed remotely via a modem connection over telephone lines. For Portland the initial intention was to make use of an INTERNET connection, but for organizational reasons METRO took more than six months to implement their INTERNET connection. During that time a modem connection over telephone lines was used for Portland as well, but in later stages of the project the INTERNET connection was available. For both Portland (METRO) and Los Angeles (SCAG), the connection was to a workstation, a Sun SparcStation in the first case and an IBM RISC/6000 in the second. For the other three regions, where the models were being run on PC's the connection was made via modem and telephone lines by use of PC Anywhere software.

These remote connections turned out to be surprisingly effective for this work. There were various details, sometimes more than a little frustrating, to be overcome, but once done, the connections worked well, and telephone charges were not exorbitant.

The next chapter of this report contains the first part of the discussions of the empirical work of the study.

6 - Empirical Comparison of Model System Configurations

6.1 Introduction

Well above one thousand numerical experiments were performed for this project. Clearly the description of results presented here can cover only a fraction of the results obtained. Our intent is to provide the reader with the evidence for the conclusions reached, without, quite literally, inundating her or him with numbers, charts, and graphs. In this chapter we present results that establish certain specific points regarding the model system configurations and related issues. In the next chapter we continue the presentation of results with a comparison of the various issues across the several different metropolitan regions which we were able to examine.

In sections 2 -7 of this chapter we present comparisons of model system results for the Portland region using different model configurations to forecast a single five year time period, from 1990 to 1995. Sections 8 and 9 contain a description of the means by which the conversions between the land use model level of detail and the transportation model level of detail are accomplished. As will be discussed, this is a matter of some importance, as it can have a significant effect on the models' forecasts. The tenth section of the chapter is the first of four sections in which we present the results of comparing forecasts out to the year 2010 horizon made by each of the two model configurations, sequential (BLN) and equilibrium (EQL) for three different regions. After these the final section of the chapter contains some general conclusions.

6.2 Initial Model Sensitivity Experiments for the 1995 Forecast Year - Portland

The initial round of model sensitivity experiments made use of the 100-zone, 1990 Portland data as an input to the two land use model components and to the travel demand model. Two alternate zonal geographies were used in testing the trip assignment model: *a 100-zone network* description, and *an 1189-zone network* description. The sequential and equilibrium model configurations were used to develop ***five*** sets of alternate forecasts of employment and household location, land use, travel demand, and inter-zonal travel times. The **first** forecast, called the ***baseline*** **(BLN)** forecast, used the **sequential** model system configuration. The baseline forecast then served as the benchmark for comparison with the other model sensitivity experiments. The **second** and **third** forecast experiments make use of the **equilibrium (EQL)** land use - transportation model configuration, with a variation between the two with respect to additional (inner) iterations of the travel model components of the system, and use METRO's 100-zone network description for 1995. Forecast experiments **four** and **five** use the same linked land use - transportation model configurations, but use METRO's 1189-zone network for 1995. In all the experiments, EMPAL and DRAM, and the travel demand model, are configured to produce forecasts at the 100-zone level of geographic detail. When the 100-zone network is used, the load nodes for the model network are defined as the nodes closest to the zone centroids for the 100-zone geography. When the 1189-zone network is used, the 100-zone trip distribution matrix produced by the travel demand model is disaggregated to 1189 zones before it is assigned to the network. After trip assignment is complete, the travel time matrix is collapsed to 100 by 100 zones by using a representative zone scheme. Inter-zonal travel times for the 100-zone geography are found by identifying the zones from the 1189-zone geography (i.e., representative zones) that are closest to the zone centroids of the 100-zone geography. The inter-zonal travel times between the representative zones are then used to construct the 100-zone travel time matrix. The differences in design of the five forecast runs compared here are tabulated below.

Exp. Number	Configuration	Num. D/E Zones	Num. TD/TA Zones	TD/TA Iters.
1	Sequential	100	100	none
2	Equilibrium (EQL)	100	100	none
3	Equilibrium (EQL)	100	100	**three**
4	Equilibrium (EQL)	100	**1189**	none
5	Equilibrium (EQL)	100	**1189**	**three**

Note that here and elsewhere in the report the abbreviation D/E Zones refers to the level of geographic detail used for the location and land use modeling, in this case, of 100 zones. The abbreviation TD/TA Zones refers to the level of geographic detail used in the travel models (Trip Distribution/Trip Assignment), in this case either 100 or 1189 zones.

In the discussion of the model test results a set of evaluation measures is used to describe the outcomes. The *location surplus* statistic is a measure of the aggregate benefit households receive from accessibility to employment opportunities. As households become more dispersed, or as network congestion increases, the location surplus will decrease. The *user equilibrium* (UE) *objective function* summarizes the disutility trip-makers receive from highway travel, and is inversely related to the location surplus statistic -- lower values of the user equilibrium objective function indicate higher levels of utility for trip-makers (and households). Five different statistics are used to summarize highway network usage. These are: *total trips* (with subtotals for trips which are assigned to the network and trips which are not-assigned[29]), *total vehicle hours*, *total vehicle miles*, *average trip length* (in miles and minutes), and the average *volume/capacity ratio* for all of the network links.

6.3 Preparation of the Baseline Forecast

The baseline forecast serves as the benchmark for comparing all of the model sensitivity experiments. The baseline forecast was prepared by use of the **sequential** model system configuration. In these first experiments, the model system was only run for a single five year time period, so that in the sequential configuration there was no need to run the travel models. The baseline forecast is also comparable to METRO's Base Case IIA forecast.[30] It should be noted

[29]The number of trips which are not assigned to the network depends upon the geography of the models' zone system. The larger the zones, the more trips are intra zonal. Intra zonal trips are not assigned to the network.

[30] See (METRO, 1993) for a description of the Base Case IIA forecast.

that it was not the intent of this project, for any of the regions whose model systems and data were used for the analyses, to produce forecasts which would be used for the regional agencies' purposes. As such, it was not necessary that the forecasts match any existing forecasts prepared by the local planners. Even so, it did seem appropriate to attempt in each case to work with a baseline which was at least reasonable in terms of its resemblance to local forecast expectations. To accomplish this goal, during this baseline forecasting procedure, a set of modified attractiveness adjustments was created so that the 1995 forecasts of employment and household location from these experiments would closely match the METRO Base Case IIA forecasts[31]. The Mean Absolute Percentage Differences-MAPD on a zone-by-zone basis, between the baseline DRAM and EMPAL forecasts and the METRO's Base Case IIA forecasts were used as criteria for determining the proper modifications to the unmodified set zonal attractiveness variables.[32]

The modifications to the zonal attractiveness measures were made by using an iterative procedure, which compared the EMPAL and DRAM forecasts after each new attractiveness modification to the Base Case IIA forecasts. A target MAPD range of 5% to 7.5% was used as the stopping criteria for the Zonal attractiveness modification procedure. The *final set of modified attractiveness measures was used for the baseline forecast **and** for the four equilibrium land use - transportation model experiments described in this section of the report.* This was done in order to ensure that the various sets of forecasts would be kept directly comparable. The resulting MAPD statistic for the 1995 employment location forecast is 6.01%, and for the 1995 household forecast is 6.11%, thus corresponding rather closely to the Base Case IIA forecasts which METRO were at that time using for their own agency purposes. It should be noted that in the case of all the regions examined the use of model forecasts always involves additional adjustments to combine the statistical and information processing capabilities of the model systems with the informed local

[31] Attractiveness adjustments are a mechanism for incorporating the information contained in the DRAM and EMPAL calibration residuals to improve forecasts of employment and household location. By making careful modifications to the Zonal attractiveness, it is possible to adjust the employment and household forecasts produced by DRAM and EMPAL to match a pre-specified target or exogenous forecasts of employment and household location.

[32] The equation for the MAPD criterion is defined as:

$$\text{MAPD} = \frac{100}{N}\left[\sum_{i}^{N}\frac{\left|\hat{y}_i - y_i\right|}{y_i}\right]$$

with

y_i = the METRO Base Case IIA 1995 forecast of employment or household location,

$\hat{y}_i$ = the EMPAL or DRAM 1995 forecast of employment or household location,

N = the number of zones.

planners' knowledge of what is happening in the region. From region to region, for the purposes of this study, there were different levels of emphasis on adjustment of the baseline. In no case is the baseline or any of the test forecasts described in this report to be considered as anything other than a model test run. Actual forecast work for the individual regions is the responsibility of the regional agencies and may or may not yield results which resemble those analyzed here.

6.4 Equilibrium (EQL) Land Use-Transportation Model Runs: 100-Zone Network

The **second** forecast experiment used the equilibrium (EQL) land use - transportation model configuration and the 100-zone network. The results of this experiment were nearly identical to those of the baseline forecast. The mean absolute percentage differences between the baseline forecasts of employment and household location and the forecasts produced by the equilibrium land use - transportation model system configuration are 0.38% for households and 0.42% for employment.

The close correspondence of the baseline forecast and the equilibrium land use - transportation model forecast is due principally to the highly aggregated network representation used for the second forecast experiment. When the 100-zone network is used, many trips are not assigned to the network, since many short trips never cross a zone boundary for these rather large zones. For this second forecast experiment, 22.3% of total trip demand was not assigned to the highway network. In addition, the capacities of the aggregated links are, in effect, artificially inflated. Consequently, the volume on most network links was far below design capacity, and overall congestion levels for the region were unrealistically low as evidenced by the average link volume capacity ratios being only 0.48, i.e. each link carrying, on average, only half of its design volume. As a consequence, there is virtually no congestion, and the estimated inter-zonal travel time matrix barely changes from one iteration to the next, and therefore the location of households and employment remains the same across iterations, just as if the zone-to-zone travel times were constant.

6.5 Equilibrium (EQL) Model Runs with Travel Demand Iterations: 100-Zone Network

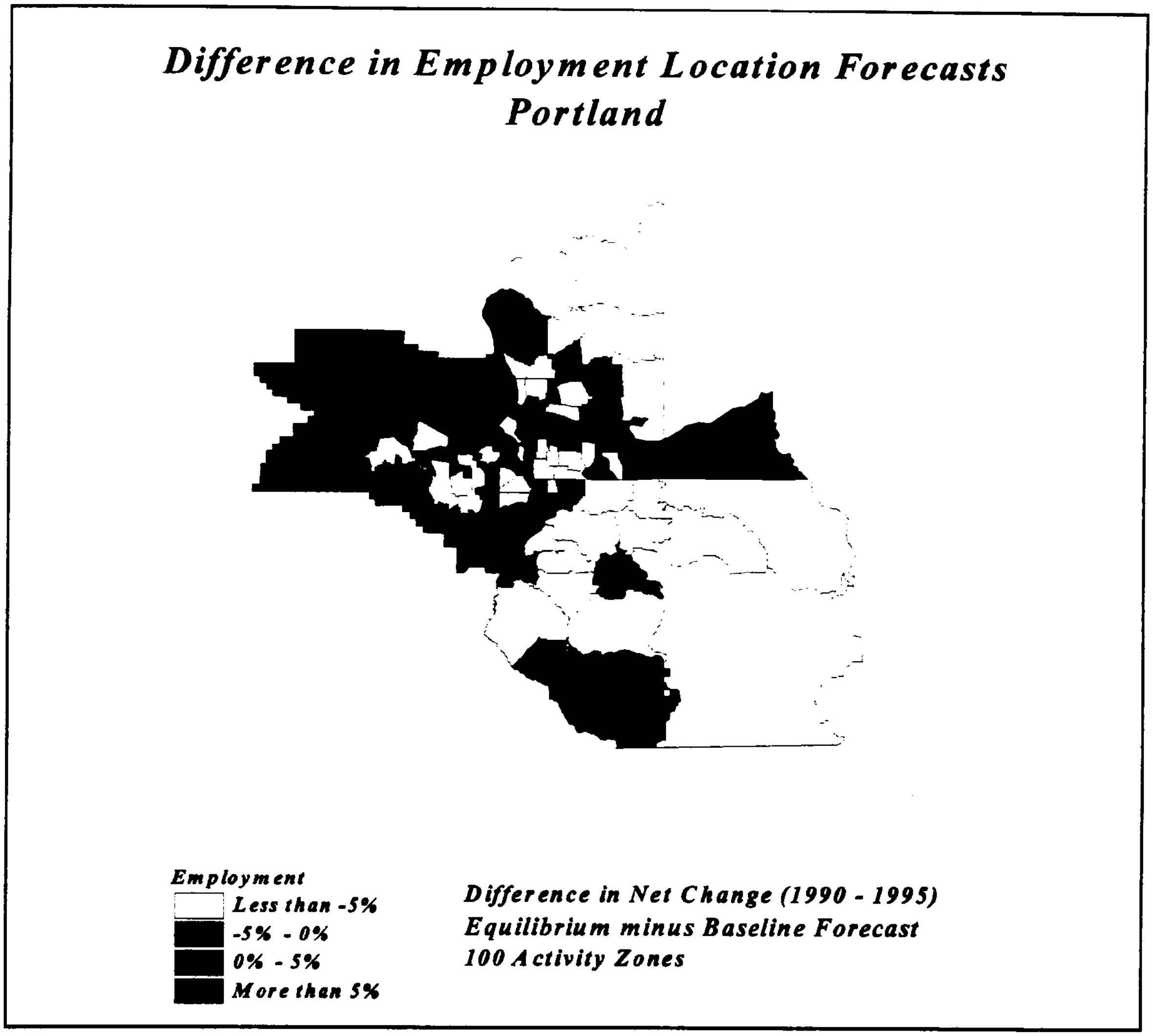
The **third** forecast experiment, used the equilibrium model configuration, the same as that for the second experiment, but with the addition of three (inner) travel demand - trip assignment iterations that are calculated within each (outer) land use - transportation iteration. Note that both the second and third model system experiments reach the same equilibrium solution, giving empirical confirmation to the theoretical assertion that the solution to the equilibrium (EQL) land use - transportation model system, for a given input data set (here using the 100-zone network) is unique, and that it is independent of the configuration of inner travel demand - trip assignment iterations.

The only differences between the second and third forecast experiments are the rates of convergence of the convex combinations algorithms. When the *inner*, travel demand - trip assignment iterations, are used, the transportation models produce more evenly distributed estimates of inter-zonal trips within each *outer* land use - transportation iteration. This reduces fluctuations in the inter-zonal travel time matrix between each land use - transportation iteration, and leads to a smoother convergence path. It should be noted that as the land use - transportation iterations progress, the forecast locations of employment and households become more efficient, that is, they move towards an optimal spatial pattern. This notion of optimality is, of course, a limited one, as the current model structure lacks an explicit representation of the land and housing market. Yet, the market dynamics are represented in surrogate form in terms of the differential locations of the households of different income groups. Further, optimality is contingent on the base year patterns of location, and on the exogenously specified transportation network with its given links and link attributes. For both forecast experiments, the location surplus increases and the UE objective function decreases as the iterations progress. In fact, it appears that the equilibrium solution to the linked land use - transportation model system configuration, after an initial set of adjustment iteration(s), is optimal with respect to location surplus and the UE objective function.

6.6 Equilibrium (EQL) Land Use-Transportation Model Runs: 1189-Zone Network

One of the issues raised in the preliminary work was that of modeling geography. The first three experiments were done with both the DRAM/EMPAL modeling and the travel demand modeling being implemented at the 100 zone D/E level of detail. At this geographic scale there were a significant number of unassigned trips, i.e. intra-zonal trips which were not included in those to be assigned to the network. Our concern here was that the gross geography used for the travel models had the effect of obscuring, by omission, the effects of traffic congestion which was expected on the network. To examine this hypothesis, a set of experiments was done for which the travel modeling was implemented at the finer 1189 zone geography at which METRO did most of its transportation analyses. Thus the **fourth** forecast experiment uses the equilibrium model system configuration, and **the 1189-zone network**. *The results of this forecast experiment, as expected, were significantly different from the baseline forecast and the second and third equilibrium land use - transportation model system forecasts that made use of the 100-zone network.* Taking the baseline forecast as a benchmark, the MAPD statistics describing the differences between baseline and the fourth forecast experiment are 1.82% for households and 5.98% for employment.

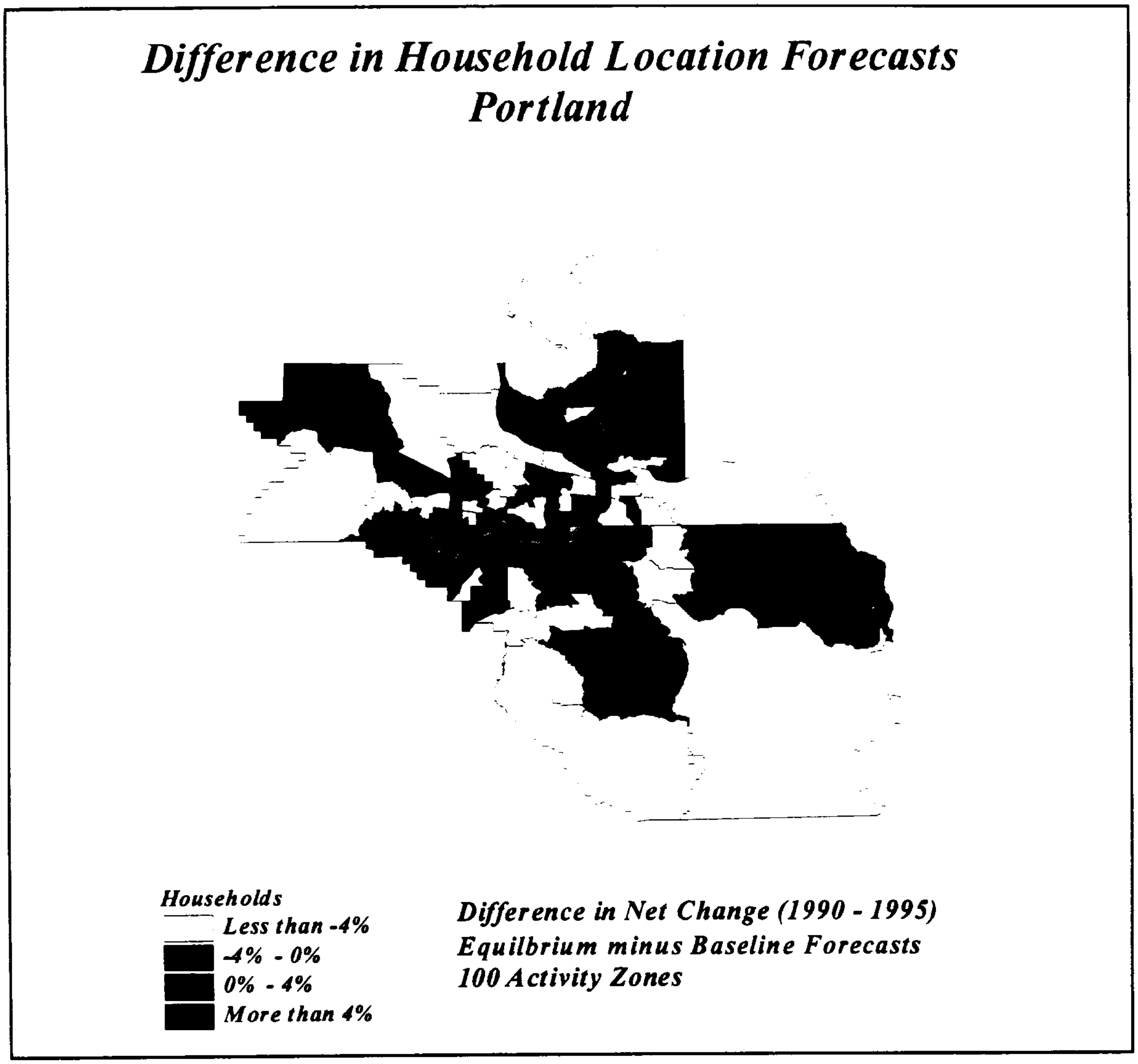
Map 6.1 shows, for total employment, a zone-by-zone comparison of the baseline forecast to the fourth equilibrium land use - transportation model forecast using the 1189-zone network. The map shows the percent difference between the net change from 1990 to 1995 in the baseline (BLN) run and the net change from 1990 to 1995 in the equilibrium (EQL) run. A "solid" zone on the map is one where the change in the EQL run was *greater* than the BLN by 5% or more. An "empty" zone is one where the MSA change was *less* than the BLN change by 5% or more. Map 6.2 shows the results for total households. When the 1189-zone network is used for the linked land use - transportation model system configuration, more households are allocated to zones at the eastern and western edges of the Portland region, and fewer households are allocated to zones in the south. The employment forecast follows a similar pattern -- more employees are allocated to eastern and western zones outside of the urban core, and fewer employees are allocated zones in



Map 6.1 - Difference in Employment Distributions Between BLN and EQL

the souther quadrant of the region. These differences are probably due to a more realistic loading of trips onto the network, and as a consequence, a more realistic set of estimates of trip congested network travel times. When the 1189-zone network is used, 97.1%, nearly all, of the trips forecast by the travel demand model are assigned to the highway network, as compared to just 77.7% assigned when the 100-zone network was used. This produces a more accurate representation of actual trip-making behavior, and a more accurate simulation of network usage.

The **fifth** forecast experiment is analogous to the third experiment, it too made use of the equilibrium model system, with the addition of three inner travel demand - trip assignment iterations calculated inside each outer iteration. The results of the fifth forecast experiment were nearly identical to the results for the fourth forecast experiment. The mean absolute percentage differences between the forecasts produced by the fourth and fifth experiments are 0.04% for households and 0.07% for employment. This again confirms the supposition that the correctly



Map 6.2 - Difference in Household Distributions: Between BLN and EQL

specified and correctly calculated equilibrium solution to a linked land use - transportation model system is independent of the internal configuration of inter-model linkages such as travel demand iterations.

6.7 Conclusions from the Preliminary Portland Experiments

Based on the results of these initial experiments, a number of initial conclusions can be made about the use of linked land use - transportation model systems. We note first that the equilibrium solutions to linked land use - transportation model systems are *optimal with respect to the location surplus and UE objective function criteria*. Thus it is possible that, given the structure of the land use - transportation model systems, the equilibrium forecasts of employment and household location represent utility maximizing behavior, subject to constraints and imperfect information availability and including dispersion of preferences, by households and trip-makers.

Perhaps the most important point from these first experiments, beyond the fact that the model system configurations are shown to work properly, is that the ***specification of model system geography, i.e., the level of spatial detail, does have a significant effect on the forecast outcomes***. This is because the larger levels of geographic detail will cause the travel demand models to "miss" greater numbers of intra-zonal trips. These trips will not cross a zone boundary, and thus they will not be included in the trip assignment portion of the modeling process. Further to this, it appears that ***the use of what are popularly known as "sketch level networks" is likely to give poor forecast results***.

The ***differences between forecasts from unlinked and linked land use - transportation models can be significant if the level of congestion on the modeled highway network is significant***. In the absence of network congestion, the feedback from the transportation model components to the land use model components is redundant. This is because there will be no increase in link times due to the small link volumes, thus the travel times will remain constant. This is not so much a finding as a confirmation of what is obvious from theory. If there is no congestion, then there is no flow dependent change in link travel times and/or costs.

Before moving to the discussion of the multiple time period experiments, it is appropriate to discuss the types of procedures that are used to perform the aggregation of travel times and disaggregation of land use location which are necessary to link the transportation and land use models when they are operational at different geographical scales.

6.8 Aggregation of Travel Times

We have concluded above that, in general, it is not advisable to use "sketch" level highway networks when modeling transportation demand within an integrated land use and transportation model[31]. As the geographic detail of a model highway network decreases, the number of intrazonal trips increases. Since intrazonal trips are not assigned to the model highway network, network congestion and the effects of changes in land use activities on travel times will be underestimated when "sketch" level networks are used. However, "sketch" level networks can sometimes have one advantage over more detailed model highway networks: if the geography of the "sketch" network is appropriately defined, then it is possible to use the same zone system for both the land use models and the transportation models. For example, the Portland "sketch" level highway network is defined for 100 traffic analysis zones that exactly correspond to the land use zones used for modeling land use activities. When there is an exact correspondence between the traffic analysis zone geography and the land use zone geography, it is not necessary to disaggregate land use activities before they are input to the transportation models or to aggregate

[31]In point of fact, it is worth considering whether it is ever a good idea to use sketch level networks, as there are so many problems which result from the information lost in aggregation. Even so, it is also wise to guard against extreme disaggregation wherein the trips per link may fall to such small values as to be smaller than the likely error terms of the models.

travel times before they are input to the land use models. Unfortunately, as was the case for the Portland runs, this can result in a geographic structure which is too highly aggregated overall.

In all five of the FHWA study regions (except for the Portland "sketch" level network model), the number of traffic analysis zones exceeds the number of land use zones. Within the transportation model, travel times are estimated for each pair of traffic analysis zones (TAZ). Before the estimated travel times can be input to the land use models, the TAZ-level travel time matrix must be aggregated to the land use zone geography. Two types of procedure were used in the FHWA study for aggregating TAZ-level travel times to the land use zone geography. A trip-weighted averaging procedure was used in Los Angeles, Colorado Springs, Detroit, and Kansas City. A "representative" zone procedure was used in the Portland model system.

For the trip-weighted averaging procedure, the travel time from one land use zone to another land use zone is assumed to be equal to the weighted average of the travel times between the traffic analysis zones contained in each land use zone. The weights are defined as the number of trips between each traffic analysis zone. For some pairs of land use zones, there will be no trips between the corresponding traffic analysis zones. To avoid estimating "zero" travel times for these zones, all elements of the TAZ-level trip matrix that are equal to zero are reset to one before the trip-weighted travel time averages are calculated.

Because, all other factors being equal, trip-makers prefer shorter trips to longer trips, *the mean value of an aggregate travel time matrix calculated with a trip-weighted averaging procedure will always be less than the mean value of the original disaggregate travel time matrix*. For example, the mean of the zone-to-zone travel time values of the 1995 baseline aggregate travel time matrix for Detroit is 42.6 minutes, while the mean of the zone-to-zone travel time values for the corresponding disaggregate travel time matrix is 48.8 minutes. In fact, for most pairs of land use zones, the estimated aggregate travel time will be less than the unweighted average of the travel times between the origin and destination TAZs. This is because fewer trips will be on the longer paths than are on the shorter paths and thus the longer paths will contribute less to the mean of the path lengths. In terms of model system implementation, this suggests that the finer the level of geographic detail in the location modeling the better. There will always be a countervailing force, in that the greater the level of geographic detail, the more difficult the data collection tasks, and the more likely it is that there will be higher error levels in the data. Here, clearly, is a place in the modeling process where there is a need for the making of tradeoffs between improved performance from greater geographic detail, and debilitated performance for a level of geographic detail which cannot be supported by the reliability of the source data.

For land use zone pairs without trip interchanges, the trip-weighted averaging procedure outlined in the previous paragraphs collapses to an unweighted averaging procedure, since the number of trips between each TAZ-to-TAZ pair will be arbitrarily set to one. This means that the trip-weighted aggregation procedure may not be well-suited for regions with sparse trip matrices, where there are many zone-to-zone pairs with zero trips (i.e., trip matrices with a significant number of elements equal to zero).

For the "representative" zone aggregation procedure, which is an alternative to trip-weighted aggregation procedure, the elements of the aggregate travel time matrix are completely independent of the numbers of trips between each traffic analysis zone. In this procedure, "representative" zones are defined as the traffic analysis zones closest to the centers of each land use zone. Since there is a one-to-one correspondence between representative traffic analysis zones and land use zones, the aggregate travel time matrix can be found by extracting the elements of the disaggregate travel time matrix that correspond to the representative zones.

While the "representative" zone aggregation procedure is independent of the distribution of trips between TAZs, it is not independent of the geography of the traffic analysis and land use zone systems. In general, the statistical distribution of the aggregate travel times produced by a "representative" zone aggregation procedure will be skewed to the right when compared to the statistical distribution of the unweighted, disaggregate travel times (i.e., the aggregate travel times will, on average, be larger than the disaggregate travel times). This is because the "representative" zones are always near the centers of the land use zones. Most TAZ-to-TAZ trips occur between TAZs near the edges of land use zones, and are shorter than trips to and from TAZs near the centers of land use zones. As with the trip-weighted aggregation procedure, the bias in the aggregate travel times produced by the "representative" zone procedure is not random error, but reflects the assumption that all trips originate and terminate in the centers of the land use zones. Such an assumption may be valid when the numbers of land use zones and traffic analysis zones are nearly equal, or the size and shapes of the land use zones are uniform across a region. Here, too, caution should be used in the interpretation of the results of these processes.

6.9 Disaggregation of Land Use Activities

Before the forecasts of employment and household location and land use can be used as input to the transportation models, the distribution of land use activities must be disaggregated to the TAZ-level geography. In all five of the FHWA study regions, *observed* locations of land use activities by traffic analysis zone are used to construct marginal distributions of activities by TAZ, and in some cases by other socio-economic categories (such as, household income and/or life-cycle, or employment category). To find the disaggregate estimates of land use activities, the aggregate forecasts are multiplied by the marginal distributions. For each land use zone, the marginal percentages of the land use in each TAZ (and socio-economic category) necessarily sum to one, so the regional sums of the land use levels at both the land use zone and traffic analysis zone geography will be equal (ignoring any rounding error.)

The accuracy of this sort of disaggregation procedure is almost completely determined by the accuracy of the observed marginal distributions of activities by TAZ and socio-economic category, and of their stability over time (over the forecast period). The geographies of the land use zone and traffic analysis zone system can also effect the accuracy of the land use land use disaggregation. It is more difficult to estimate disaggregate land use levels for regions where the number of TAZs is much larger than the number of land use zones, or where there is a wide range in the relative sizes (with respect to area or land use level) of the TAZs. This argues for smaller rather than larger ratios of TAZ to land use and land use allocation zones.

Since employment location is usually less uniform than household location, a disaggregation procedure based on fixed marginal distributions will usually be less "accurate" (i.e., the statistical distribution of the aggregate activities will be more unlike the statistical distribution of the disaggregate activities) for employment activities. As an example, standardized distributions of aggregate and disaggregate land use activities were calculated for Colorado Springs. For each land use zone and traffic analysis zone, the total numbers of households and employment in each zone were standardized, so that the statistical distribution of each land use has a mean of zero and a standard deviation of one. This standardization allows us to compare the statistical distributions of the land use activities at both the land use zone and traffic analysis zone level.

As Figure 6.1 shows, the standardized distributions of the aggregate and disaggregate household land use totals are quite similar. The similarity in distributions reflects the accurate allocation of activities by land use zone to activities by traffic analysis zone, but also indicates that within each land use zone, households are distributed fairly evenly between TAZs. The stability of these marginals over time is, of course, unknown, but must be assumed, due to the lack of any other possibilities for straightforward disaggregation procedures.

The standardized distributions of the aggregate and disaggregate employment land use levels are somewhat more dissimilar. In Figure 6.2 the results of a comparison of the geographically aggregate and disaggregate employment distributions are shown. The two distributions are quite different from each other. However, this dissimilarity is mainly due to the uneven geographic distribution of employment in the Colorado Springs region and a resulting rather few traffic analysis zones with high levels of total employment. Approximately 50% of total employment is

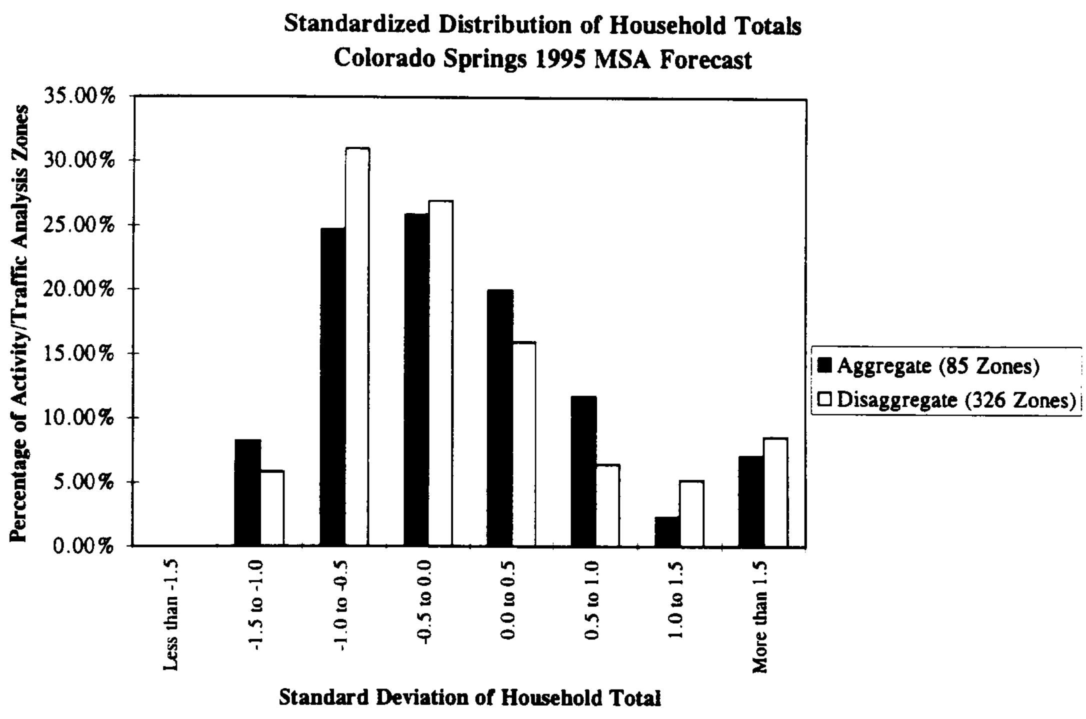


Figure 6.1: Frequency Distributions of Aggregate and Disaggregate Zonal Households

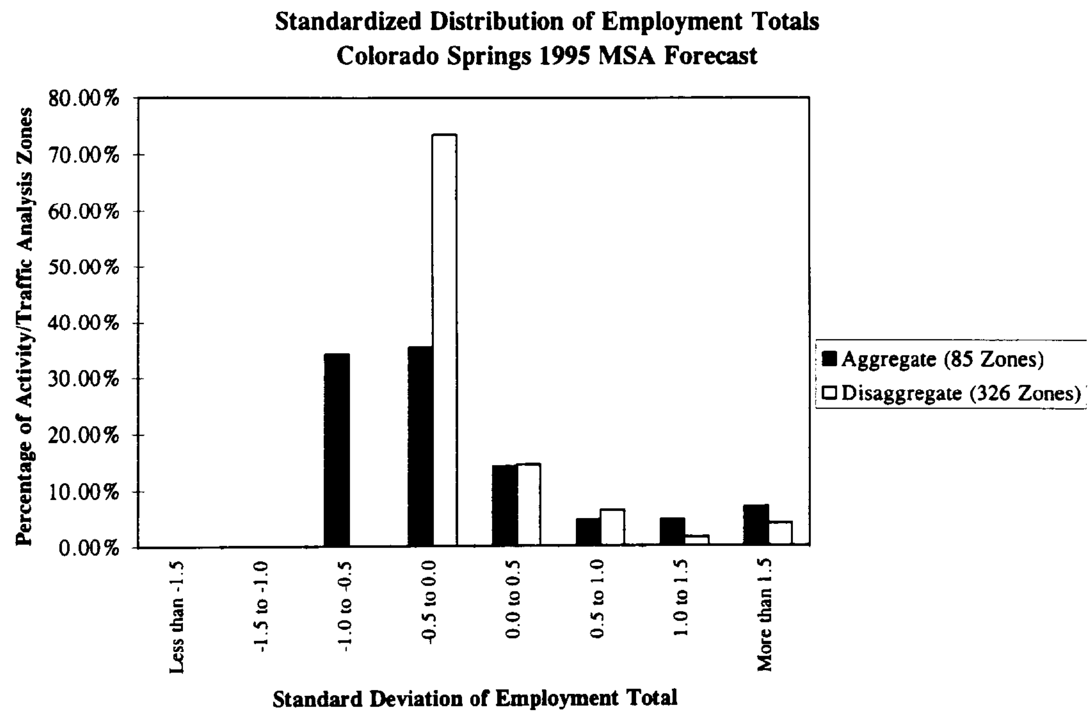


Figure 6.2: Frequency Distributions of Aggregate and Disaggregate Zonal Employment

concentrated in 10% (32 out of 326) of the traffic analysis zones, while approximately 26% of total employment is concentrated in 10% (8 out of 85) of the land use zones. Again, the moral of the story is that these aggregation and disaggregation procedures must be evaluated carefully in terms of the distortions they may produce in the distributions of the variables of interest in the linked transportation and land use model systems.

6.10 Initial Model Sensitivity Experiments for the 1990 - 2010 Forecast Period - Portland

Having completed the experiments for the single 1995 forecast period, the next step in the project was to perform a full set of model run experiments following the various model configuration options all the way out, through four five year time periods to the 2010 forecast horizon. In general terms, two different "runs" were done for each of the study regions. The first of these was a baseline (BLN) run making use of the sequential model configuration. The second run was of the linked (MSA) model configuration. In both cases, the runs began with 1990 inputs, and the proceeded to the 2010 forecast horizon in five year steps. Within the two generic run types, several additional experiments were conducted to address "side" issues that arose during the course of these experiments. The purpose of this set of runs was to compare the sequential and linked (MSA) model configuration performance over a multiple time period forecast.

The Portland data with 100 D/E zones and 1189 TD/TA zones was used for the first of these experiments, which were extensions of the runs described in the earlier sections of this chapter. First a **sequential** model configuration was run, continuing from the sequential run to 1995, and proceeding out to a forecast horizon year of 2010. METRO does not have a different network for each of the five year time points. They have networks for 1990, 2000, and 2010 only. The 1990 network was used for the 1995 forecast, while the 2000 network was used for the 2000 and 2005 forecasts, and the 2010 network was used for the 2010 forecast. A second set of runs was done using the **equilibrium** model configuration. Keeping in mind that the question(s) here are not about whether the model system converges (a point proved in the earlier experiments), several different comparisons were done between the two runs.

6.11 Aggregate Comparisons: UE, VMT, Mean Travel Times, Mean Trip Lengths

First, from the theoretical perspective, we compared the values of the UE objective function at each forecast year, 1995, 2000, 2005, and 2010. These results are shown in Figure 6.3, where

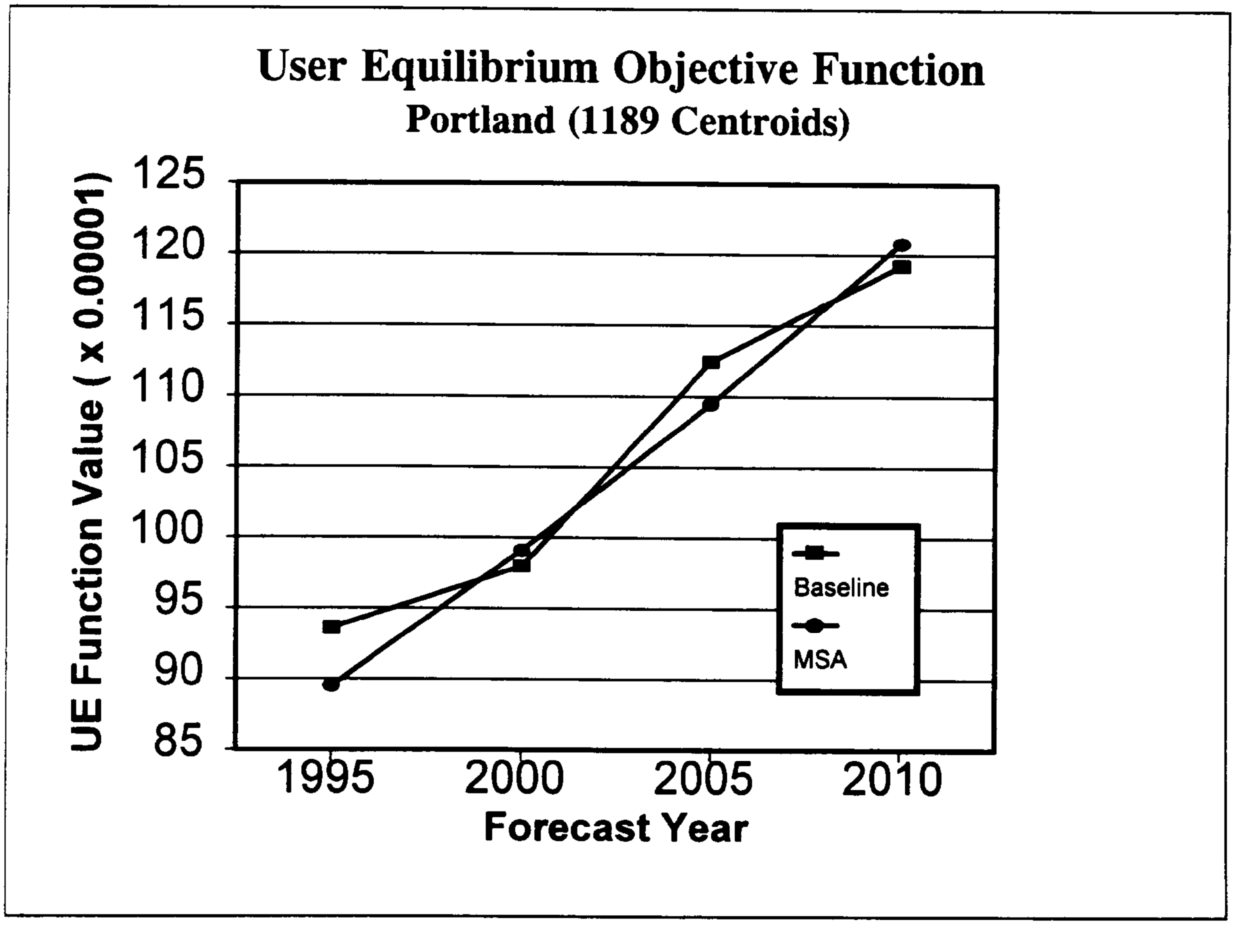


Figure 6.3: Comparison of UE Function Values for BLN and EQL Runs

it may be seen that the UE function values from the BLN run oscillate around the UE function values from the EQL (note that in several of the figures, the term MSA is used, referring to the algorithm which is used to solve the equilibrium model configuration) run. In the Portland model runs, where there is not much congestion on the networks, the magnitude of these oscillations is not great, though it does point to the fact that, depending upon which forecast year is chosen, the BLN approach can give results which are *either* greater or less than the EQL approach. As will be discussed elsewhere in this report, this can be a matter of considerable importance in situations where policy evaluations are being based on the modeling results. With the sequential model

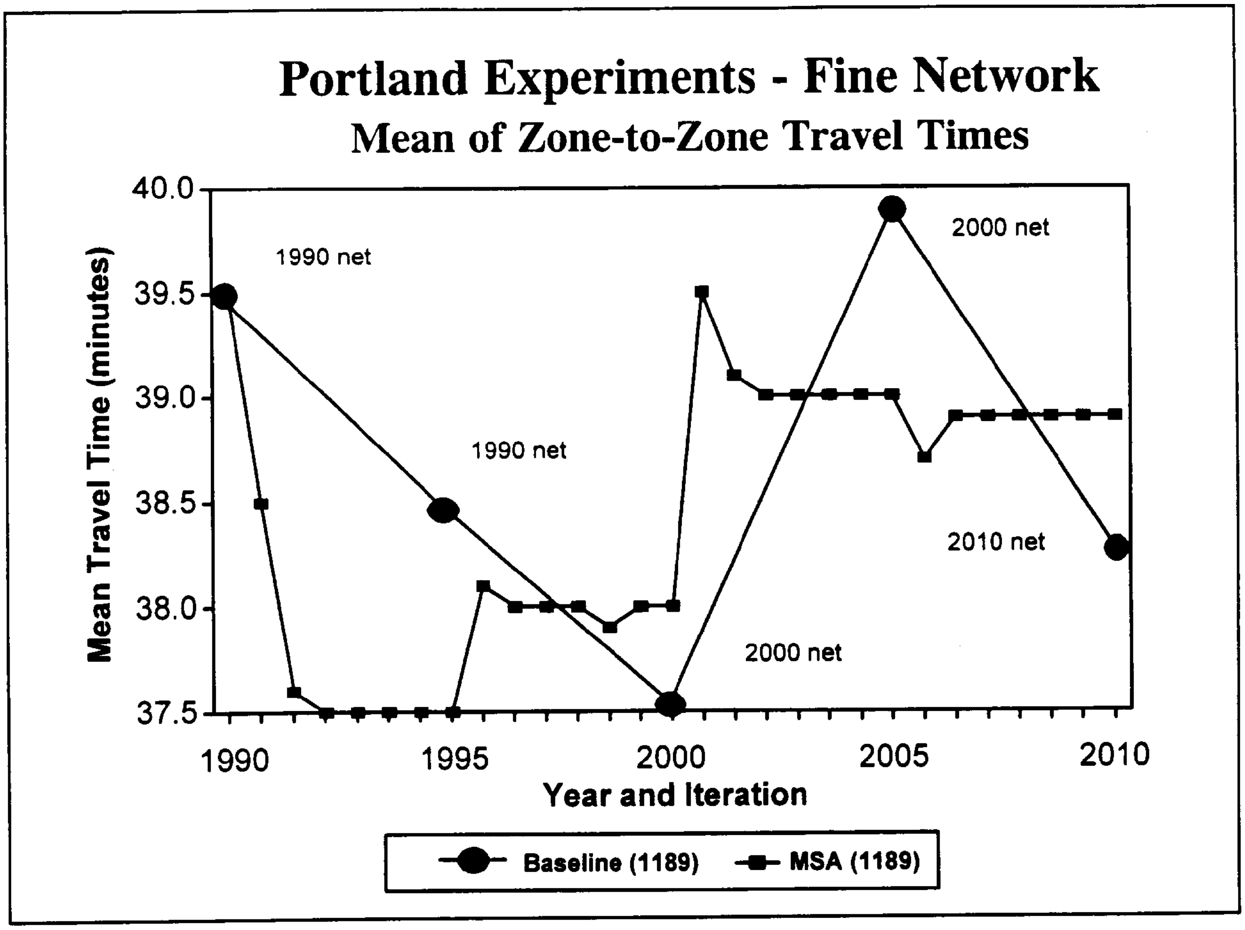


Figure 6.4: Trajectory of Zone-to-Zone Travel Times, Portland 1990-2010

configuration, it will sometimes be possible to change the policy analysis conclusions simply by selecting one time period versus another for the policy result comparisons. The location surplus values calculated in these experiments do not, however, show such substantial variations. For both Vehicle Miles Traveled (VMT) and average trip lengths, there are results similar to those for the UE function, with the BLN values oscillating around the EQL values. Another way of looking at the two different sets of run results is by looking at the average of the zone-to-zone travel times of the impedance matrices used as input to the successive iterations of DRAM and EMPAL. In Figure 6.4 these values are plotted. The plot shows seven MSA iterations for the 1990 to 1995 forecast, and six iterations each for the 1995 to 2000, the 2000 to 2005, and the 2005 to 2010 forecasts. In each case the iterations are started from the final travel time value from the prior time period (or in the case of 1990 to 1995,from the initial 1990 travel times). Within each five year period the travel times in the EQL run can be seen to make a "large" jump followed by a series of progressively smaller adjustments. For comparison, the values of the mean zone-to-zone travel times for the BLN run, made by use of a sequential model configuration, follow a rather different trajectory. They begin with rather congested times for the exogenously created 1990 travel time inputs to the model runs. The travel times drop somewhat for 1995 as a consequence of the modest centralization of activities and the resultant modest reduction in trip making. There is a further reduction in travel times for 2000, due primarily to the introduction of a "new" highway network with some link and capacity additions. The somewhat more significant increase in location dispersion (of employment and households) and the attendant increase in trip making yield noticeably higher travel times for the year 2005. This is followed by a drop in travel times with the introduction of another "new" highway network for the year 2010. The results from the EQL run, while showing a response to the relocation tendencies of activities and the introduction of "new" networks, give more stable results for the forecast years between the introductions of new networks. This same pattern can be seen in the trajectories taken by average trip lengths as shown in Figure 6.5. We note here, in passing, the issue of how new networks might better be introduced into a modeling sequence. Evidence from various studies of the actual train of events after the decision to construct a new network addition shows that development often precedes facility construction. That is, some residential and employment location decisions are made in anticipation of network improvements, while others take place during facility construction, and yet others follow the completion of facility construction. With this hypothesis for the staging of transportation induced land use location and travel demand, it is clear that work is needed to develop ways of representing this process in the modeling process. *One of the easier improvements to modeling practice would involve simply "spreading" the introduction of facility changes by use of "new" networks at five year intervals rather than the ten year intervals used by Portland's METRO and most of the other agencies. Another improvement could be had by performing one or more initial adjustment runs to develop a better consistency between the starting (1990) impedances, which are prepared exogenously, and the values which come from the initial period's integrated model run results.*

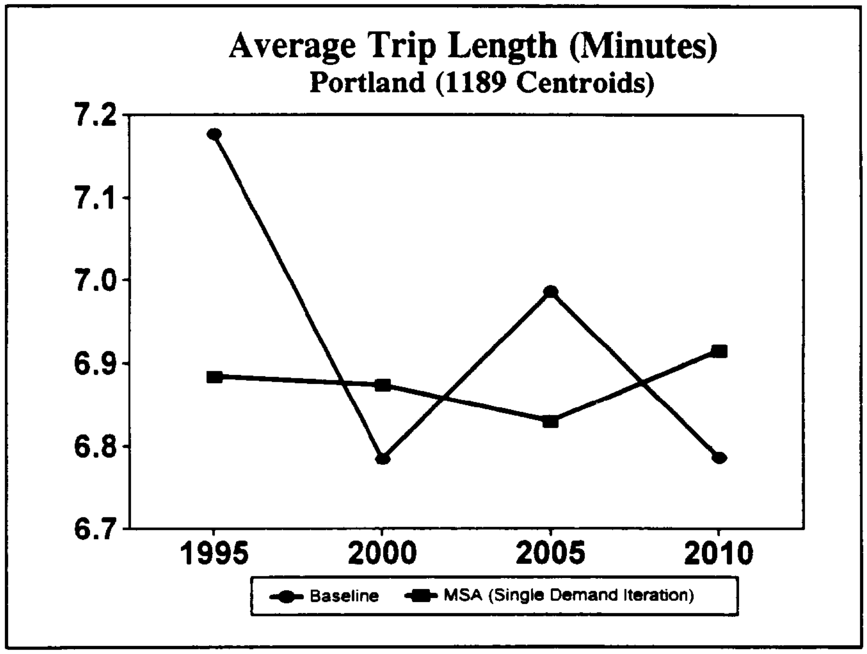


Figure 6.5: Trajectories of Average Trip Lengths

6.12 Model Sensitivity Experiments for the 1990 - 2010 Forecast Period - Colorado Springs

As part of this series of model tests the data for Colorado Springs, too, were used to do a pair of runs from 1990 to 2010. As was the case for Portland, first a **sequential** model configuration run was done, and then an **equilibrium** model configuration run was done. At present. the

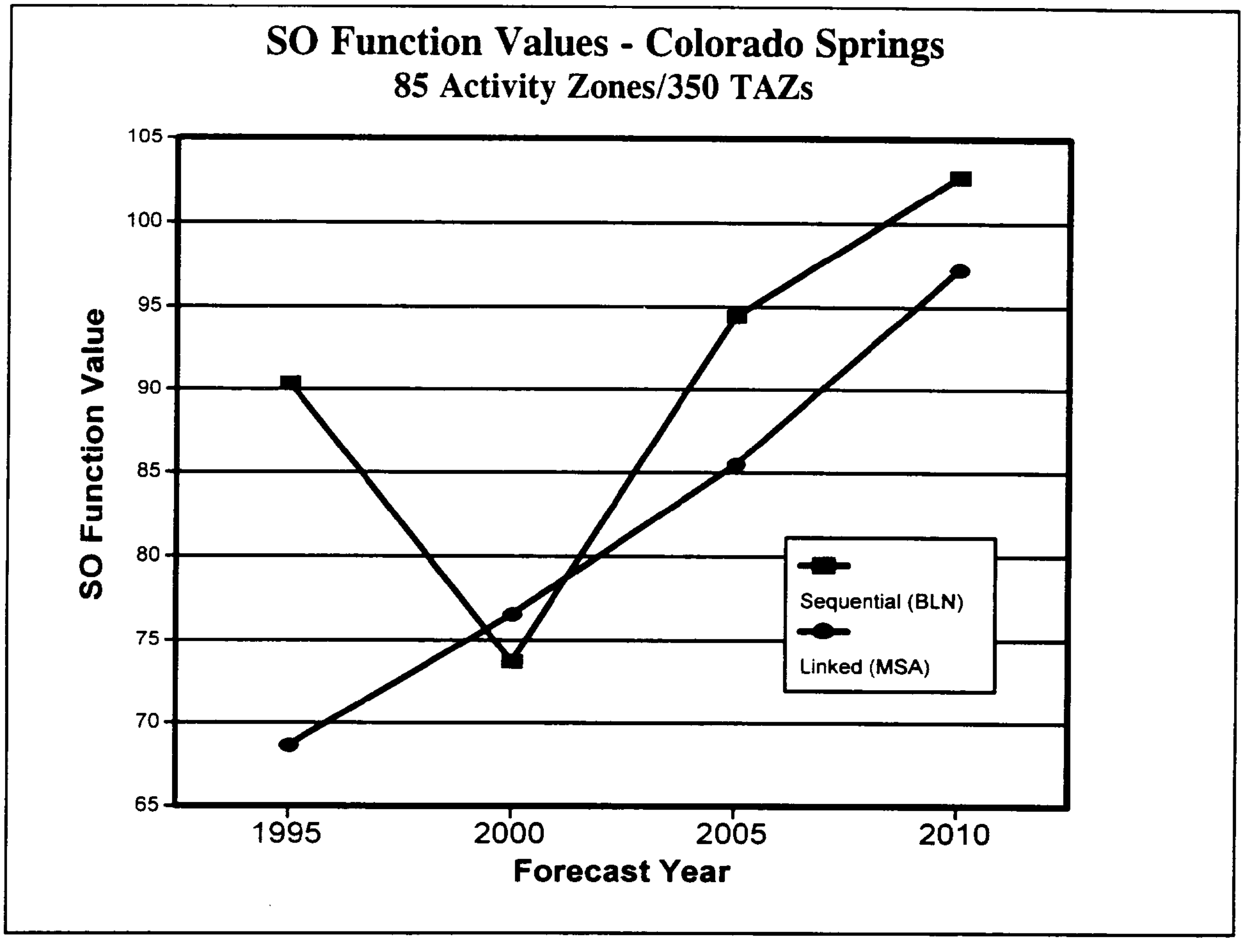


Figure 6.6: Comparison of SO Function for BLN and EQL Runs

TRANPLAN software does not calculate, for output purposes, the UE objective function value. However, it does calculate a system optimum (SO) function value[32]. The SO function value is is an acceptable surrogate measure for purposes of analyzing model system behavior. As such, the trajectories for the SO function for both the sequential and EQL runs for Colorado Springs are shown in Figure 6.6. Here again, we see the BLN trajectory from 1990 to 2010 fluctuating around the EQL trajectory from 1995 to 2005, and then, perhaps, moving more or less in

[32] Several sets of numerical experiments were done as part of this project to demonstrate that the two function values, UE and SO, do move in parallel for a common network. For more discussion as well as some of the algebraic definitions, see Chapters 6 and 7 of Putman (1991).

parallel.[33] Again, it is clear that the choice of year for comparison could, with use of the BLN sequential model configuration, determine the outcome of the analysis of alternative policies. In addition to the SO function values, it is worth examining the trajectories of the average trip lengths as was done for Portland and was shown in Figure 6.5 above. In the case of Colorado Springs we again see that the BLN trip lengths fluctuate sharply while the EQL trip lengths progress smoothly from one time period to the next. Again, clearly, depending upon which forecast year is selected, one gets quite different results when the BLN model system configuration is used. In practice, the EQL configuration will always yield more consistent and less erratic forecast results, forecasts which are less subject to fluctuations that result more from adjustments taking place within the model system than from a proper representation of the region being modeled.

6.13 Model Sensitivity Experiments for the 1990-2010 Forecast Period - Los Angeles

By far the largest region examined in this study, both in terms of geographic area and in terms of land use levels, both population and employment, is the Los Angeles region which includes much of southern California. The MPO with which we worked was the Southern California Association of Governments (SCAG). In addition to being unique with respect to the size of the Los Angeles region, SCAG was also unique amongst the regions studied, with regard to its model system configuration. In our test runs for all the other regions, we made use of congested travel times as input to their travel demand calculations, while the SCAG runs, made by use of SCAG's entire existing model package without the option of making any modifications, used free flow (or "design") times[34]. The result of this practice is to produce model system behavior which is not at all like that we observed in the other regions. The first evidence of this was manifested when the SO objective functions from trip assignment were plotted for both the BLN and the EQL model system configurations. The function values just keep increasing from the 1990 base year to the 2010 forecast horizon. These results are entirely different from the results from the other study regions. The SO function values from the sequential baseline (BLN) runs rose steeply and monotonically, never crossing the trajectory of the linked (EQL) run values of the SO function. It is, however, of considerable importance to note that the trajectory of the linked (EQL) runs is quite like the results obtained for the other study regions. What could be concluded from this results was that ***even if parts of the travel demand model structure are poorly defined, the use of the equilibrium model configuration will stabilize the results and provide useful model system outputs.***

A better understanding of this phenomenon can be had from taking a closer look at the performance of the SCAG model system by examination of the iterations within the EQL

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[33] For the present these runs were run out only to 2010. We intend, in subsequent work, to run them to a further forecast horizon, but this was not possible for the current study.

[34] A detailed examination was made of the issue of starting values in the travel demand model components. It is worth noting that while the Detroit and Portland MPO's made regular use of congested travel time inputs to their travel demand models, the other three regions didn't. We altered, for the purposes of these project tests, the model system configurations for Colorado Springs and Kansas City so that they, too, used congested times as input to the travel models, but were unable to do the same for Los Angeles.

procedure. The trajectories of the two configurations of the model system are plotted on the graph in Figure 6.7. The points along the x-axis correspond to the outer iterations, which are the iterations of the equilibrium transportation and land use model system along with the inner iterations. Thus the point 0.1 represents the first inner iteration. The point 0.2 represents the second, and the point 0 represents the end of the initial pass through the complete model system. The point 1.1 represents the first inner iteration within the second outer iteration. The point 1.2 represents the second inner iteration within the second outer iteration, and the point 1 represents the completion of the first iteration, the second pass, through the entire combined model system. It may be seen that the value of the SO function is diverging in successive inner iterations. This is a most undesirable situation. The same phenomenon continues in the second pass, the first outer iteration, as the SO function again diverges from point 1.1 to 1.2, to the third inner iteration, shown at the point 1 on the x-axis. The MSA procedure for the equilibrium solution begins to function in the combined system after the completion of the second pass through the system. As an obvious consequence, the oscillations of the system are greatly reduced, and the system appears to settle down. The other trajectory plotted in Figure 6.7 is the trajectory of the SO function for the case of only one travel demand iterations within each outer iteration. In that case, there are no intermediate points, and due to the salutary effect of the MSA procedure the overall system is convergent. It should be noted, as it is of considerable importance, that both model system configurations do converge to the same final solution. This is consistent with our previously stated conclusion that the solution to the combined transportation and land use model system, when solved by use of the MSA algorithm, is unique. Even though the travel demand components of the SCAG model system are not convergent in and of themselves, the MSA procedure for the combined system is able to bring the overall system to a proper solution.

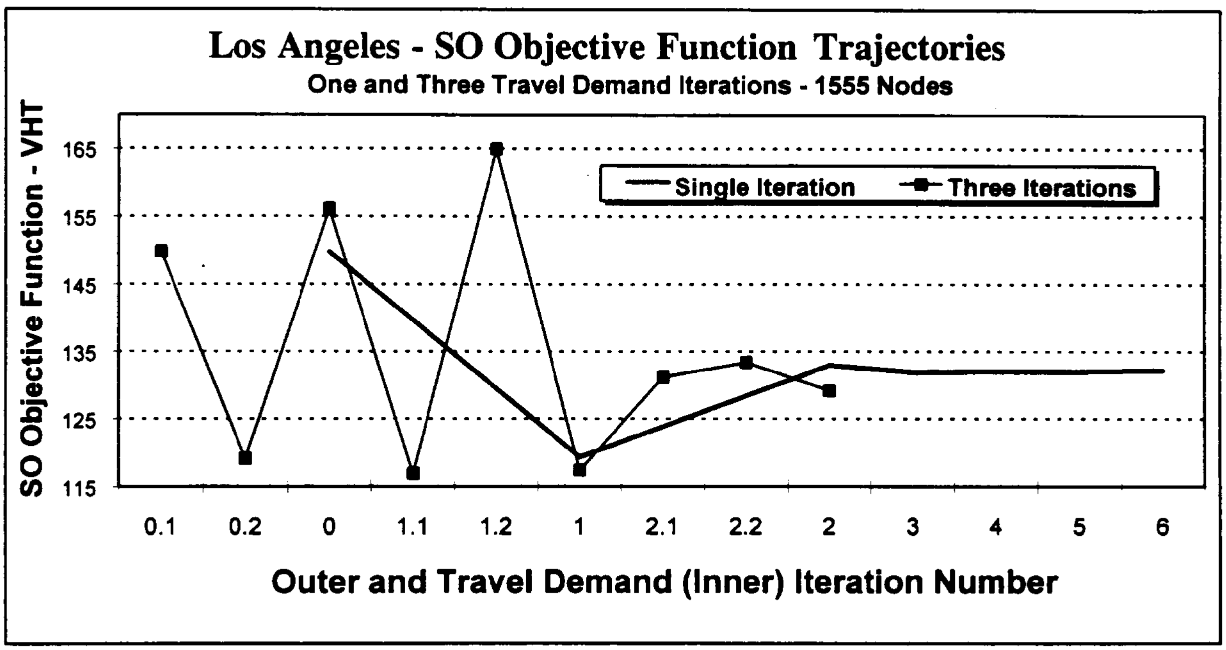

Figure 6.7: SO Function Trajectories for Los Angeles (SCAG)

The other issue which should be noted here is that travel demand iterations are supposed to have the effect of speeding convergence of the overall combined system, not of slowing or impeding it. Our experiments with the combined model system for METRO in Portland demonstrated this fact, and was briefly discussed earlier in this chapter. To see it more clearly, we have included Figure 6.8, which gives the UE function trajectory plots for Portland. These are equivalent to the SO function trajectories that were given for Los Angeles in Figure 6.7, and clearly show the difference in model system behavior. Here the first three inner iterations are obviously converging, and are followed by even greater convergence in the second three inner iterations. What is perhaps most interesting, however, is the fact that despite the "bad" behavior of the SCAG travel demand models, when the equilibrium system is used the overall performance of the linked transportation and land use model system behaves in almost the same way for both regions.

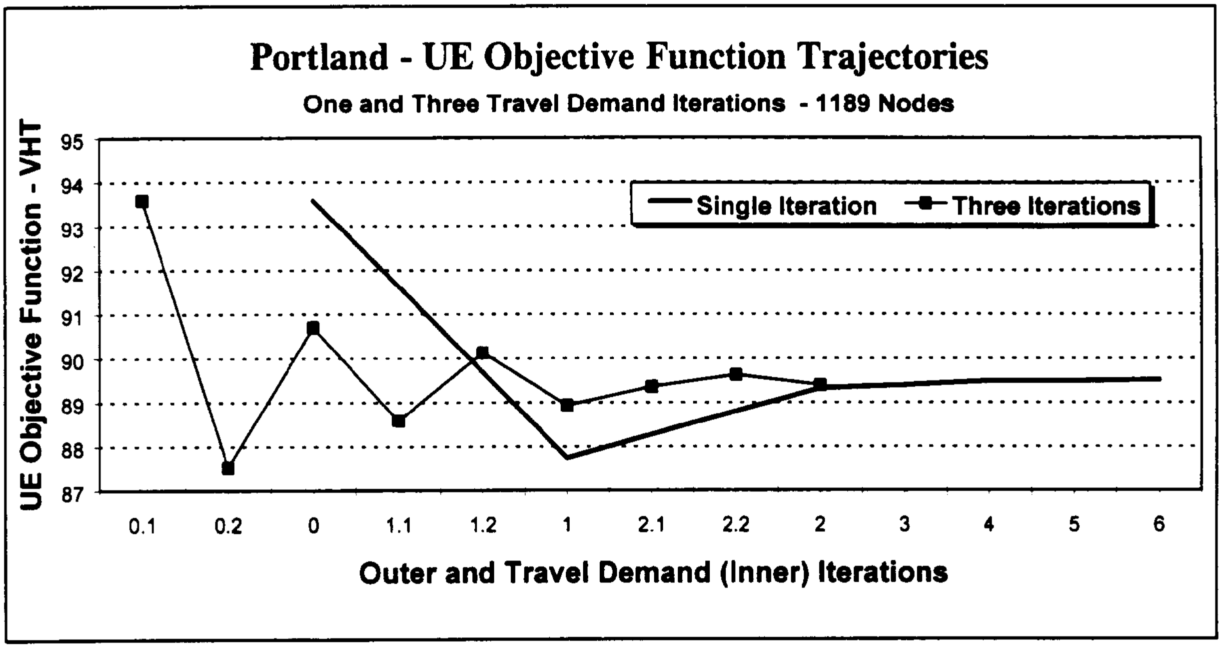

Figure 6.8: UE Function Trajectories for Portland (METRO)

The frequency distributions of travel times and of v/c ratios for the SCAG highway networks raise some further questions regarding the performance of their model system. More than 70 percent of the highway network links have ve/c ratios less than 0.75, with more than one quarter of them having v/c ratios of less than 0.25. This suggests the possibility that too few trips are being generated, distributed, and assigned to the network.

In terms of differences in the changes in the location of employment and households, Los Angeles, like the other study regions shows numerous differences when we compare the BLN results to the EQL results. Employment, too, showed differences in location as a consequence of the different model system configurations.

6.14 Conclusions

There are no standard procedures, amongst planning agencies, for aggregating travel times and disaggregating land use activities, even though the design of these procedures is extremely important for an integrated land use and transportation model. Any aggregation or disaggregation procedure adds error to forecasts of land use activities and travel times. Good aggregation and disaggregation procedures should be based on reasonable assumptions and should replicate observed distributions of land use activities and travel times.

The specification of the geography for transportation and land use modeling can make a significant difference in the forecast results. In particular, based particularly on the Portland (METRO) model tests, the practice of economizing on modeling effort costs by making use of an aggregated, sketch level, highway network is probably not a good idea. In the Portland experiments, as there were both sketch level (100 load nodes) and detailed level (1189 load nodes) networks available for experiment, it was possible to compare the results of using either one or the other. First, by virtue of the larger traffic zones used, a significant portion of the vehicle trips on the network become intrazonal trips, and intrazonal trips are not modeled on the network. Second, the sketch network will, of necessity, have fewer network links, and the flow pattern will, perforce, be less smooth across the network links. As discussed in the next chapter, the level, or degree, of congestion will have an effect on the resulting forecasts, and will also have an effect on the extent to which one model system configuration may produce forecasts significantly different from the other. In this way, network geography and model system preference are related.

In general, the use of the equilibrium (EQL) model system results in smoother, more stable, trajectories of model forecasts than does the sequential (BLN) model system configuration. Several factors, some of which are explored and subsequently discussed in greater detail in the next chapter, affect the degree of difference between the EQL and BLN derived model forecasts. Model geography, as mentioned above, and by virtue of its affect on the network loadings, is important. The overall regional level of network congestion is important too, as it affects the degrees of responsiveness of the entire model system to changes in land use location and the subsequent trip distributions, loadings and assignments. This issue assumes particular importance if it is realized that by virtue of the forecast oscillations which can result from the sequential model system configuration, the choice of year of comparison of model results can completely change the conclusions of the analysis.

Even so, *with an adequately detailed network representation and with good practice in the development of the travel demand forecasts, the sequential (BLN) model system configuration will often give quite satisfactory results.* Two suggestions for improvement, particularly if the sequential configuration is to be used, emerge from these experiments. First, the overall behavior of the model system could be made more stable if changes to highway networks could be introduced in five year steps, rather than in a single ten year step which may contain a great number of network modifications even when it is recognized that these modifications would in fact be rather gradually implemented if the transportation plan were to be approved and acted upon. Second, there are considerations to be taken with respect to starting the model system runs. In the case of the EQL configuration this is of consequence only in the sense that some computer processing time might be saved. In the case of the sequential runs this may be of greater import, as we have shown that the forecasts from a sequential system do depend upon the starting values. Here, then, it would be appropriate, in virtually of the cases studied, to perform several initial iterations of the land use and transportation models on the base year data in order to assure consistency between the model system components, most particularly between the zone-to-zone travel times and the land use distributions with which they should be compatible.

Reviewing the results presented here, based on the different regions studied, it is not possible to state unequivocally that one combined model system configuration is always to be preferred to another. It is possible to say that the no-feedback configuration, where the transportation, location, and land use models are run independently of each other will almost certainly give incorrect and inconsistent results. The sequential system however, in many cases, gives results that are not greatly different from those given by the linked EQL system. In cases where there may be problems with one or another of the individual models in the system, the equilibrium configuration will serve to yield a stable solution in any case, and will, in effect, "wash out" some of the problems. In certain cases the sequential system is far more likely to give misleading forecast results. In the next chapter we will discuss some more detailed investigation into exactly what circumstances can be expected to amplify or attenuate the differences between the results of the two model system configurations.

7 - Empirical Comparison of Model System Configurations: Region-to-Region

7.1 Introduction

One of the purposes of this project was to determine how, a) the attributes of a region, and b) differences in modeling methods affect forecasts of land use and transportation demand. In particular, we sought to determine if it is possible to identify the specific attributes of a region, or properties of the land use and transportation demand model system components, that would indicate whether or not forecasts made with a equilibrium model configuration would more accurately represent actual location and travel behavior than forecasts made with sequential model configurations.

The five regions we examined, Portland, Los Angeles, Colorado Springs, Detroit, and Kansas City, are quite different with respect to size (population and land area), regional growth in population, employment and highway trips, the geographic concentration of employment and household activities, and the extent and capacity of the highway network. The metropolitan planning organizations in each of the study areas have customized their land use and transportation demand models to meet the individual requirements of their forecasting and planning processes. For this reason, in addition to differences in the region's attributes, there are significant differences in the components used to construct the land use and transportation demand model systems.

In this chapter, cross-sectional comparisons of forecast results for the individual study areas are used to identify the attributes of a region, and the properties of the model components, that lead to differences between forecasts made with *sequential* model configurations and forecasts made with *equilibrium* model configurations. In general, the magnitude of these differences depends on the strength of the "feedback" between the activity and transportation demand models. By strength we mean the responsiveness, or the sensitivity, of any one component of the model system to the inputs which it receives from any other component. ***The responsiveness of the land use models to changes in travel times (i.e., "feedback" from the transportation demand models) is primarily determined by the travel time elasticities of the employment and household location models and the travel time aggregation procedure. The responsiveness of the transportation demand models to changes in land uses (i.e., "feedback" from the land use models) is primarily determined by the level of congestion on individual network links.***

In the next section of this chapter we describe the notion of travel time elasticities. This is followed by a section where we discuss the relationship between the travel time elasticities of the employment and household location models and the responsiveness of land uses to changes in travel times is examined. The effects of network congestion on the responsiveness of the transportation demand models to changes in land uses are described in the third, fourth, and fifth sections. Specific properties of the transportation demand model components that reduce the responsiveness of the transportation demand models to changes in land uses are also identified. The sixth section of this chapter describes how travel time aggregation procedures mediate the "feedback" from the transportation demand models to the land use models.

7.2 Travel Time Location Elasticities

For a given level of network congestion[35], the magnitudes of the zonal differences between forecasts made with sequential or with equilibrium model configurations depend on the responsiveness of the land use models to changes in travel times. It should be noted that for EMPAL and DRAM, travel time is but one of several variables which determine location. The relative importance of travel times to location determination has been shown, statistically, to vary by activity type and by region. The responsiveness of employment and household locations to changes in travel times is primarily determined by the *travel time location elasticities* of the land use models. In general, if the magnitudes of the travel time location elasticities are more negative, then employment and household locations will be more responsive to changes in travel times and the zonal differences between forecasts made with sequential and equilibrium model configurations will be larger.

Travel time location (TTL) elasticities measure the sensitivity of household and employment location to changes in zone-to-zone travel times. The TTL elasticities are defined for a single employment or residential zone and a single employment or household type. For a 1% increase in the travel times from *all* employment zones to a specific residential zone, the household TTL elasticity measures the resulting percentage change in the number of households in that zone. Similarly, for a 1% increase in the travel times from *all* residential zones to a specific employment zone, the employment TTL elasticity measures the resulting percentage change in the number of employees in that zone. For example, suppose that for low-income households in zone 12 the TTL elasticity is equal to -0.2500. This means that a 1% increase in travel times, from all employment zones to zone 12, will result in a 0.25% decrease in the number of low-income households residing in zone 12.

The value of the TTL elasticity for a specific activity type and zone is a function of: 1) the values of the calibrated travel time parameters (α and β), 2) the numbers of households or employees in the zone, 3) the magnitude of the travel times to the zone, and 4) the relative attractiveness of

[35] In the absence of network congestion, the transportation components of a equilibrium model will be unresponsive to changes in land uses -- the travel time between each origin-destination pair will always be equal to the shortest path between the origin and destination through an *uncongested* network. Therefore, if the model highway network remains unchanged, the travel times that are input to the land use models will remain constant and there will be no differences between forecasts made with either the sequential or the equilibrium model configurations.

other zones in the region[36]. Travel time elasticities will be more negative when the calibrated travel time parameters are more negative or the number of households or employees is small (relative to other zones in the region).

Because the TTL elasticities are defined for *specific* zones and employment or household types, for every region, there will be hundreds of travel time elasticities. Clearly, it is not possible to report the values of each of these elasticities -- it is easier to report average travel time elasticities. The household and employment travel time elasticities may be defined for the entire region (individual elasticities averaged over activity types and zones), for specific household and employment types (individual elasticities averaged over zones), or for specific zones (individual elasticities averaged over activity types). In all cases, the average TTL elasticities are calculated as *weighted* averages, where the weights are the numbers of households or employees by activity type in each zone.

7.3 Regional Comparisons of Sequential and Equilibrium Model Forecasts

If we compare the 1995 forecasts of household and employment location for Colorado Springs, Portland and Detroit, there is a discernible relationship between the average value of the TTL elasticities, the level of network congestion, and the regional differences between the sequential and equilibrium model forecasts of land use. In Figure 7.1 we show the regional differences, expressed in terms of MAPD, between the *sequential* and *equilibrium* model forecasts of 1995

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[36] These TTL's are rather complex in their formulation, for DRAM, the equation for the TTL elasticity is defined as:

$$\epsilon^n_{c_{i\cdot}} = \frac{\partial N^n_i}{\partial c_{i\cdot}} \frac{c_{i\cdot}}{N^n_i} = \sum_j \left[\left(\sum_k a_{kn} E^k_j \right) \left(\left(\alpha^n / c_{ij} \right) + \beta^n \right) \left(p^n_{ij} \left(1 - p^n_{ij} \right) \right) \left(c_{ij} / N^n_i \right) \right]$$

where

$\epsilon^n_{c_{i\cdot}}$ = elasticity of type n households to changes in travel times from all employment zones to residential zone i,

a_{kn} = a matrix of conversion coefficients of type n households per type k employees,

E^k_j = employment of type k (place-of-work) in zone j,

c_{ij} = travel time between zones i and j,

N^n_i = households of type n residing in zone i,

p^n_{ij} = the probability of a type n household, with an employed head-of-household in zone j, residing in zone i (a multivariate function), and

α^n, β^n = the calibrated DRAM parameters for travel time.

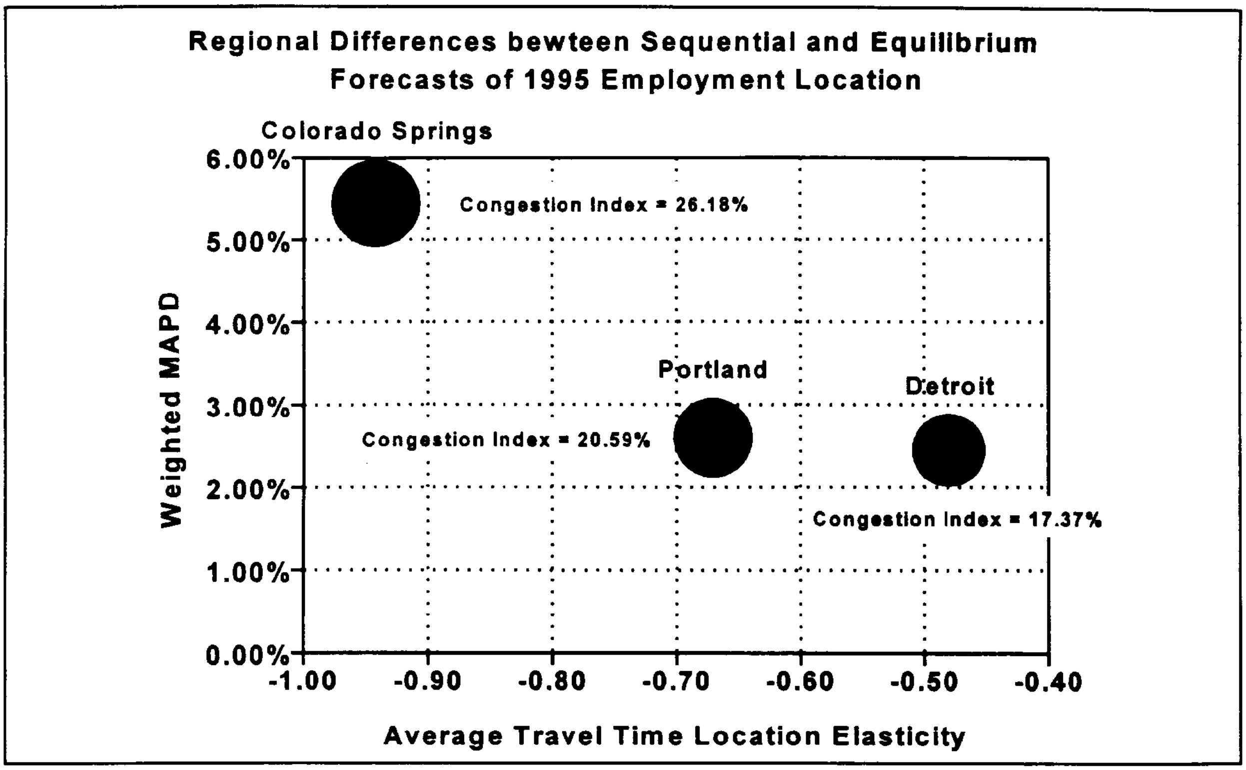

Figure 7.1: Travel Time Elasticities and Differences between Sequential and Equilibrium Model Forecasts of Employment Location

employment location for Colorado Springs, Portland and Detroit, as a function of average TTL elasticity (plotted on the X-axis) and network congestion (which is proportional to the size of the "bubble" data points.) In this graph it can be seen that as the average value of the TTL elasticities becomes more negative (i.e., the sensitivity of the land use models to changes in travel times increases), the regional differences[37] between the sequential and equilibrium model forecasts of land use increase. Similarly, as network congestion[38] increases (i.e., the sensitivity of the transportation demand models to changes in land uses increases), the regional differences between

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[37] In these graphs, the differences between the sequential and equilibrium model forecasts of land use are summarized by weighted MAPD statistics. The weighted MAPD statistics are defined as the weighted average of the absolute percentage differences between the sequential and equilibrium model forecasts of household or employment location by zone and/or locator type. The weights are equal to the sequential forecasts of activity levels by zone and/or locator type.

[38] In these graphs, network congestion is measured by congestion index statistics. For a particular region, the congestion index is equal to the percentage of zone-to-zone travel time that is attributable to network congestion (for the final iteration of the 1995 equilibrium model forecast.) To calculate the congestion index, the elements of a trip-weighted, uncongested zone-to-zone travel time matrix are subtracted from the elements of the trip-weighted, congested travel time matrix for the final iteration of the equilibrium model forecast. The congestion index is equal to the sum of these differences divided by the sum of the elements of the uncongested travel time matrix.

the sequential and equilibrium model forecasts of land use become more pronounced. The weighted MAPD statistics for the forecasts of both employment and household location are largest for Colorado Springs which, not coincidently, has the most negative average travel time elasticities and the highest level of network congestion. The differences between the sequential and equilibrium model forecasts in the Detroit region, which has the least negative average travel time elasticity for employment and the least amount of network congestion, are the smallest of the three regions. It is likely, based on this statistical evidence, that other factors beside travel time are more important in the residence location decisions of households in the Detroit region.

If we disaggregate the weighted MAPD statistics by locator type, then the differences between the sequential and equilibrium model forecasts of employment locations are also negatively correlated with the values of the average travel time elasticities and the level of network congestion. In Figure 7.2, each data point represents the MAPD for a single employment type used in the modeling -- Colorado Springs has seven endogenous employment types, Portland has four employment types, and Detroit has eight employment types. For each region, a regression of the weighted MAPD statistics by locator type against the average travel time elasticities by locator type was calculated. These regression lines, which are also plotted in Figure 7.2, show that for all three regions, the differences, as measured by MAPD, between the sequential and equilibrium model forecasts of employment location are negatively related to the values of the travel time elasticities. The strength of this relationship increases as network congestion increases.

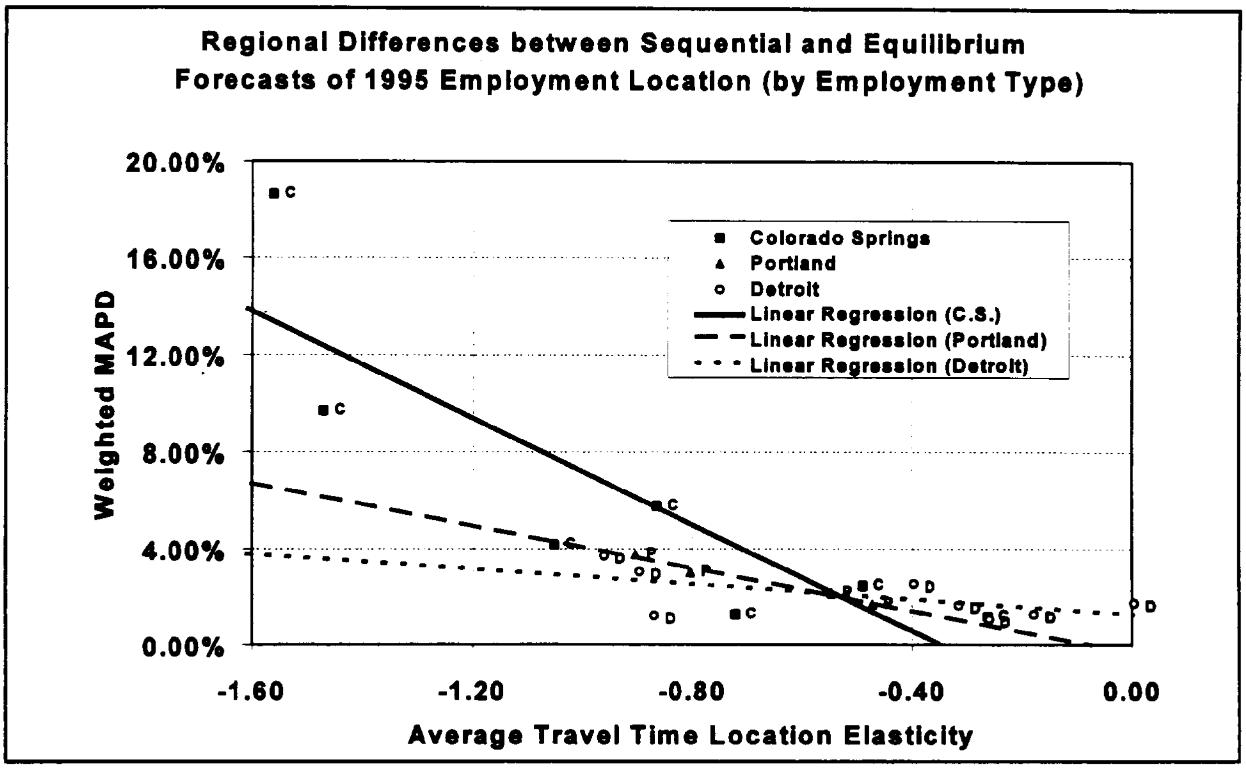

Figure 7.2: Travel Time Elasticities and Differences between Sequential and Equilibrium Model Forecasts of Employment Location

Because the differences between two activity forecasts are not uniformly distributed across activity zones, regional summary measures used to compare two forecasts (i.e., weighted MAPD statistics) can sometimes obscure important zonal differences between the sequential and equilibrium model forecasts. In Colorado Springs, for example, the regional difference between the 1995 sequential and equilibrium model forecasts of employment location, as measured by the weighted MAPD statistic, is 5.45%. However, for nine out of the eighty-five activity zones in Colorado Springs, the percentage difference between the sequential and equilibrium model forecasts is greater than 10%. Figures 7.3 and 7.4 show that the statistical distribution (i.e., the distribution of points along the Y-axis) of the *zonal* differences between sequential and equilibrium model forecasts of employment and household levels can be quite dispersed, with the differences for many zones being well above the average differences for a region.

In Figure 7.3, the zonal differences, expressed as absolute percentage differences, between the sequential and equilibrium model forecasts of 1995 employment and household locations for Colorado Springs are plotted as a function of their zonal travel time elasticities (which are calculated as the weighted average of the elasticities for the individual locator types). The employment travel time elasticities are more negative than the household travel time elasticities, and consequently the zonal differences between the sequential and equilibrium model forecasts of household location are smaller than the differences in employment location. For both employment and households, the differences between the sequential and equilibrium model forecasts are

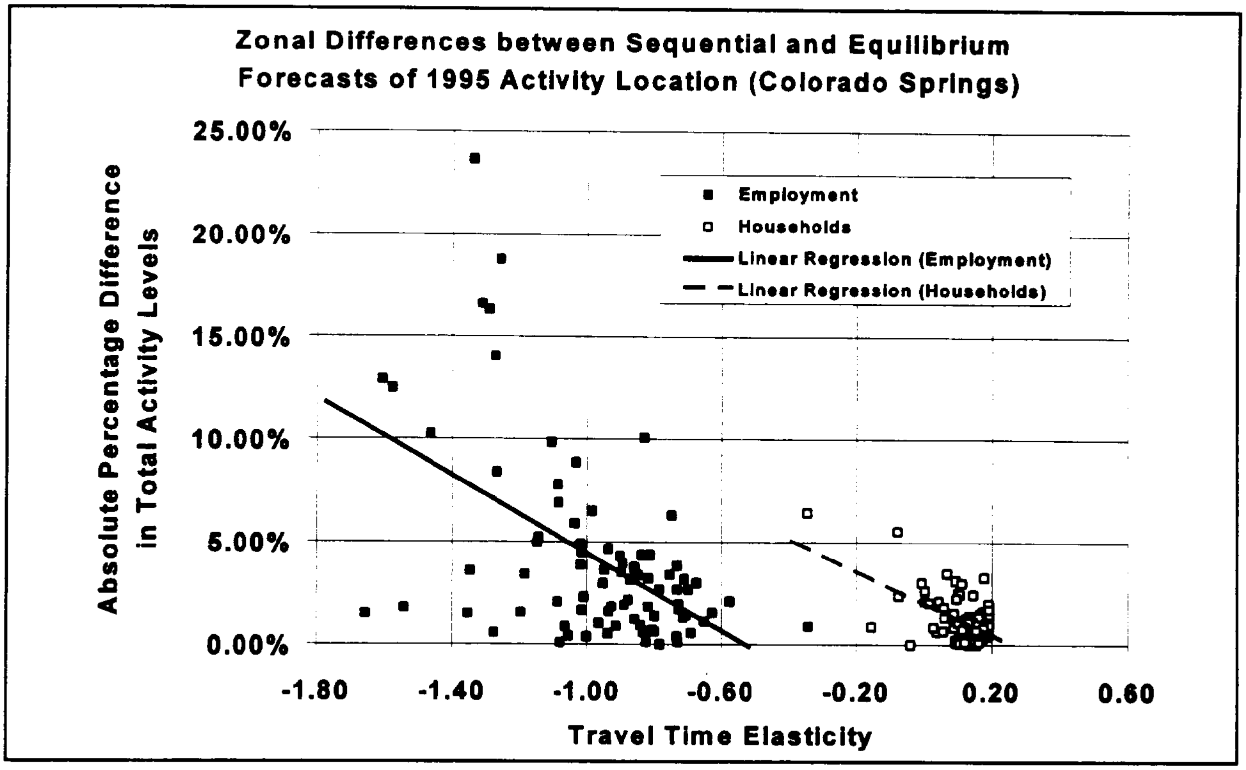

Figure 7.3: Travel Time Elasticities and Differences between Sequential and Equilibrium Model Forecasts of Employment and Household Location

negatively related to the values of the travel time elasticities. The range of the *household* travel time elasticities is -0.35 to 0.19 while the range of *employment* travel time elasticities is -1.66 to -0.35. Consequently, the absolute percentage differences in *employment* levels are larger than the absolute percentage differences in *household* levels.

In Figure 7.4 we compare the zonal differences between the sequential and equilibrium model forecasts of *household* location for Colorado Springs and Detroit. As was the case for the regional MAPD statistics and the regional MAPD statistics disaggregated by locator type, the zonal differences between the two forecasts tend to increase as the values of the travel time elasticities become more negative. The regression lines indicate that the strength of this relationship is

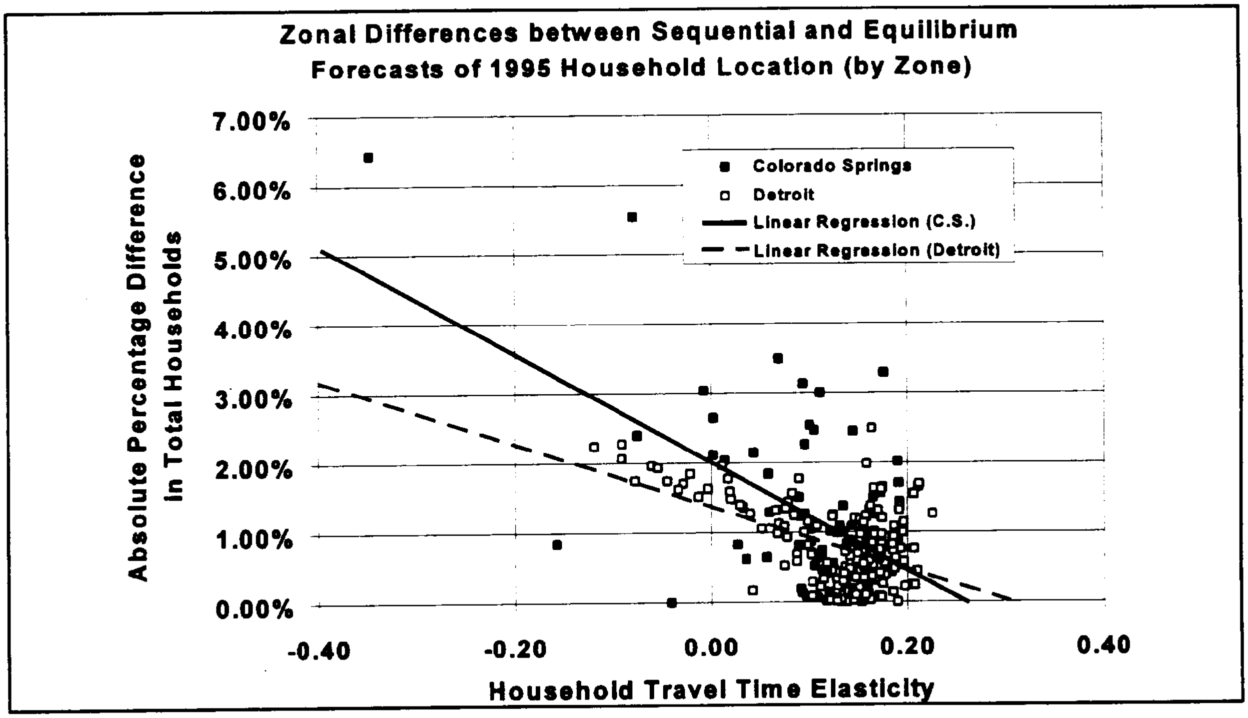

Figure 7.4: Travel Time Elasticities and Differences between Sequential and Equilibrium Model Forecasts of Household Location

correlated with the level of network congestion -- the slope of the regression line for Detroit, which has a congestion index equal to 17.37%, is less (in absolute value) than the slope of the regression line for Colorado Springs, which has a congestion index equal to 26.18%. Analyses of the zonal differences between the sequential and equilibrium model forecasts of employment location also showed that the correlation between network congestion and the responsiveness of zonal activity levels to changes in travel times.

7.4 Network Models and Network Congestion

For given values of the employment and household TTL elasticities[39], the magnitudes of the differences between forecasts of travel times made with sequential and equilibrium model configurations depend on the responsiveness of the transportation demand models to changes in

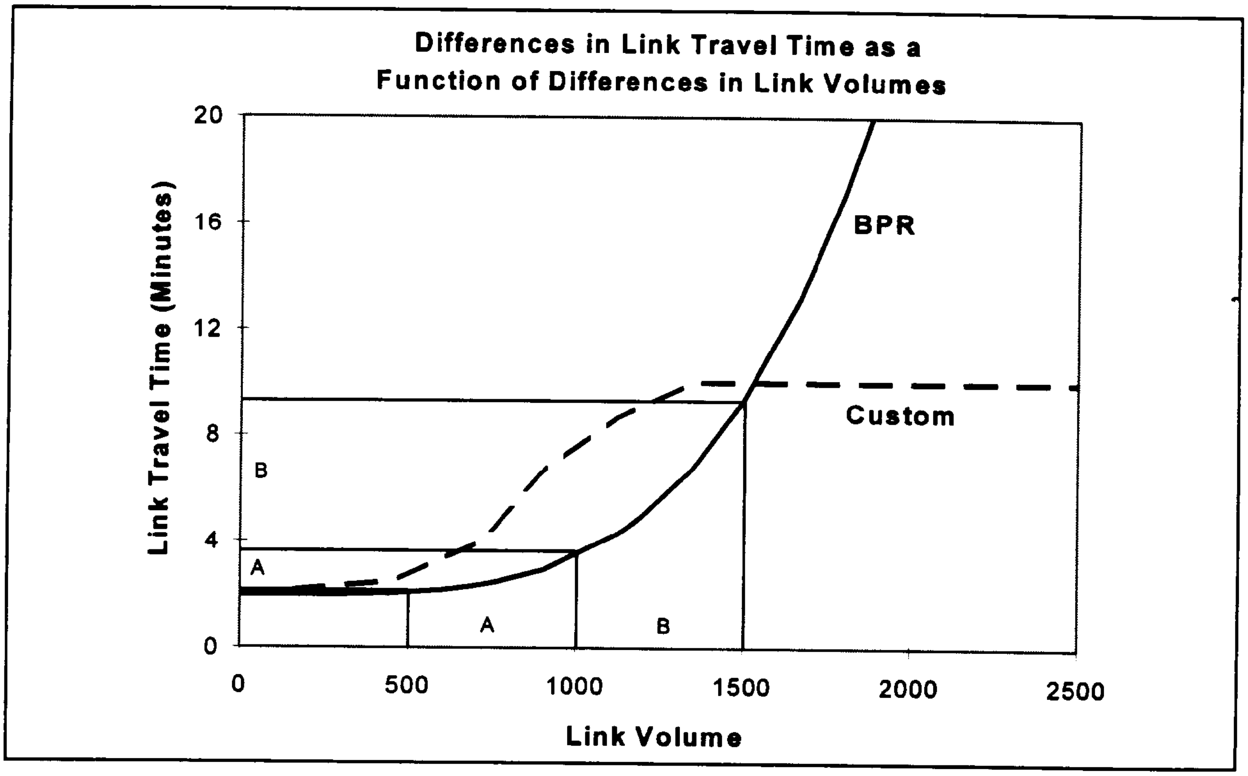

Figure 7.5: BPR and Custom Volume-Delay Functions

employment and household levels. The responsiveness of the transportation demand models to changes in the land use forecasts is primarily determined by the *levels of congestion on individual network links*. If the average level of network congestion is high, then the transportation demand models (most importantly, the network assignment procedure) will be more responsive to changes in employment and household levels, resulting in larger differences between the sequential and equilibrium model forecasts of zone-to-zone travel times. At the most disaggregate level, the mathematical form of individual volume-delay functions determine the response of link travel times to changes in link flows that follow directly from changes in activity levels.

In Figure 7.5, two sample volume-delay functions are plotted. The curve drawn as a solid line

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[39] In the unlikely event that the TTL elasticities are equal to zero for all zones and locator types, then the land use models will be unresponsive to changes in travel times. In this situation, the forecasts of activities that are input to the transportation demand models will remain constant and there will be no differences between forecasts made with sequential and equilibrium model configurations.

represents a standard BPR[40] volume-delay function, while the dashed curve labelled "custom" represents a customized volume-delay function similar to the ones used by PPACoG in Colorado Springs, designed to improve the stability of the transportation demand models for high traffic (link) volumes. Within the transportation demand model, changes in the forecasts of employment and household location are translated into changes in trip productions and attractions (trip generation), changes in zone-to-zone trip volumes (trip distribution), changes in vehicle and transit trips (mode split), and changes in vehicular trips by time-of-day (peak-period factoring). Finally, at the level of individual network links, changes in zone-to-zone vehicular trips by time-of-day are translated into changes in link volumes by the network assignment procedure. Depending on the slopes of the volume-delay functions, these changes in link volumes may lead to smaller or larger changes in link travel times, and ultimately to smaller or larger changes in zone-to-zone travel times.

The responsiveness of the network assignment procedure (as measured by changes in link travel times) at any particular instant is determined by the slopes of the volume-delay functions evaluated at the current levels of link volume. For example, in Figure 7.5, over the range of link volumes from 0 to 500, the network assignment procedure is almost completely unresponsive to changes in link volumes -- link travel time will remain constant, regardless of any changes in link volume. If link volume increases from 500 to 1000 (marked as A in the figure), then link travel time increases by approximately 1.5 minutes. If link volume increases from 1000 to 1500 (marked as B in the figure), link travel time increases by approximately six minutes. In this way, as link volume increases, the responsiveness of the BPR volume-delay function to changes in link volumes (which are determined by changes in activity levels) also increase.

Unlike the BPR function, the responsiveness of the customized volume-delay function which appears in Figure 7.5 does not continuously increase as link volume increases. Over the range of link volumes from 0 to 750, the customized volume-delay function has a similar mathematical form as the BPR function, but beyond link volumes of 750 the responsiveness of this function to changes in link volumes decreases. For values above 1350, the customized volume-delay function is completely insensitive to changes in link volumes. If volume-delay functions of this type were used within a equilibrium model system, the responsiveness of the transportation demand models to changes in activity levels would be reduced (when compared to a model that uses BPR volume-delay functions), and the differences between forecasts made with sequential and equilibrium model configurations would be smaller.

For an individual network link, the relationship between changes in link volume and link travel time and the slope of the volume-delay function is simple to understand -- the slope of the volume-delay function completely determines any changes in link travel time. For an entire network (thousands of individual links), the effects of changes in link volume on link travel times are more complex. At any instant, the volumes on individual links will correspond to different points (and

[40] The Bureau of Public Roads (BPR) volume-delay function has long been a standard in transportation modeling practice.

slopes) on their volume-delay functions. At the network level, the average responsiveness of link travel times is determined by the ratio of forecast transportation demand (total link volumes) to regional transportation supply (total link capacity). However, transportation demand and network capacity will be unevenly distributed across a region. As a consequence, total transportation demand and supply will not completely determine the responsiveness of the transportation demand models to changes in land uses. If link volumes are concentrated on a small subset of network links, or network capacity is sparse in certain areas of a region, localized network congestion may exceed the average congestion level on the entire network and the responsiveness of the transportation demand models to changes in land use levels may be increased.

Regardless of the geographic distribution of link volumes and network capacity, the aggregate level of transportation demand is an important determinant of the level of network congestion. For this reason, the attributes of the individual components of the transportation demand models will have a significant effect on the responsiveness of the transportation demand models to forecasts of land use.

The trip generation model converts the disaggregate forecasts of land use into trip productions and attractions, determining the total number of person trips. Differences in the generation rates and the types of trip purposes used in the trip generation procedure will result in differences in number and types of person trips. The division of productions and attractions between trip purposes is important, since some purposes are more likely to use transit, and transit trips are removed from the total demand for highway trips.

After trip generation, the trip distribution model converts the forecasts of each zone's total trip productions and attractions into zone-to-zone person trips, leaving the total number of trips unchanged (but reconciling the differences between total attractions and total productions.) The trip distribution procedure, because it determines the geographic distribution of transportation demand, can have a significant effect on localized network congestion. Furthermore, since the geographic extent of the traffic analysis zone system often exceeds the geographic extent of the activity zone system, the trip distribution determines the number of zone-to-zone person trips that are internal to the activity zone system.

The mode split and peak-period factoring procedures convert the matrices of total zone-to-zone person trips produced by the trip distribution model into several matrices of trips on the various modes, including a single matrix of peak-period vehicle trips that is directly assigned to the model highway network. Both procedures, mode split and peak-period factoring, have the effect of reducing the forecast level of transportation demand on the highway network -- the mode split procedure removes non-highway trips, while the peak-period procedure extracts trips for a specified time period from forecasts of daily vehicle trips. *The peak-period factoring procedure is especially important in determining the total level of network demand. Small differences in the peak-hour factors can add or subtract thousands of trips from the model highway network, affecting the overall ratio of network demand and supply, and reducing or increasing localized* *network congestion.*[41]

7.5 Regional Differences Between Sequential and Equilibrium Model Forecasts

All of the factors described above -- total transportation demand and network supply, the geographic distribution of transportation demand and network supply, the mathematical form of the volume-delay functions, the configuration of the trip generation, trip distribution, mode split and peak-period factoring procedures -- determine the level and geographic distribution of network congestion. In turn, ***the level and distribution of network congestion determines the responsiveness of the transportation demand models to changes in land uses and the magnitude of the differences between sequential and equilibrium model forecasts of zone-to-zone travel times.***

Table 7.1 presents statistics which summarize regional congestion levels, the average percentage differences between the sequential and equilibrium model forecasts of 1995 land uses, and the differences between the sequential and equilibrium model forecasts of 1995 travel times for Colorado Springs, Portland, and Detroit. In the table, the MAPD (mean absolute percentage difference) statistics for the travel times are unweighted and are calculated for the aggregate travel time matrices. The average volume/capacity ratios statistics are also unweighted -- the volume/capacity ratios of each network link are counted equally. The MAPD statistics for the employment and household locations are weighted by the 1995 sequential model forecast of land uses and the 1990 base year distribution of land uses, respectively.

Region	MAPD Travel Times	Congestion Index	Average V/C Ratio (Sequential)	Weighted MAPD Employment	Weighted MAPD Households
Colorado Springs	6.22%	26.18%	1.37	5.45%	1.53%
Portland	2.74%	20.59%	0.75	2.61%	1.10%
Detroit	3.53%	17.37%	1.14	2.45%	0.82%

Table 7.1: Summary Statistics of Congestion, Elasticities, and Differences between Sequential and Equilibrium Model Forecasts

The statistics in Table 7.1 show that there is a relationship between the differences between the sequential and equilibrium model forecasts of travel times and the overall level of network congestion. For the most part, the differences between the travel time forecasts increase as network congestion increases, and the strength of this positive relationship is intensified by the magnitude of the differences between the sequential and equilibrium model forecasts of land uses. In effect, the responsiveness of the transportation demand models to changes in activity levels (measured by the MAPD travel time statistics) creates "feedback" that is returned to the land use

[41] In early experiments with linked model systems (Putman, 1983) we often made adjustments in these peak hour factors in order to balance regional vehicle trips to the limited capacity of a specific network representation.

models, while the responsiveness of the land use models to changes in travel times (measured by the weighted MAPD statistics) creates "feedback" that is returned to the transportation demand models. As a consequence, the differences between sequential and equilibrium model forecasts are not solely determined by the responsiveness of either the land use models or the transportation demand models in isolation. The interaction between the two sets of models is of equal, or more, importance in determining the differences between sequential and equilibrium model forecasts.

In Figure 7.6 we plot the regional differences between the sequential and equilibrium model forecasts of aggregate *travel times* against the congestion index (i.e., the percentage of trip-weighted travel time that is attributable to network congestion for the final iteration of the 1995 equilibrium model forecast.) The size of the plotted "bubbles"is proportional to the weighted MAPD statistics for employment location.

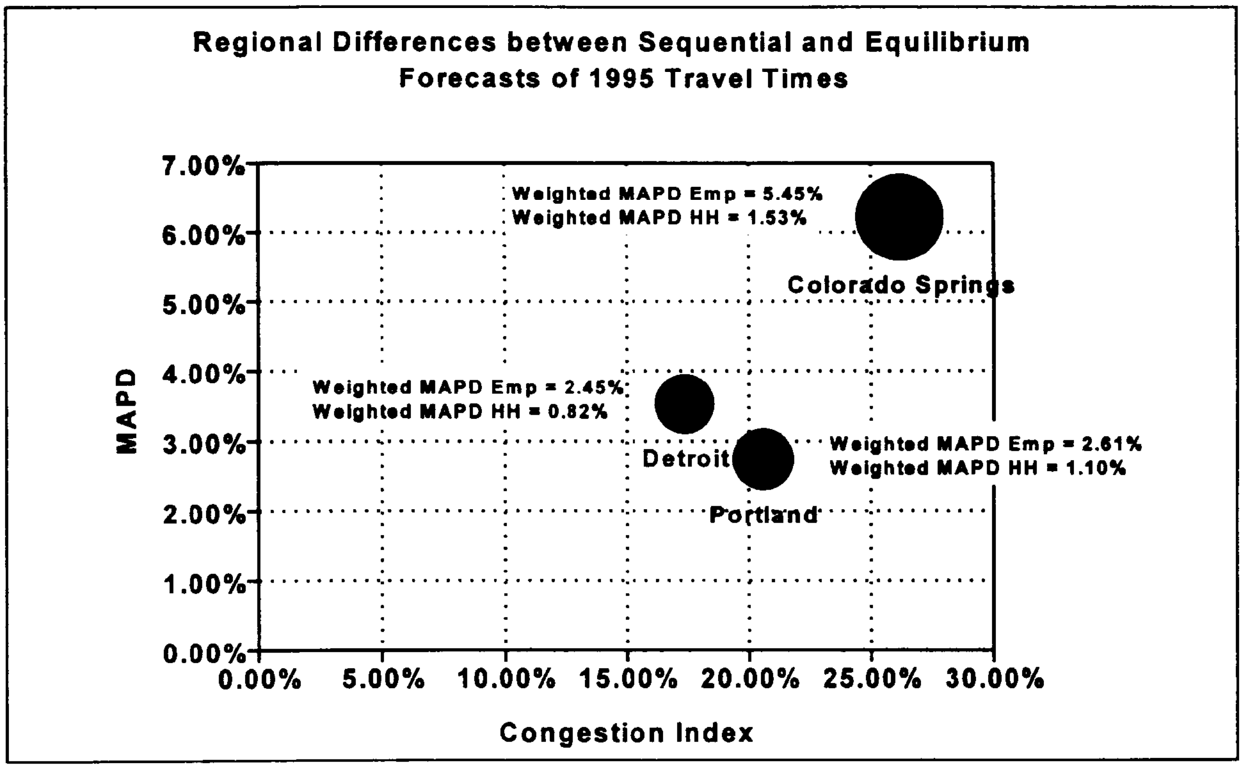

Figure 7.6: Network Congestion and Differences between Sequential and Equilibrium Model Forecasts of Travel Times

Of the three regions, in 1995, Colorado Springs has the highest level of overall network congestion, the most negative travel time elasticities, and the largest differences between the sequential and equilibrium model forecasts of aggregate travel times and land uses. The percentage differences between the sequential and equilibrium forecasts for Portland and Detroit are similar, although the differences between the forecasts of land use are larger for Portland, while the differences between the forecasts of aggregate travel times are larger for Detroit.

However, for both regions, the level of network congestion is much lower than in Colorado Springs, and, as a consequence, the MAPD statistics for the forecasts of aggregate travel times and land uses are also lower.

Even though the congestion index for Portland is larger than for Detroit, the average difference between the two forecasts of travel times is larger for Detroit. This is probably due to the geographic distributions of land uses and network congestion in the Portland and Detroit regions. In the Portland region a legislatively defined urban growth boundary prevents development in the rural areas surrounding the Portland urbanized area. In effect, the urban growth boundary concentrates network congestion onto the subset of network links within the Portland urbanized area, since the number of trip origins and destinations (which are determined by the levels of employment and residential activities) is restricted in the surrounding rural areas. Thus, network congestion is unevenly distributed across the Portland model highway network, leaving many network links with rather little trip volume and congestion[42]. In the Detroit region, there is no equivalent to Portland's urban growth boundary, and development is more evenly spread across the region. Consequently, transportation demand is more uniformly distributed throughout the Detroit region. Network coverage is also quite uniform in the Detroit region, since a large majority of network links are arranged in an evenly-spaced, grid pattern which owes its origins to George Washington's survey of the region in the 18th century. Since both network demand and network supply are more evenly distributed (when compared to Portland), congestion is more uniform across the Detroit region, and extreme concentrations of localized network congestion are less likely.

The MAPD statistics used to measure the differences between the aggregate travel time matrices are unweighted -- each element of the zone-to-zone travel time matrices contributes equally to the average percentage difference. This means that an uneven distribution of network congestion (as in Portland) will tend to produce lower MAPD statistics, since the elements of the travel time matrix representing uncongested areas carry the same weight as elements representing congested areas. The congestion index statistics, on the other hand, are calculated using trip-weighted travel times, so the geographic distribution of transportation demand and network coverage should not affect their magnitude.

The values of the average volume/capacity ratios for the network links, which are unweighted, are also a function of the geographic distribution of transportation demand and network capacity. In the Portland region, the low value of the average volume/capacity statistic is mostly due to a large number of unused, or lightly used, network links in the rural areas of the region. Since both the MAPD statistics for the travel times and the average volume/capacity ratios are unweighted, if we assume that the geographic distribution of transportation demand and supply acts similarly on both statistics, these statistics may be more closely related to each other than the congestion index statistic.

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[42] It is also true that of all the five regions studied Portland uses the most highly detailed network description.

In figure 7.7, the MAPD statistics for the differences between the sequential and equilibrium forecasts of *aggregate travel times* are plotted against the average volume/capacity ratios for each of the regions. As before, the size of the plotted "bubbles" is proportional to the weighted MAPD statistics for employment location. In this figure, there is a continuously increasing, positive relationship between the level of network congestion (as measured by the average volume/capacity ratio) and the responsiveness of the transportation demand models to changes in land uses (as measured by the MAPD statistics). This sensitivity, or responsiveness, of the transportation demand models to changes in land use can also be seen as a consequence of the considerable nonlinearity of the volume-delay functions. If the link volumes are lower than the design capacities of most network links, where the volume-delay functions are relatively flat, increases

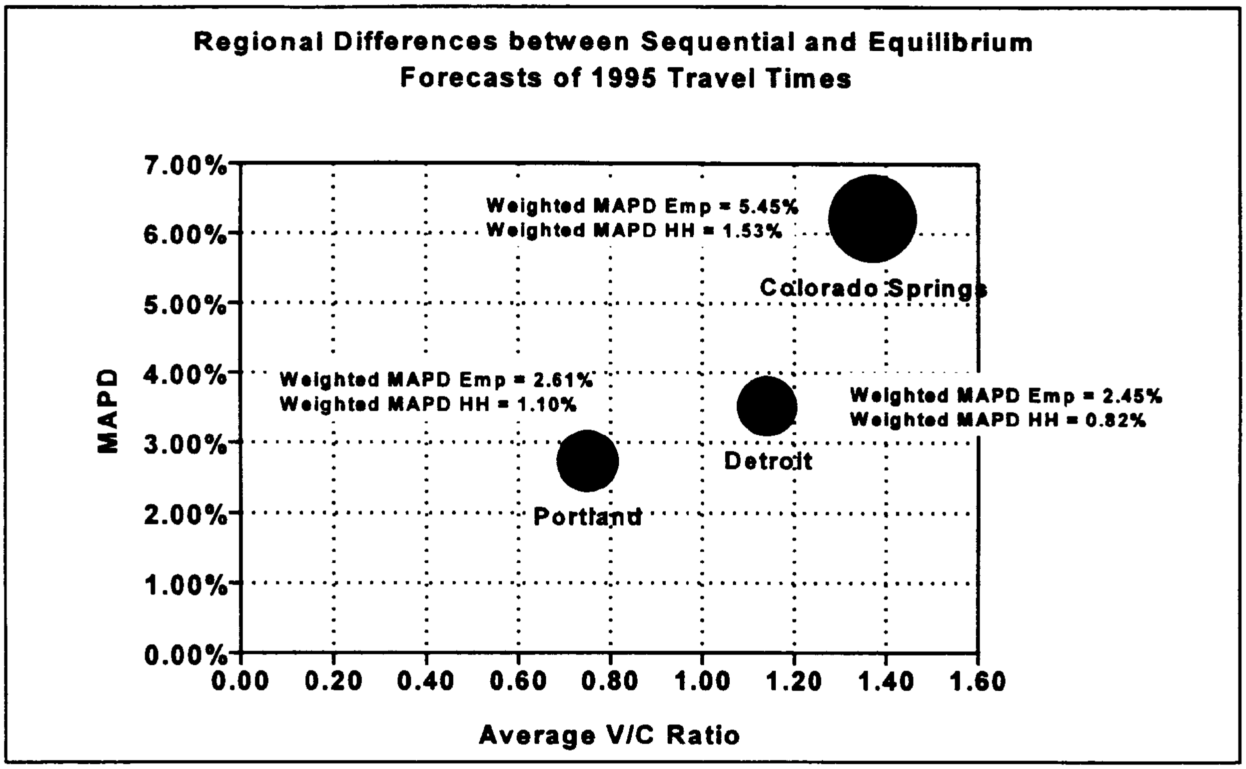

Figure 7.7: Network Congestion and Differences between Sequential and Equilibrium Model Forecasts of Travel Times

in link volumes will not result in much change in travel times. If, however, many of the modeled network links are on the steeper portions of the volume-delay curves and are more congested, then similar changes in link volumes will cause much greater changes in zone-to-zone travel times.

The positive correlation between network congestion and the magnitudes of the regional differences between the sequential and equilibrium forecasts of aggregate travel times that is evident in the comparison of the three study regions, also holds for zonal measures of network congestion and MAPD statistics for individual zone pairs. Zonal measurements of the differences between the two forecasts of aggregate travel times and local network congestion also illustrate the connection between the responsiveness of the transportation demand models to changes in land uses and the responsiveness of the land use models to changes in travel times.

Because there are travel times for each origin-destination pair, it is not possible to present graphics of zonal statistics for every element of the aggregate travel time matrix. The Colorado Springs region has 85 activity zones and 7,225 origin-destination pairs, Portland has 100 activity zones and 10,000 origin-destination pairs, and Detroit has 174 activity zones and 30,276 origin-destination pairs. Instead, it is necessary to select a subset of origin-destination pairs when presenting statistics for individual zones. In Figure 7.8 the absolute percentage differences

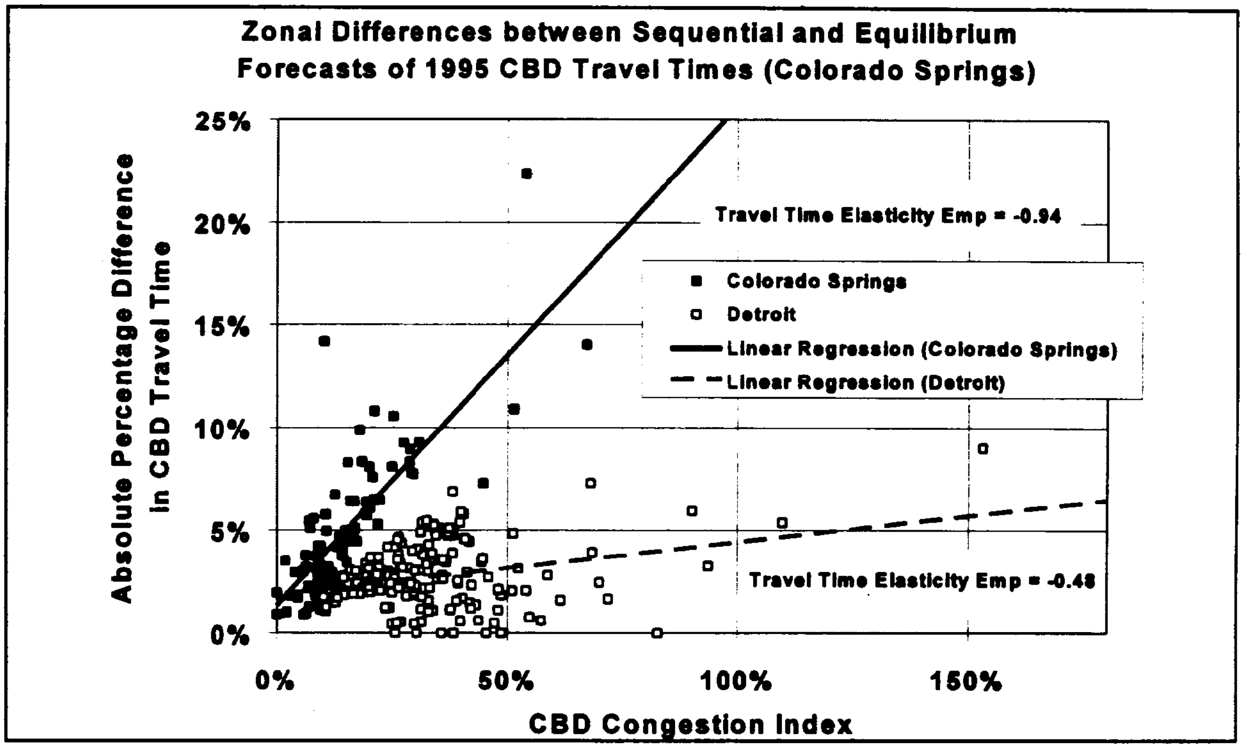

Figure 7.8: Network Congestion and Differences between Sequential and Equilibrium Model Forecasts of Travel Times

between the sequential and equilibrium forecasts of aggregate travel time are plotted against zone-level congestion indices. Each data point represents the same origin zone, the central business district (CBD) of the region, and a single destination zone. (This is a single row of the travel time matrix, arranged so that the row elements are equal to the work-to-home travel time, during the afternoon peak-period, from the CBD to every residential zone.) The congestion indices measure the percentage of work-to-home travel time, from the CBD to a particular residential (destination) zone that is attributable to congestion.

Here we again see that the responsiveness of the transportation demand models (as measured by the absolute percentage differences between the sequential and equilibrium model forecasts of aggregate travel times) is positively related to the level of network congestion. Furthermore, the linear regression lines indicate that the strength, or intensity, of this relationship is magnified as the responsiveness of the land use models to changes in travel times increases. The regression line for Colorado Springs is more steeply sloped than the regression line for Detroit, reflecting the differences between the travel time elasticities in the two regions. In fact, the upper range of the zonal congestion indices for Detroit exceeds that for Colorado Springs. If network congestion was the only determinant of the differences between the sequential and equilibrium forecasts of the aggregate travel times, we would expect that for the zones in the upper range, the absolute percentage differences in zonal travel times would be larger for Detroit. This, however, is not the case. For equivalent levels of local congestion, absolute percentage differences between the two forecasts of travel times are larger for Colorado Springs. This is because the "feedback" from the Colorado Springs land use models (i.e., changes in land uses) is stronger than the "feedback" from the Detroit land use models. (The travel time elasticities measure the strength of this "feedback".) There is a more synergistic effect between the land use and transportation components of the Colorado Springs equilibrium model than exists in the Detroit equilibrium model.

7.5 Travel Time Aggregation Effects

In all five of the FHWA study regions (except for the Portland "sketch" level network model), the number of traffic analysis zones exceeds the number of activity zones. This means that any changes in the forecasts of disaggregate travel times made by the transportation demand models will be processed, or filtered, through a travel time aggregation procedure before being transmitted to the land use models. *The travel time aggregation procedure mediates the "feedback" from the transportation demand models to the land use models and is an important determinant of the responsiveness of forecasts of employment and household location to changes in travel times.*

Since the number of traffic analysis zones exceeds the number of activity zones, a disaggregation procedure is also required, to convert forecasts of employment and household location by activity zone into forecasts by traffic analysis zone. In this case, however, unlike the travel time aggregation procedures, which can have a significant effect on the magnitudes of the changes in travel times transmitted from the transportation demand models to the land use models, the activity disaggregation procedures have no effect on the magnitude of the changes in land uses transmitted from the land use models to the transportation demand models. For all five study regions, the aggregate forecasts of land uses are multiplied by fixed marginal distributions to produce forecasts of land uses disaggregated by traffic analysis zone (and, if required, by socioeconomic categories). In all cases, for each analysis zone, the marginal probabilities sum to one, so as the activities are disaggregated to traffic analysis zones, the regional levels of each activity remain unchanged. Therefore, any changes in activity levels in a particular activity zone will be exactly equal to the sum of the changes in the constituent traffic analysis zones. Of course, if the marginal probabilities are inaccurate, then the geographic distribution of activities across traffic analysis zones may be incorrectly estimated, and the distribution of the changes in activity levels transmitted to the transportation demand models will also be inaccurate. But the total magnitude of the changes in activity levels will be the same for both the activity zone system and the traffic analysis zone system. The activity disaggregation procedures do not increase or decrease the magnitude of the changes in activity levels that are transmitted from the land use models to the transportation demand models.

The two travel time aggregation procedures (trip-weighted averaging and representative zone) used within the sequential and equilibrium model systems do modify the magnitude of the changes in travel times that are transmitted from the transportation demand models to the land use models. Since travel times are not defined as levels, it is not possible to construct an aggregation procedure that simply sums all of the travel times for the traffic analysis zones that make up each activity zone (i.e., a procedure that would be analogous to the activity disaggregation procedure.) Instead, the individual elements of the disaggregate travel time matrix must be averaged (trip-weighted averaging) or extracted (representative zone) to produce an aggregate travel time matrix. Both procedures modify the average magnitude of the elements of the travel time matrices -- the trip-weighted averaging procedure produces aggregate travel times that are significantly lower than the disaggregate travel times, the representative zone procedure produces aggregate travel times that are significantly greater than the disaggregate travel times. Since both travel time aggregation procedures modify the statistical distribution of the elements of the travel time matrix as they are aggregated from traffic analysis zones to activity zones, any changes in travel times produced by the transportation demand model may be magnified or dampened as they are transmitted to the land use models.

It is important to note that the aggregate and disaggregate travel time matrices used to initiate the 1995 sequential and equilibrium model forecasts are not necessarily consistent with each other. In most cases, the aggregate travel time matrix used as input for the sequential model and the first iteration of the equilibrium model is identical to the matrix used for the calibration of the land use models. The initial disaggregate travel time matrix is found by assigning the transportation demand for base year employment and household locations to a 1990 model highway network. The initial aggregate travel time matrices are not aggregations of the initial disaggregate travel time matrices, and it is likely that some elements of the initial aggregate travel time matrices will be inconsistent with the forecasts of travel times produced by the transportation demand models.

In Table 7.2 we show the mean *trip-weighted* percentage differences between the sequential and equilibrium model *forecasts of the elements of the aggregate and disaggregate travel time matrices* (intrazonal travel times are omitted.) These statistics indirectly measure the degree of magnification or dampening of the travel times created by the travel time aggregation procedure and the changes in travel times that occur as inconsistencies in the elements of the initial aggregate travel time matrices are reconciled with the equilibrium forecasts of transportation demand.For all three study regions, the mean difference between the elements of the sequential and equilibrium model forecasts of the aggregate travel time matrix is unequal to the mean difference between the elements of the disaggregate travel time forecasts.

Mean Absolute Percentage Difference between Interzonal Elements of Sequential and Equilibrium Model Forecasts of 1995 Travel Times			
	Colorado Springs	Portland	Detroit
Aggregate Travel Times	6.64%	2.40%	4.35%
Disaggregate Travel Times	2.71%	1.25%	2.65%

Table 7.2: Differences between Sequential and Equilibrium Model Forecasts of Travel Times

In Figure 7.9, frequency distributions of the individual *percentage differences* between the sequential and equilibrium model forecasts of the interzonal elements of the aggregate and disaggregate travel time matrices are shown for Colorado Springs. As the figure shows, relative to the differences between the two forecasts of disaggregate travel times, the equilibrium model forecasts of aggregate travel times are significantly lower than the sequential model forecasts of aggregate travel times. There many reasons why the differences between the aggregate travel time matrices are larger (in absolute value) than the differences between the disaggregate travel time matrices. First, the geographic extent of the traffic analysis zone system is greater than the extent of the analysis zone system. In the Colorado Springs region, 24 of the 350 traffic analysis zones

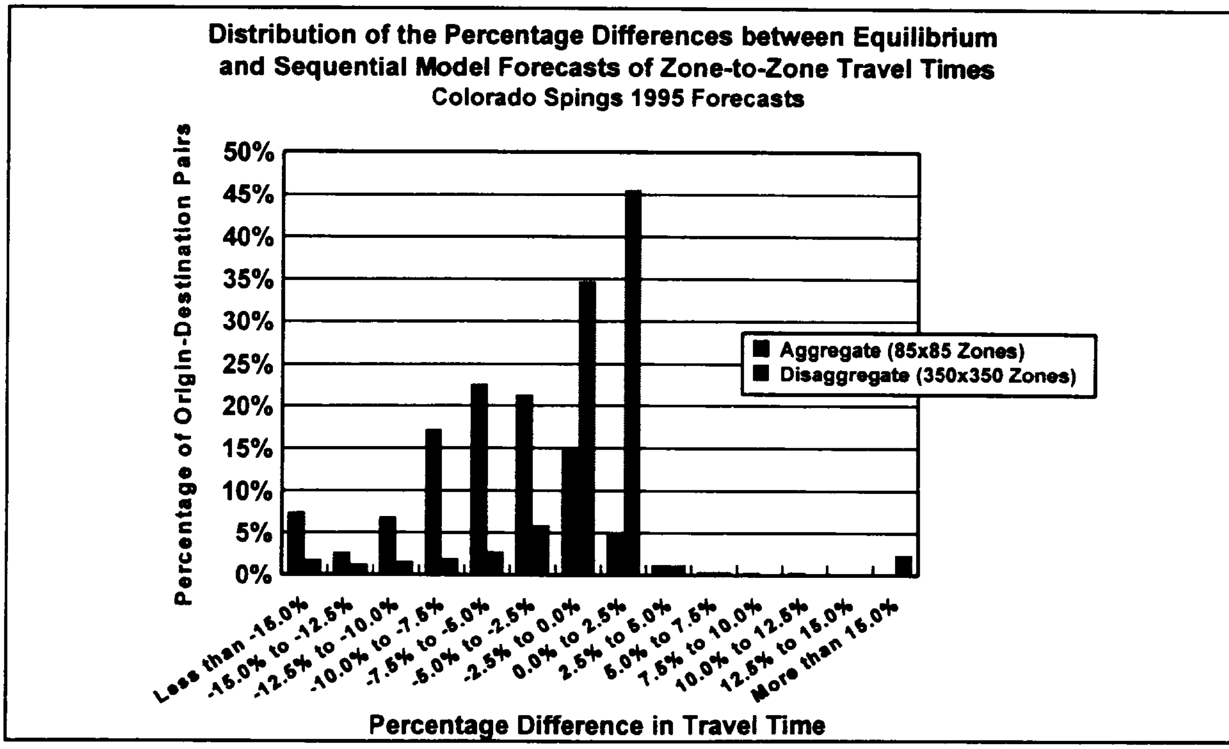

Figure 7.9: Differences between Sequential and Equilibrium Model Forecasts of Travel Times

are "external" to the activity zone system. For these external zones, the numbers of trip attractions and productions are essentially fixed, so the zone-to-zone travel times for trips to and from these zones are unlikely to be very different for the sequential and equilibrium model configurations. Second, for the 1995 forecasts, the aggregate travel time matrix used as input to the sequential model configuration and the first iteration of the equilibrium model configuration is partially inconsistent with the travel times that would result from modeling transportation demand given the base year locations of employment and households. Therefore, much of the difference between the sequential and equilibrium model forecasts of 1995 aggregate travel times reflects the adjustment of individual travel times to become consistent with the transportation demand model's response to employment and household location. Usually, the initial disaggregate travel time matrix is generated in a manner that is consistent with base year employment and household locations, so the differences between the sequential and equilibrium model forecasts of disaggregate travel times will be less, since no adjustment to eliminate inconsistencies in travel

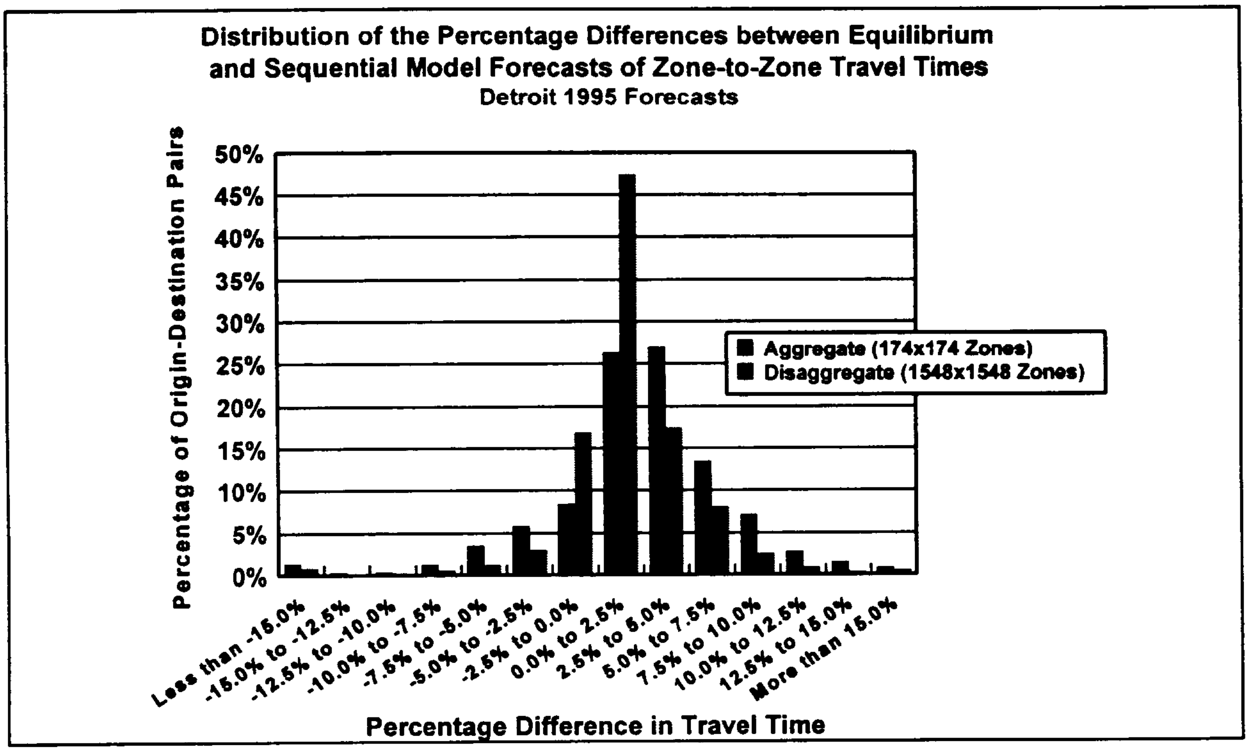

Figure 7.10: Differences between Sequential and Equilibrium Model Forecasts of Travel Times

times occurs. For Portland and Detroit, the initial disaggregate travel time matrices were found by modeling transportation demand using base year employment and household locations, and the initial aggregate travel time matrices were calculated by aggregating the disaggregate travel times. Thus, unlike the travel times for Colorado Springs, the initial aggregate and disaggregate travel times for Detroit and Portland are consistent. As a consequence, the frequency distributions of the percentage differences between the sequential and equilibrium model forecasts of 1995 travel times are similar for both the aggregate and disaggregate travel times. The frequency distributions for Detroit are shown in Figure 7.10.

7.7 Conclusions

Because of the complexity of integrated land use and transportation demand model systems, it is usually not possible to identify (a priori) regional attributes or modeling procedures which will cause forecasts made by a sequential model configuration to be very different from forecasts made by a equilibrium model configuration. A reasonable land use and transportation demand model system will consist of five or more sub-models, with direct and indirect connections between each of the sub-models, as well as aggregation and disaggregation procedures to reconcile the differences between transportation and activity zone system geography. This complexity makes it difficult to isolate the direct effect of regional attributes (e.g., population growth) or modeling procedures (e.g., duration of the peak-period) on the feedback between the land use and transportation components of an integrated model system.

The results from this chapter do show that certain relationships between regional attributes, modeling procedures, the responsiveness of land use forecasts to changes in travel times, and the responsiveness of travel time forecasts to changes in land use activities can be identified, even if the individual, direct effects cannot be isolated. ***In general, for a given level of network congestion, the differences between forecasts made with sequential model configurations and equilibrium model configurations increase as the travel time location elasticities of the land use models become more negative***. Similarly, ***for given values of the employment and household travel time elasticities, the differences between forecasts made with sequential model configurations and equilibrium model configurations increase as the level of network congestion increases***. Furthermore, the effects of the travel time elasticities and network congestion on the feedback between the land use and transportation demand model components are not simply additive -- there is a more complex, positive, nonlinear relationship between the responsiveness of the land use models to changes in travel times and the responsiveness of the transportation demand models to changes in land uses.

The values of the travel time location elasticities are determined when the parameters of the land use models are calibrated against observed employment and household locations. Travel time elasticities tend to be more negative for zones that are farther from concentrations of activities, zones that have fewer numbers of employees and households, and zones that are relatively less attractive (with respect to the attractiveness variables of the land use model.)

The level of network congestion is determined by the balance between network supply (the total level and geographic distribution of link capacity) and network demand (the total number and geographic distribution of highway trips.) For a specific forecast year, the level of network supply is fixed, so network congestion will be determined by network demand. The total number of highway trips (and, therefore, the level of network congestion on the model highway network) is very sensitive to the configuration of the individual transportation demand model components. The trip generation, mode-split, and peak-period factoring procedures can add or subtract thousands of trips from the model highway network. For this reason, ***the configuration of the components of the transportation demand model can create large differences between forecasts made with sequential model systems and forecasts made with equilibrium model systems***.

In the next, and last chapter of this report, we will give a set of overall conclusions drawn from the work, and thereby, a set of guidelines for agencies who might be considering these questions with reagard to their own transportation and land use modeling efforts.

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8 - Conclusions and Implementation Guidelines

8.1 Introduction and Summary

First, recall from the Executive Summary, ***the four questions posed for this project:***

> ***1. Does a linked transportation and land use model system produce results, forecasts, which are different from an unlinked system?***
>
> ***2. Is the implementation of such linked model systems practical in a planning agency context?***
>
> ***3. If the answers to both one and two are yes, are the results sufficiently different to warrant the additional cost of obtaining them?***
>
> ***4. If the answer to three is yes, is there a way in which an agency could determine, without actually having to do all the work of implementing an integrated model system, whether it will be worth the effort in their particular region?***

Stated succinctly, ***the answers are: Yes, yes, sometimes, and often.***

In this chapter we will elaborate on these conclusions, and point to the places in the text where the detailed justifications for the conclusions may be found.

8.2 Are the Results Different?

All the many computer runs done for this study are properly regarded as numerical experiments. A full set of linked transportation and land use computer models was used for each of five U.S. metropolitan areas[43]. Any one of these sets of computer models will, in the normal course of events, generate hundreds of thousands of numbers as part of the results of its running. For each of the five study areas a great many computer runs were done. In order to have any hope of interpreting this vast panoply of numbers, we classified them according to several categories. First, of course, we had the results by metropolitan region, or as we sometimes refer to them here, by city. Within each region we have runs which made use of either of two principal model system configurations, ***sequential*** or ***equilibrium.*** Both of these principal model system configurations include a connection between transportation and land use. The *sequential configuration uses the output of the land use models as input to the transportation models in the succeeding forecast time period.* The *equilibrium configuration is solved for an equilibrium solution within each forecast period, before moving to the next forecast time period.* The formal descriptions of the two principal model system configurations were given in Chapter 3. In addition to the two principal

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[43] As mentioned earlier in this report, a sixth region was examined as well, as part of a separate project.

model system configurations, there were several variations within the principal configurations which were tested as well. For both of the principal model system configurations, in all five cities, the models were run from a base year (starting point) of 1990 to a final forecast horizon of 2010. All of these forecasts were made in a progression of five year steps[44].

The first set of comparisons of model outputs was for a single five year forecast (1990 to 1995) for Portland. There were differences in the forecasts, but they were not very great. In others of the regions we studied, we found that the differences between the sequential and the equilibrium model runs were greater than they were in Portland. Further examination revealed the reasons why the amount of difference between sequential and equilibrium runs varies from region to region, and these reasons will be discussed below.

The second set of comparisons was again made between sequential model configuration run results and equilibrium model configuration run results, but this time for the year 2010. To get to 2010, in all cases examined here, the models were run in a series of five year steps beginning with 1990 and progressing to 1995, 2000, 2005, and 2010. For both model system configurations, this step by step process provided for greater interaction between employment location, household location, travel demand, and trip assignment. Smaller differences between the results from the two model configurations could, by interaction between the model system components, one with the other, either be amplified or attenuated over the four five year forecast periods. The differences between the forecasts produced by the sequential model configuration and those produced by the equilibrium model configuration were greater for 2010 than they had been for 1995.

All North American cities, in their present forms, are the result of decades, sometimes centuries, of development and evolution. It must be remembered that even in the most rapidly growing of our study regions, Colorado Springs, there is major sunk capital underpinning the region's spatial patterns, its regional form. Such growth as may occur in the twenty year period from 1990 to 2010 will, for the most part, result in rather modest changes to the region's form. In individual zones of the region there will be some dramatic shifts, but on average, the overall form of the region will not change dramatically. This said, a comparison of the forecasts from the two different model configurations cannot be expected to show dramatic differences either. Our model runs, generally, and quite properly, showed no dramatic differences. We then turned to a comparison of the change in activity levels from each time period to the next, and a comparison of these changes between the two different model system configurations. Here the results were a good deal more visible, with significant differences between various of the activity types, i.e. employment, households, or transportation network link volumes, in terms of the change, say, from 1990 to 1995. In many cases, the differences were even greater when the comparison was between the changes forecast to take place from 1990 to 2010. ***When the comparisons are made in terms of changes in activity level, there were, for at least some variables in all regions,***

[44] As a side matter, some experiments were done to examine the effect of using longer forecast time steps, of ten or twenty years. The results confirmed the wisdom of using five year steps.

significant differences in the results produced by the sequential model configuration runs when compared to the results produced by the equilibrium model configuration runs. We note that when we say significant differences here, we mean measurably or observably different. The question of whether these differences are socially, economically, or politically significant, is more a judgmental issue, to which we will turn later in this chapter.

8.3 Can These Model Systems be Implemented in an Agency Context?

It was actually some months prior to the start of this project that a prototype equilibrium model system configuration was successfully tested in an agency setting. The major problems encountered in conducting that demonstration were organizational, not technical. Tests of the equilibrium configuration had already been completed with full scale data sets for Washington, DC and for Houston, TX in an academic setting several years earlier (Putman, 1991). While the academic tests were done on a mainframe computer, the first agency implementation, at SCAG, was done on workstations. As a consequence, we knew that it could be done in an agency setting, but we didn't know if it could be repeated, and with what difficulties. At the completion of the research for this project (Summer 1996) all five study regions have operational linked model system setups, though not all are making use of them. In addition, two other agencies that were not a part of this study are implementing such systems, and at least two others are making preparations to do so. These implementations are all on workstations or PC's. Care must be exercised in file management, as the linked runs produce many files which must be carefully routed to and from appropriate input and output streams, but much of the file management can be handled by the computers themselves, in the form of batch routines. In certain circumstances the question of actual running times can be problematic, but as computing speed continues its rapid increase, running time becomes a minor matter. All in all, we can state unequivocally, that ***these model system configurations can be implemented within a regional planning agency (MPO) context.***

8.4 Are the Results Sufficiently Different to Warrant their Additional Cost?

The key word here is the word *sufficiently*. To some degree, this is a judgement call. A sensible response to this question might be to ask how much difference is a significant difference. Is it measured in numbers of employees, numbers of households, average link volumes, congestion levels on networks, etc.? Is a significant difference measured in terms of percentage differences from some base, or by a combination of absolute differences with percentage differences? Depending upon the base from which it is calculated, a fifty percent difference may be five employees, and a one percent difference may be five hundred employees. If a region is at or near some critical point, say for air quality attainment, a difference of a percent or two in travel produced pollutants may mean the difference between the region's meeting air quality standards, or not. Is a significant difference one which happens immediately, i.e. is a short term outcome, or are only long term outcomes significant? It is often the case in complex systems, such as those which determine a region's patterns of location and transportations, that a short term response to some system stimulus is opposite to the long term response. Overall, then, the issue of "significance" is very much contextual, and subject to interpretation.

Let us divide the question into two. First we ask whether the difference between doing forecasts without any connection between transportation and land use, and with either of the two forms of connection examined here, is worth the cost. We may then ask, second, about the difference between the two model system configurations, sequential and equilibrium. The answer to the first question of "no feedback" versus "some form of feedback" between transportation and land use is rather clear. ***Only under the most unusual of circumstances would we not expect significant systematic errors in forecasts made without any feedback between transportation and land use.*** It would be necessary to assert that there was not now, nor would there ever be, any congestion on the region's transportation networks in order to justify the omission of feedback between transportation and land use. Further, it would also be necessary to assert that there would never be any addition to (or deletion from) the regions's transportation networks. Only if both these assertions were true, would it be possible to claim that no errors would be introduced to forecasts made with procedures that incorporated no feedbacks between transportation and land use.

Once having taken the step of deciding to implement either form of model system configuration with feedback, the difference in "cost" between system configurations such as those examined here is minimal. There are, as stated above, increased file management requirements. For very detailed transportation network representations there are also possible issues of computer running times and the consequent increase in the time (in hours or days) necessary to produce a forecast. We summarize the "warning" signals below, the items that will suggest the need or absence of need for the use of a equilibrium system over a sequential system. These signals relate to congestion levels on the transportation network, regional growth rates, the components of the transportation model system, as well as to some statistical matters that can be examined during the calibration of the models. In the implementation of the sequential model system configuration, the evidence necessary to estimate the need for use of an equilibrium model system configuration will become available. Since a sensible approach would be to implement the sequential system first in order to gain both staff experience, as well as to establish model system consistency, ***the final decision as to the need for the full equilibrium system can be deferred until the completion of the sequential system implementation.***

8.5 Can the Need (or Not) for an Integrated Model System be Determined in Advance?

Here we must ask, in advance of what? If we take as a given that virtually all MPO's have already implemented some form of transportation model system, incorporating travel demand, mode split where appropriate, and trip assignment, then all we are asking is whether it can be determined in advance whether or not they also need to implement a land use model? On the occasion that they already have one implemented, we are asking whether they need to develop the formal feedback connections between the travel models and the land use models? The answer to the first of these questions is the same as the answer given in Section 8.4 above. Here it is a matter of stating that ***only under the most unusual of circumstances would we not expect significant systematic errors in transportation forecasts made without any input (or feedback) from land use.*** In order to forecast travel demand it is necessary to "know" where households and employment will be located. This requires forecasts of the future locations of households and employment. It would be necessary to assert that both employment and household location took place independently of each other, and of travel time or cost, to justify not using some form of model to forecast their future locations. Given this answer to the first part of the question, the second part of the question is answered as well. The reason that a land use model is necessary to provide inputs to transportation models is that the location of households and employment are, to varying degrees, dependent upon transportation facility attributes such as travel time and travel cost. In order to make transportation sensitive forecasts of these activity locations, there must be a connection from the transportation models to the land use models.

Each of the two sets of models, transportation, and land use, requires inputs from the other in order to make reliable forecasts. The minimum degree of connection between the models is embodied in the sequential model system configuration. The use of unconnected transportation or land use models to make forecasts, most especially long term forecasts, in regions of 250,000 or more population is virtually guaranteed to produce errors in the results. This said, there remains the question of exactly what form of connection there should be between the transportation and land use models. We have compared two general forms of connection, the sequential form and the equilibrium form.

Before comparing the two configurations, their advantages and disadvantages, as well as the circumstances which would argue for the selection of one versus the other, we provide a brief review of the operation of the two configurations. The *sequential model system configuration* proceeds from starting, base year, data (which include employment and household location as well as travel times or costs), to make a forecast of employment and household location five years into the future. This forecast becomes input to a forecast of travel demand and trip assignment for the future year, which, in turn, yields a forecast of trip volumes and of congestion on the future year transportation network(s). The future year congested network attributes, along with the previously calculated forecasts of employment and household location, become input to a second forecast, five more years into the future, of employment and household location. This forecast, now ten years beyond the base year starting point, becomes input to a second forecast of travel demand and trip assignment for the future year, which, in turn, yields a forecast of trip volumes and of congestion on the future year transportation network(s), now also ten years beyond the starting point. The sequential model system configuration continues in this fashion, in five year time steps out to the forecast horizon of say 2010, 2020, or beyond. Because the process is run in five year steps, all of the forecasts have an opportunity to influence the outcomes of all the other forecasts (though not simultaneously). Thus employment location affects household location, which, in turn, affects subsequent employment location, and so forth. Both employment and household location are affected by conditions on the transportation network, and, in turn, affect, via trip generation, distribution, mode split, and assignment, the subsequent levels of network congestion.

The *equilibrium model system configuration* does everything that the sequential configuration does, with one addition. Within each forecast (five year) period, additional runs of both the land use and the transportation models are done in such a way as to achieve an equilibrium solution. This equilibrium solution to both land use (employment and household location), and transportation (trip generation, distribution, mode split, and assignment), is a simultaneous or combined solution to all these models linked together, and may take anywhere from three to five iterations within each five year forecast period. Having achieved an equilibrium for the first five year forecast period, the procedure continues on to the next five year period, using the prior equilibrium solution as its input, and solving for an equilibrium solution to the next five year forecast period. From a strictly computational perspective, this approach will take three to five times as much computation as the sequential approach. Depending upon the size of the models and the computing platform this could mean anywhere from hours to days more elapsed time. Most frequently, even for the largest model systems, a full run of this system from a 1990 base year to a 2010 forecast year, with equilibrium being calculated for each five year forecast step, will be completed in several days elapsed time.

The numerical experiments done in this study show that there are differences between the forecasts produced by the sequential model configuration runs and by the equilibrium model system configuration. These differences range from apparently trivial, to quite significant. The determinants of the magnitude of these differences are both complex and interconnected. In general, the magnitude of these differences depends upon the strength of the "feedback" between the activity and transportation models. By strength we mean the responsiveness, or the sensitivity, of any one component of the model system to the inputs which it receives from any other component. ***The responsiveness of the activity models to changes in travel times (i.e., "feedback" from the transportation models) is primarily determined by the travel time elasticities of the employment and household location models and by the travel time aggregation procedure. The responsiveness of the transportation models to changes in activity locations (i.e., "feedback" from the activity models) is primarily determined by the level of congestion on individual network links.***

Taking the *first point, regarding the travel time elasticities*, we first recall that an elasticity is the measure of how much response there is in one variable, the output of a model, per unit change in another variable, one of the inputs to the model. Thus a travel time elasticity of -1.20 for low income households in zone i, means that for a 1% increase in travel time, there would be a 1.2% decrease in the number of low income households choosing to reside in zone i. The travel time elasticities can be calculated as a part of the initial statistical work that would be done while a land use model was being prepared for use in a particular region. ***If the particular household and employment location models being used, or considered for use, provide for the calculation of these elasticities as part of the process of calibration, or the statistical estimation of their equation coefficients, then it will be possible to have some advance indication of the likely responsiveness of the activity models to changes in travel times or costs.***

Taking the *second point, regarding the responsiveness of activity models to changes in travel times with respect to the travel time aggregation procedure*, it is less likely that an advance indication can be had. Regardless of which of the two model system configurations is utilized, there will be issues of conversion from one level of geographic detail to another when transferring data from one model to another in the combined model systems. In Chapter 4 we described the various geographies used for modeling work in the five study areas. In all cases the level of geographic detail used for the activity models is based on census tracts or aggregates thereof. Further, in all cases, the travel models are run at a finer level of geographic detail, with the ratio of activity model zones to travel models zones ranging from 1:2 to 1:12 amongst the five regions. In each case, after the activity models calculate their forecasts, the forecasts must be disaggregated down to the travel model level of detail. Then, after the travel model forecasts, including trip assignment, are calculated, the congested zone-to-zone travel times must be aggregated back up to the activity model zone system. ***Errors are introduced into the forecasts in both the disaggregation and the aggregation procedures. The tension here is because, for the foreseeable future it will be impossible to get the data necessary to operate the activity models at the same fine geography that the travel models use. Similarly, the more one aggregates the travel model geography the less reliable are the estimates of network link flows and congestion. This is the main cause of the poor results to be had from sketch level network analysis***[45]. The agency using models for transportation and land use forecasting will be faced with a never ending balancing act, trying to deal with the data problems on the one hand, and the model reliability problems on the other.

Taking next the *third point, regarding the responsiveness of the travel models to changes in employment and household location and land use*, it will help to consider an extreme case first. If each link of the transportation network had infinite capacity, then no matter what the link volume, there would be no change in the link travel time, and thus no change in zone-to-zone travel times. In this case, land use would have no effect on the travel model forecasts. Further, as there would be no congestion effect, the only changes in the network which would affect activity location would be the addition or deletion of links. The more realistic situation is when there is a specified capacity for each network link, and a functional relationship between the trips using the link and the time and/or cost to traverse the link. In this case, as the link volume increases, so does the time and cost of traversing the link. Here, changes in land use, through the consequent changes in travel demand, will cause changes in link flows. The changes in link flows, through the operation of the link volume/delay functions, will cause changes in link travel times and costs. In the succeeding run of the land use model, these changed link attributes, expressed in terms of changes in the zone-to-zone travel times, will affect the land use forecasts. This said, we must have a closer look at the link volume/delay functions. These functions should, if plotted on a graph, slope upwards to the right, so that increased link volume (on the horizontal axis), will result in increased link time (on the vertical axis). If the functions are relatively flat, then an increase in trip volume will have only a small effect on link time. If the functions are relatively steep, then a small increase in link volume will have a large effect on link time. Most volume

[45] As part of the initial work with the Portland model system, we examined the use of a sketch level transportation model and concluded that it was unsatisfactory for most purposes. This work is described in Chapter 6.

delay functions are nonlinear, with some portions of the function being flat, and some being steep. If a substantial number of the links in a network being modeled are on the steep portions of their volume/delay functions, then small changes in land use, resulting in small changes in link volumes, will cause larger changes in link times. In a subsequent run of the land use model we will see the results of this as a larger change in the zone-to-zone travel time input. Depending upon the travel time elasticities of the land use model this may or may not result in a larger change in the employment and household location and land use forecast. If, on the other hand, many of the links in the network being modeled are on the flat portions of their volume/delay functions, then even large changes in link volumes may yield only small changes in link times and, subsequently in zone-to-zone travel times. Here, almost certainly, there will be little or no change in the subsequent land use forecasts. ***By examining the frequency distributions of the link volume/capacity ratios for the modeled network, along with knowing the functional forms of the volume/delay functions, it will be possible to estimate the likely sensitivity of the combined model system forecast to changes in travel patterns and link flows***.

In addition to the need for use of one integrated model system versus another being determined by empirical and substantive aspects of the region and the modeling approach, there is also some consideration to be given to the specifics of the models being used and the manner in which they are being implemented. In particular, ***the use of the equilibrium model system configuration can compensate for certain errors in the application of specific models or submodels in the overall system***. The principal reason for this is that the final solution, or forecast, of activity location and trip patterns which result from the use of the equilibriummodel system configuration is independent of the starting point, or initial values, which were used. Thus, for example, if the travel demand models are initiated with uncongested travel times, which appears to be an improper approach, the equilibrium system configuration corrects for this error[46]. It is also a help in improving forecasts in situations where the zone-to-zone travel times used in calibration appear to be inconsistent with those used in the actual forecasting procedure[47].

Another difference between the sequential and the equilibrium model system configuration is found in the stability of their solutions. Proceeding from the fact that the solution to the equilibrium configuration is unique, is its independence of the initial (starating) values used to compute it. From a practical perspective, this results in a much more stable time path, or trajectory of model forecasts from one forecast period to the next. When compared, the forecasts from the *sequential* model system configuration may, in fact, oscillate around the forecasts from the *equilibrium* model system configuration. As a consequence, a policy outcome is evaluated, say, for 2005, it might give entirely different results than if it was evaluated for 2010. Thus a particular regional transportation improvement plan, were it compared to a "do nothing" scenario for 2005, would appear beneficial to regional goals, while if the same policy were compared to the "do nothing"

[46] The problems with this approach, taken by SCAG for Los Angeles, are discussed in Chapter 6.

[47] This problem, too, was inherent in the SCAG forecasting process, and is discussed in Chapter 6.

results for 2010 it might appear to be detrimental to regional goals. It is true that longer term policy results can differ from shorter term results, but these differences should be based on substantively correct forecasts, and should not be subject to known, and remediable, errors in the forecast process itself. Thus ***for policy comparison, the equilibrium model system configuration will provide more reliable estimates of the differences between policy forecasts.***

Taken all in all, it really is not possible to make a universal statement regarding whether it is worth the extra cost to do the equilibrium runs. It clearly is necessary to do sequential runs at a minimum. Once done, it will be possible for the agency to determine the need for, as well as the additional cost of doing the more complex equilibrium runs.

8.6 A List of Substantive Findings Across Regions

In Chapters 6 and 7 we present the results of numerous computer experiments. Specific experiments were done using data from different study regions based on the question being examined. The following is a very briefly stated summary listing of the results from these experiments.

Regarding overall model system configurations:

- Many aggregate statistics (location surplus, VMT, VHT) follow a more realistic trajectory when land use/transportation iterations are used. For sequential model configurations, the trajectories of these statistics oscillate around the trajectories for the equilibrium configurations.

- In the absence of significant traffic congestion, the differences between forecasts from sequential model configurations and forecasts from equlibrium model configurations are minimal.

- For regions with significant traffic congestion, the differences between the forecasts of activity locations from sequential model configurations and forecasts from equilibrium model configurations are directly related to the travel time elasticities of the land use models.

Regarding sub-model structure of linked model configurations

- The use of travel demand iterations is unnecessary when land use/transportation iterations are used.

Regarding "errors" in sub-model structure

- Land use/transportation iterations are useful when the base year travel time matrix is inconsistent with base year activity locations (e.g., uncongested travel time matrix used for input to the 1995 land use model forecast).

- Land use/transportation iterations are useful when the land use models are calibrated against base year data that is inconsistent with a land use/transportation equilibrium (e.g., when and uncongested travel time matrix is used for DRAM/EMPAL calibration).

- Some errors in model structure (e.g., uncongested travel times used for first iteration of trip distribution) are "fixed" by the use of land use/transportation iterations.

- The MSA link averaging procedure to solve for an equilibrium increases the rate of convergence for model structures with land use/transportation iterations (Portland, Colorado Springs), and is required for convergence if traffic congestion is very high (Los Angeles).

Regarding the scale, or detail, of model geography

- In general, more disaggregate geographic systems are preferable to more aggregate geographic structures. DRAM/EMPAL should be calibrated for the most disaggregate geographic system, unless data quality is compromised

- The traffic analysis system should also be as disaggregate as possible, while maintaining consistency with the DRAM/EMPAL zone system (Portland).

- Disaggregation of activities and aggregation of travel times are important, since these procedures can add error to a model system.

In Chapter 7 we presented the results of detailed investigation into the sources of variations in responsiveness amongst and within the models to changes in their input and output variables.

Factors that influence the responsiveness of land use models to transportation model outputs

- Travel Time Aggregation Procedure

  a. Ratio of the number of traffic analysis zones to the number of activity zones
  b. Trip-weighted travel times vs. aggregation by representative zones

- Estimates of Travel Time Parameters in Land Use Models

  a. Size of activity zones (i.e., population per activity zone)
  b. Use of congested or uncongested travel times in the model calibration procedure
  c. Accuracy of observed activity distributions used for model calibration

d. Collinearity between independent variables of land use model and travel times

Factors that influence the responsiveness of transportation models to land use model outputs

- Regional Demographics

  a. Population and employment density
  b. Population and employment growth
  c. Geographic distribution of land use activities
  d. Changes in automobile usage
  e. Peaking characteristics of vehicle trips

- Activity Disaggregation Procedure

  a. Ratio of the number of activity zones to the number of traffic analysis zones
  b. Degree of socio-economic disaggregation

- Trip Generation Model

  a. Number and type of trip purposes
  b. Level of geographic and socio-economic detail in the independent variables of the trip generation model

- Trip Distribution Model

  a. Congested or uncongested travel times used to calculate travel deterrence
  b. Estimates of parameters of trip distribution model

- Mode Split Model

  a. Number and type of trip purposes
  b. Level of geographic and socio-economic detail in the independent variables of the mode split model

- Peak-Hour Factoring

  a. Use of P.M./A.M. peak period or daily vehicle trips and link capacities
  b. Duration of period used to measure vehicle trips and link capacities

- Model Network Characteristics

  a. Ratio of the number of network links to the number of traffic analysis zones
  b. Accuracy of model network representation of actual transportation network

c. Capacity of model network relative to the number of vehicle trips
d. Mathematical form of link-delay functions
e. Incorporation of transportation network improvements.

There are many more things to be said about integrating transportation and land use models than can possibly be summarized here. More detailed discussion of the points presented here will be found in the Technical Appendix to this report. More experiments can certainly be designed and performed. The results given here, based as they are on extensive work with five rather different regions and transportation models, may be regarded as a reliable guide for agency consideration.

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