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16. ABSTRACT

Peak spreading is relevant in several types of analyses, particularly analysis for capital construction investments, air quality analysis for conformity requirements, and analysis for transportation demand management investments. This review was conducted in response to issues raised at the Washington State Department of Transportation (WSDOT) regarding the benefit/cost assumptions and calculations that could or should be made regarding the phenomenon of peak spreading. This report identifies the transportation planning issues associated with peak spreading, reviews efforts that have been made to account for it in analysis, and makes recommendations specific to the priorities of the State of Washington.

Four categories of analysis approaches were reviewed: (1) a post-processing technique in which hourly factors are applied to the daily traffic volumes output by a forecasting model; (2) peak spreading adjustments that were made to the four-step modeling process; (3) attempts to develop more sophisticated stand-alone peak spreading models, which could then be used as sub-models within the more traditional forecasting process; and (4) stand-alone models that were completely independent of the four-step forecasting process.

Because consistent statewide forecasting methods have not yet been implemented, peak spreading analysis methods developed for WSDOT in the short term should be independent of four-step forecasting models. However, the establishment of a common travel demand forecasting framework throughout the state would definitely make longer-term modeling approaches more feasible. In the short- to mid-term, directional historical traffic data that have been collected by WSDOT should be compiled for key freeway locations. These historical traffic profiles could be used to formulate simple models on the basis of future estimated growth rates to predict future traffic conditions. In the longer term, a departure time element should be included in the ongoing research at the University of Washington, the goal of which is to include a more robust variety of traveler choices in travel demand forecasting.

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PEAK SPREADING ANALYSIS:
REVIEW OF RELEVANT ISSUES AND SYNTHESIS OF CURRENT PRACTICE PHASE I

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PREFACE

This review was conducted in response to issues raised at the Washington State Department of Transportation (WSDOT) regarding the benefit/cost assumptions and calculations related to the phenomenon of peak spreading that could or should be made. This report will identify the transportation planning issues associated with peak spreading, review efforts that have already been made to account for it in analysis, and make recommendations specific to the priorities of the State of Washington.

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INTRODUCTION

This review was conducted in response to issues raised at the Washington State Department of Transportation (WSDOT) regarding the benefit/cost assumptions and calculations related to the phenomenon of peak spreading that could or should be made. This report identifies the transportation planning issues associated with peak spreading, reviews efforts that have already been made to account for it in analysis, and makes recommendations specific to the priorities of the State of Washington.

Peak spreading is defined as an expansion of peak period traffic, from the traditional height of the peak outward to the shoulders of the peak, as the number of travelers and level of congestion increase on a roadway. The effect of peak spreading is an average daily peak-period traffic profile that becomes wider (more spread out) and flatter (of longer duration at or near capacity conditions) over time.

APPROACH TO PEAK SPREADING REVIEW

To determine a reasonable technique for including the consideration of peak spreading in WSDOT analysis methods, the following approach was taken:

1. Evaluate the types of project analyses impacted by consideration of peak spreading
2. Analyze the strengths and drawbacks of the transportation demand forecasting process with regard to the inclusion of peak spreading effects
3. Review the existing and potential modeling capabilities within Washington state and regional agencies, on the basis of Washington State Modeling Initiative
4. Conduct an extensive literature review to determine the state-of-the-practice regarding how peak spreading impacts are estimated and quantified

5. Apply the conclusions of the literature review to the issues identified for WSDOT to determine short-term and long-term recommended approaches for including peak spreading in transportation analysis.

IMPACTS OF PEAK SPREADING ON TRANSPORTATION ANALYSIS

Peak spreading is pertinent to current priorities at WSDOT and within the State of Washington. If peak spreading is occurring, some traffic is shifting from the traditional peak hour to the shoulders of the peak. Failure to take this into account can result in overestimation of traffic volumes in the peak hour (thus an underestimation of average speeds) and an underestimation of traffic volumes in the shoulders of the peak (thus an overestimation of average speeds). This is consequential for several types of analyses, particularly (1) analysis for capital construction investments, (2) air quality analysis for conformity requirements, and (3) analysis for transportation demand management investments.

MODELING REVIEW

To evaluate or predict peak spreading, whether it is a desired or simply inevitable traffic phenomenon, one must first understand long-term and short-term transportation planning and programming processes. Long-term planning generally requires travel demand forecasting, which is traditionally accomplished through the "four-step" travel demand modeling process (trip generation, trip distribution, mode choice, and transportation network assignment). The major limitations of the traditional forecasting process with regard to peak spreading analysis are that (1) daily trips are initially estimated with no temporal distribution, and (2) the steps are modeled in a linear fashion (integrated by some feedback loops), even though in actuality travel decisions and their implications are not sequential, nor are they independent. These limitations make innovative analysis of a phenomenon such as peak spreading difficult. As travel decisions become more complicated (more congestion, more sprawl, more environmental considerations, more constraints on existing and future transportation systems), the

disparity between modeling techniques and actual conditions will become more pronounced. However, numerous research efforts are taking place to improve the modeling process, some of which directly address some of the limitations that hinder peak spreading analysis. In addition to focusing current research on addressing some of these limitations, University of Washington (UW) researchers are monitoring various other research efforts under way.

Peak spreading is also an important consideration for the short-term programming of the WSDOT Mobility Improvements projects because the majority of projects submitted for programming are large capital construction projects, and the arena is competitive. If peak spreading is not considered in the baseline 'no-build' scenario, unrealistically high delays may be predicted, thus exaggerating the benefits of proposed capital improvements. Peak spreading issues pertinent to TDM are meaningful as well. Much transportation policy currently focuses on the potential impacts of TDM. Under some circumstances, peak spreading may indicate that a transportation facility is being used more efficiently under congested conditions, which is consistent with TDM goals.

Traditional forecasting methods are not widely employed by the WSDOT regions, so it is not realistic to expect the WSDOT regions to adopt modeling techniques in the immediate future as part of standard analysis procedures. However, the adaptation of modeling techniques does not seem out of the question in the mid- to long-term future. A major initiative, entitled the Washington Travel Demand Forecasting Framework (WTDFF), is under way at WSDOT to promote transportation modeling throughout the regions. The main functions of the WDTFF are to (1) provide travel forecasting guidance for WSDOT and for public and private partners, (2) establish a common set of assumptions to promote consistent modeling techniques throughout the state, and (3) determine the best technical practices that should be adopted in a statewide modeling initiative (WSDOT, 1997).

Since statewide forecasting methods are not yet consistent, peak spreading analysis methods developed to be employed by WSDOT in the short-term should be independent of four-step forecasting models. However, the establishment of a common travel demand forecasting framework throughout the state would definitely make longer term modeling approaches more feasible.

LITERATURE REVIEW

Although conclusions vary regarding the extent of the benefits from peak spreading, most studies that have been conducted both in the United Kingdom and in the United States have confirmed its widespread occurrence and have included many attempts to capture its effects for more accurate transportation planning.

A literature review revealed numerous attempts to incorporate peak spreading into transportation planning and forecasting. Although all of these approaches improve upon typical analysis techniques that do not consider peak spreading, none of the reviewed methods represent the single answer to peak spreading issues, and all have limitations. Nevertheless, some innovative peak spreading analysis methods exist, and combined with the assessment of modeling limitations, they provide a solid basis on which to recommend short-term and long-term approaches for incorporating peak spreading into analysis techniques.

Four categories of analysis approaches were reviewed. The first is the most typical method for conducting time-of-day analysis, which is simply a post-processing technique in which hourly factors are applied to the daily traffic volumes output by a forecasting model. These methods can be made slightly more sophisticated by developing various factors according to the time of day and the purpose of trips. Still, these types of methods are static processes and are not sensitive to policy changes, congestion levels, or capacity constraints. In addition, these methods are not consistent with the modeling process because most of the steps are performed with daily trips. Peak spreading cannot be reflected in post-processing time-of-day analysis. This is the type of

technique that is currently employed at WSDOT to convert Average Weekday Daily Traffic (AWDT) to hourly profiles.

The second category consists of peak spreading adjustments that have been made to the four-step modeling process. There are two general methods, *link-based* and *trip-based*, for implementing peak spreading analysis within the steps of a traditional model. Both result in more realistic traffic assignments that are sensitive to congestion. Both methods address the problem of projected demand exceeding the capacity in a given corridor during peak periods, and they attempt to more accurately assess future travel conditions by considering peak spreading. Link-based measures are applied in the traffic assignment process, diverting trips that exceed link capacity to the shoulders of the peak. This results in more realistic traffic assignments that are sensitive to congestion. Some of the drawbacks of the link-based methods include the following (Cambridge Systematics, 1996):

1. no guarantee of continuity of flow between links; thus the amounts of predicted peak spreading could be substantially different between adjacent links
2. failure to account for peak spreading for a specific link that could be the result of a choke point somewhere else in the system or of the average level of congestion in the corridor
3. failure to consider peak spreading that may occur outside of the designated peak period
4. no explicit treatment determined for trips that are reduced off of the system.

Methods that focus on trip-based measures reduce the trip table interchanges for links in which demand exceeds capacity. Many researchers prefer trip-based methods because they allow continuity of flow between adjacent links. However, trip-based

methods shared many of the other limitations of link-based methods. Both methods improve upon post-processing time-of-day analysis in that they result in more reasonable demand forecasts that are capacity constrained. Nevertheless, because WSDOT does not widely utilize the four-step modeling process, and because these methods have numerous inherent limitations, it is not recommended that any analysis methods developed in the short-term or long-term employ this type of approach.

The third category of peak spreading adjustments consists of attempts to develop more sophisticated stand-alone peak spreading models, which could then most likely be used as sub-models within the more traditional forecasting process. The analysis methods developed in this category not only tend to be the most expensive and labor-intensive, but they also reflect the widest array of variables and model forms. Some of the variables include speed variances, downstream delay, average trip times, land use density and mix, trip purposes, average departure time shifts participants are willing to make, and ratio between peak hour and peak period volumes. None of the methods utilizes all of these variables, and each of the methods has limitations unique to the approach that it employs. Two efforts (one by Arezki et al, and one by Johnston et al) seem to be particularly promising with regard to the ongoing TDM research at the University of Washington. In each of these efforts, logit models have been developed that reflect more traveler choices than solely the traditional choice of modes (such as additional choices of departing by automobile either earlier or later). These research efforts have met with varying degrees of success.

Development of a more comprehensive type of choice model is complex for two reasons. First, while it presents choices in a manner more reflective of how people really make decisions, it is not consistent with how choices are modeled in the traditional four-step process. The differences would have to be reconciled for a more robust choice model to be included in the overall forecasting process. Second, the inclusion of more variables in a choice model requires more complex surveys, and thus it becomes more

difficult to produce dependable results. Of the two papers that documented modeling efforts along these lines, both reported results that were only marginally successful. However, lessons learned from these and other efforts, as well as current research that seeks to improve the traditional demand forecasting process, provide a good foundation on which to base our continuing research efforts in this area.

The fourth and final category of peak spreading analysis procedures consists of stand-alone models that are completely independent of the four-step forecasting process. Two examples of this type of approach were reviewed. Both researchers compiled historical data to first confirm whether or not peak spreading was indeed occurring at the areas under study. Then the data was used to develop relatively simple models based on historical trends that could be used to forecast future traffic conditions.

RECOMMENDED APPROACH FOR MODEL DEVELOPMENT

The overall goal of any further research efforts regarding peak spreading would be to actually develop a peak spreading model for the metropolitan areas throughout the state.

Recommended Short-Term Approach

In the short- to mid-term, it is recommended that directional historical traffic data that WSDOT has collected be compiled for key freeway locations that represent a rich variety of freeways and area types. The result would be historical trends in traffic profiles, by direction, for representative locations throughout the Seattle metropolitan area. The historical trends could be used to formulate simple models (either graphical or mathematical) to predict future traffic conditions, on the basis of future estimated growth rates. The following approach is recommended for the short-term:

1. **Collect historical traffic data**

a. Select key freeway locations on the basis of the locations of traffic counters. Other considerations in the location selection are that all freeways should be represented, as well as a variety of area types. In addition, locations with the

oldest traffic counters should be chosen to the greatest extent possible because they will yield the most historical data.

b. Choose the representative years by which to calculate historical trends given the traffic count data available through WSDOT

c. Determine what portion of annual data should be aggregated to represent an average day, and determined what, if any, screening measures should be used to ensure that the data are reasonable.

d. Compile WSDOT traffic count data from selected locations to create average daily traffic profiles, by direction, for each representative year.

e. The result will be examples of historical trends in traffic profiles for representative locations throughout the Seattle metropolitan area.

2. Determine model form

Once the historical data have been compiled, the next step is to determine how that information can be used to create a model that will predict peak spreading trends. Some considerations in model development that have been highlighted in the literature include the following:

- A variety of possibilities exist for model form, so it is beneficial to maintain an open mind.
- Active peak spreading is recognized as a different phenomenon than passive peak spreading.
- Sites with different characteristics may require different model variables or coefficients.
- The AM peak period is often more straightforward to model than the PM peak period.
- Examples of model input include congestion levels, trip purpose, land use, and area type.

- An example of model output includes estimated daily trip distributions by hour, or by 15-minute interval.

The drawback of this type of approach is that predicted results would not be sensitive to policy change or to strategies that result in anything different than traditional traveler behavior. It would be a static process that did not attempt to model behavioral responses to changing traffic conditions. However, this type of model could provide a means by which forecasts of future traffic conditions would reflect capacity constraints at congested conditions, which at the very least would avoid exaggerated estimated benefits for capital improvements.

Recommended Long-Term Approach

In the longer term, it is recommended that a departure time element be included in the ongoing research at the University of Washington, the goal of which is to include a more robust variety of traveler choices in travel demand forecasting. This research is directed generally toward TDM strategies and not specifically toward peak spreading analysis, but it is applicable because it is attempting to address the same question that hinders analysis of future *active* peak spreading trends: *how does one predict the travel choices people will make, given circumstances or conditions that do not yet exist?*

The objective of the research project is to calculate utilities for alternative travel choices travelers may make as a result of increasing congestion levels and TDM strategies. Utility is an empirical measure of the relative attractiveness of different choices and has traditionally been used for mode choice modeling. However, if empirical data are collected for other types of choices, it should be possible to model them as well. Utility functions in travel demand models have traditionally been calculated from the preferences of travelers, based on their actual travel behavior as revealed in travel surveys. While revealed preference methods have traditionally been appropriate for deriving travel utilities, they have limitations that restrict the inclusion of non-traditional choices, namely (1) they cannot be used directly to evaluate demand under conditions

that do not yet exist, and (2) it can be difficult to obtain sufficient variation in data to evaluate a wide range of choices.

Thus, researchers at the UW are examining the use of stated preference surveys to address these drawbacks. Stated preference methods consist of a series of techniques to estimate relative utility functions; these are based on survey respondents' statements about their preferences in a set of transportation alternatives (actual or hypothetical). The major drawback (and criticism) of stated preference is that respondents may not do in reality what they say they will do given hypothetical situations. However, a carefully crafted research method and statistically solid interpretation of stated preference data could enrich revealed preference data to allow estimation of a wider variety of traveler choices than has traditionally been modeled.

This is a long-term research project that is only beginning at the UW. It is not peak spreading research, per say. However, the inclusion of a "departure flexibility" element in the stated preference survey could allow departure time to be included in utility calculations, so that ultimately the behavioral aspect behind active peak spreading might be modeled. This is not a realistic goal in the short-term, but it fits well with some of the other long-term goals of WSDOT-sponsored research.

DEFINITION OF PEAK SPREADING

Peak spreading is defined as an expansion of peak period traffic, from the traditional height of the peak outward to the shoulders of the peak, as the number of travelers and the level of congestion increase on a roadway. The effect of peak spreading is an average daily peak-period traffic profile that becomes wider (more spread out) and flatter (of longer duration at or near capacity conditions) over time. By its theoretical definition, peak spreading occurs when the same traffic spreads out over a greater period of time, which would result in a slight lowering of the peak of the profile. However, in actual practice the reason that peak spreading occurs is differential growth in traffic volumes, so it is unlikely that a lower peak volume would ever be observed. More realistically, the peak would spread along the capacity volume. An example illustration of peak spreading due to differential traffic growth, occurring between a $year_0$ and a later $year_n$, is shown in Figure 1.

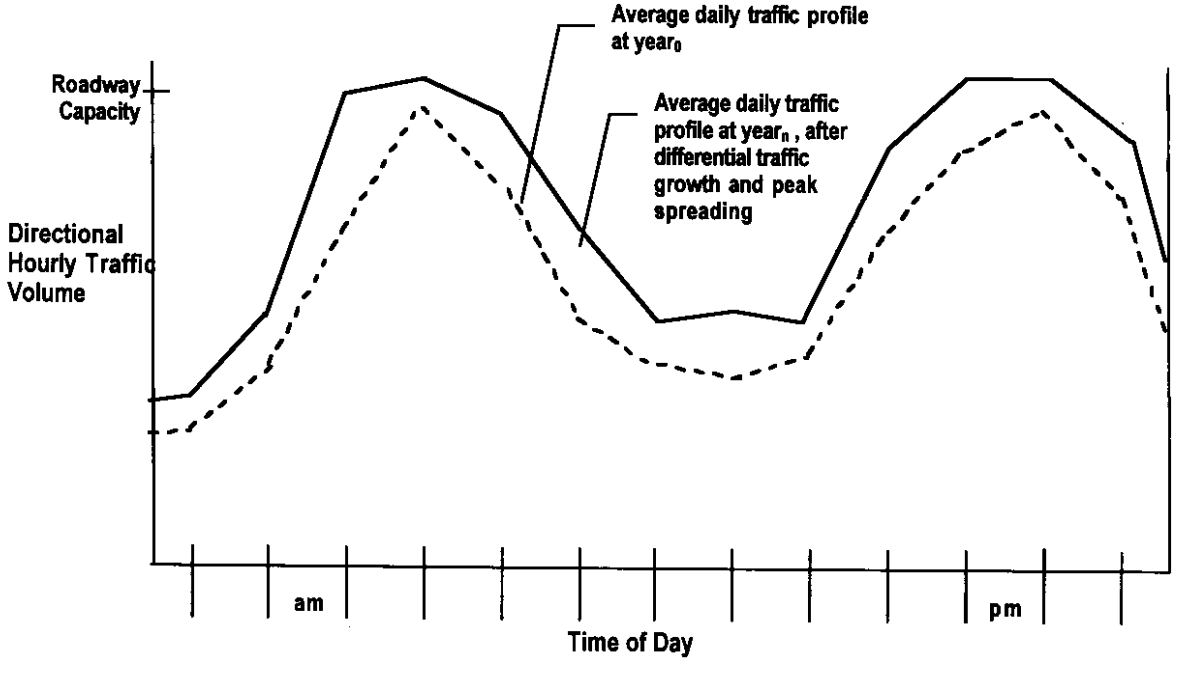

Figure 1: Illustration of Peak Spreading

Two phenomena contribute to what has been defined as peak spreading. The first, *active peak spreading,* occurs when travelers purposely retime their journeys to avoid all or part of the congested conditions of the peak period. They may begin their trips earlier to arrive at the same time as previously, or they may retime their trips to completely avoid the most congested time. Done on an aggregate level, this will result in spreading the peak period over time. The second, *passive peak spreading*, is simply journeys extending beyond the height of the peak as a result of increased delays due to congestion, with no change in the demand profile. As congestion increases, so do travel times; thus the peak period becomes more spread out because travelers are spending more time on the roadway for the same trip. It is important that these two effects be distinguished from one another, as well as from their impetus, which is simply *differential growth* in peak period travel (Porter, et al., 1995).

Historical trends of daily traffic profiles at points along Puget Sound area freeways confirm that peak spreading is indeed occurring as congestion becomes increasingly severe, thus warranting further investigation into its causes and implications. Figure 2 illustrates one example of this trend at a location along Interstate-5 in northern Seattle. Note that although this figure shows two-directional traffic volumes, if conditions were to be specifically analyzed, trends would have to be examined by direction. It is very possible that during a given peak period, traffic volumes in one direction could be at capacity (and thus experiencing peak spreading) while volumes in the other direction are well below capacity. Addition of the two directions of volumes would show total volumes under capacity, which would not accurately represent the traffic trends at that location. Even so, for illustrative purposes, the traffic profiles in Figure 2 show clear evidence of the spreading of the peak hours as traffic demand has increased over time.

1. Peak spreading is pertinent to current priorities at WSDOT and within the State of Washington. If peak spreading is occurring, some traffic is shifting from the

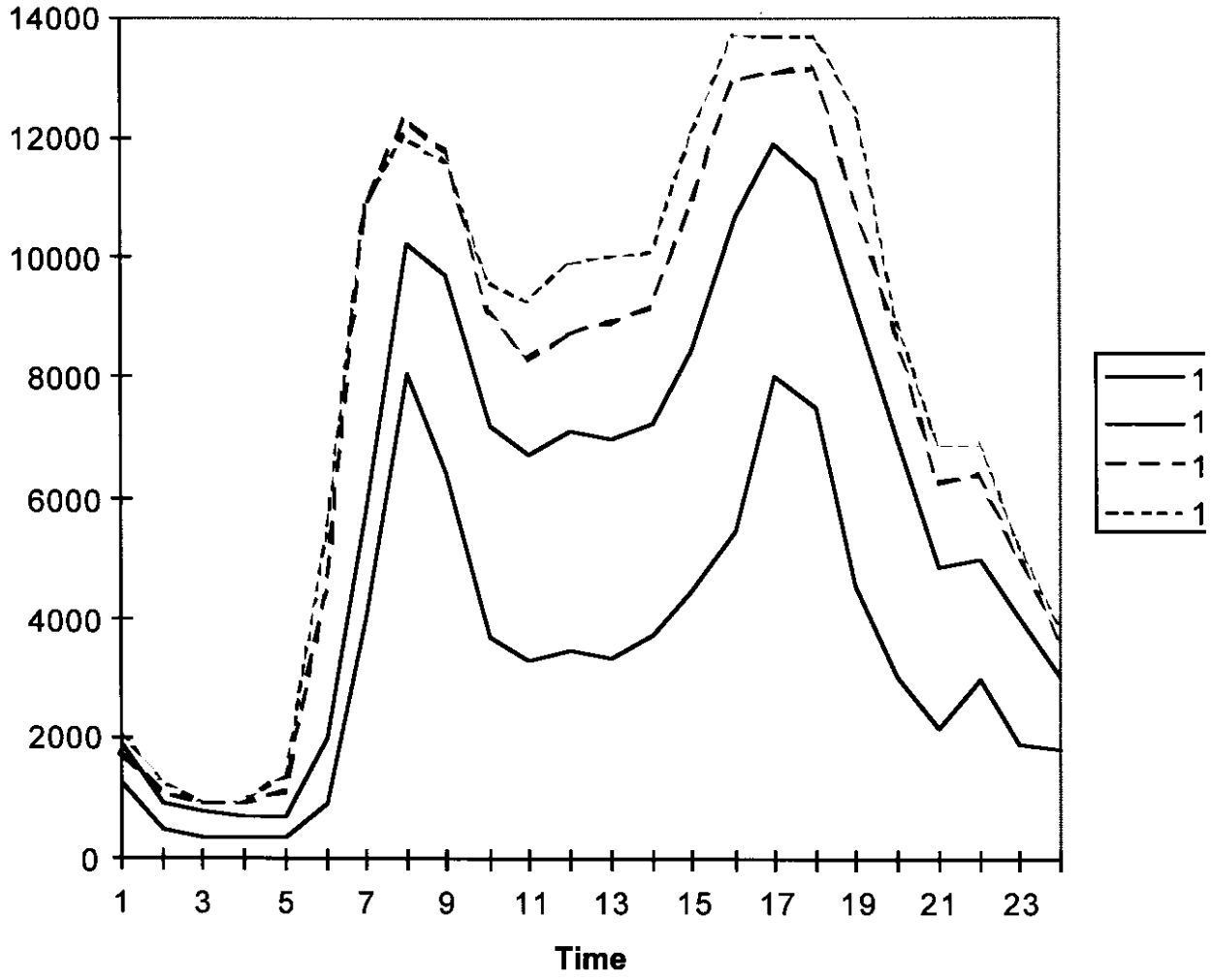

Figure 2: Traffic Profile Trends on Interstate-5 at N. 120th Street, Seattle

traditional peak hour to the shoulders of the peak. Failure to take this into account can result in overestimation of forecasted traffic volumes in the peak hour (thus an underestimation of average speeds) and an underestimation of forecasted traffic volumes in the shoulders of the peak (thus an overestimation of average speeds). This is consequential for several types of analyses, particularly (1) analysis for capital construction investments, (2) air quality analysis for conformity requirements, and (3) analysis for transportation demand management investments, all of which will be discussed later in this report.

APPROACH TO PEAK SPREADING REVIEW

To assess possible techniques for including the consideration of peak spreading in WSDOT analysis methods, the following approach was taken:

1. Evaluate the types of project analyses affected by the consideration of peak spreading.
2. Analyze the strengths and drawbacks of the transportation demand forecasting process with regard to the inclusion of peak spreading effects.
3. Review existing and potential modeling capabilities within Washington state and regional agencies, on the basis of the Washington State Modeling Initiative.
4. Conduct an extensive literature review to determine the state-of-the-practice regarding how peak spreading impacts are estimated and quantified.
5. Apply the conclusions of the literature review to the issues identified for WSDOT to determine short-term and long-term recommended approaches for including peak spreading in transportation analysis.

IMPACT OF PEAK SPREADING ON TRANSPORTATION ANALYSES

The results of three types of transportation analyses may differ, depending on whether peak spreading is taken into account in the evaluation. These are

1. analysis for capital construction investments
2. air quality analysis for conformity requirements
3. analysis for transportation demand management investments.

Each of these, as well as the impact that peak spreading consideration could have on analysis results, is described in the following sections.

ANALYSIS OF CAPITAL CONSTRUCTION INVESTMENTS

Construction of capital improvement projects, such as new or wider roadways, bridges or interchanges, has been the traditional solution for accommodating increasing traffic volumes. Typical benefits that are estimated for proposed capital roadway projects are reductions in accidents and in vehicle delay. In this type of analysis, the delays that result from a "no-build" scenario can be greatly exaggerated if a basic rule of transportation systems is not heeded: demand *cannot* exceed capacity for a given time period. Without new capacity, increased travel demand must occur outside the peak hour, and it most likely will move to the shoulders of the peak (Allen, 1991). Unfortunately, the lack of accepted methods available for handling the 'overflow' often leads to disregard for this rule, and as a result, volume-to-capacity (V/C) ratios that far exceed 1.0 may be predicted. This can lead to estimated vehicle delays that would never occur in reality because travelers can change their behavior to accommodate worsening traffic conditions. Exaggerated delay estimates will lead to exaggerated projections of benefits for a proposed facility improvement.

Furthermore, anecdotal evidence suggests that a sort of "reverse peak spreading" may occur when road networks are improved to try to increase average travel speeds. Specifically, drivers may retime their trips *back* to the traditional peak hour if conditions

improve, resharpening the peak-period profile and producing smaller than estimated improvements in average travel times (Johnston, 1991).

Note that it is possible for observed volumes to exceed calculated capacities to a *slight* degree if field conditions are less conservative than assumed conditions. In this case, a V/C ratio slightly over 1.0 does not mean that volume has exceeded capacity, but that capacity has been underestimated. It is also recognized that travelers may queue to enter a transportation system, within reasonable limits. The definition of "reasonable limits" is one of the key issues that must be addressed if peak spreading can be considered in the analysis of capital construction projects. Though the significance of peak spreading in benefit calculations may be debated, it is clear that potential capital investments cannot be realistically analyzed the interrelationship between congestion and peak spreading is not recognized.

AIR QUALITY ANALYSIS

The air quality conformity rule mandated by the Federal Clean Air Act Amendments (CAAA) of 1990 requires that transportation models provide separate peak and off-peak travel demand and travel time estimates. Peak spreading becomes important because emissions levels are a function of vehicle speeds, and estimated vehicle speeds will vary depending on whether peak spreading is considered in the estimates.

Models predict higher emissions for vehicles at the low and high ends of the speed range (DeCorla-Souza et al., 1995). Therefore peak and off-peak periods must be modeled separately because these two periods most likely will reflect speeds at opposing ends of the range. Otherwise, composite values would average out to mid-range speeds and result in underestimation of emissions levels. However, if peak spreading is incorporated into the model, predicted emissions may legitimately be estimated at lower levels because shifting traffic from the peak to the off-peak could result in average speeds in both time periods to shift to some degree toward midrange. Estimated peak speeds would be higher and off-peak speeds would be moderated. It is also conceivable in an

alternatives analysis that a no-build scenario with estimated speeds tempered by peak spreading moght show fewer emissions than a build scenario that would raise average speeds (DeCorla-Souza et al., 1995). Thus it is best for jurisdictions that are modeling air quality for conformity or for alternatives analysis to consider the effect that peak spreading will have on vehicle emissions levels.

ANALYSIS OF TRANSPORTATION DEMAND MANAGEMENT INVESTMENTS

Transportation Demand Management (TDM) seeks to address congestion by implementing strategies that control demand on a facility, rather than increase capacity. The results of successful TDM strategies can be that

1. travelers switch mode from auto to carpool or transit
2. travelers stop making certain trips altogether
3. travelers seek alternative routes
4. travelers change destination choice
5. travelers retime trips to less congested times.

The State of Washington is currently directing much of its policy focus toward TDM, the strategies of which often target peak period travelers because that is the time when congestion is at its worst. The objectives of a TDM program can be to (1) improve environmental conditions or (2) improve the effectiveness of a transportation facility or system, through trip reduction or through more efficient distribution of trips. Mode shift or the elimination of trips most dramatically satisfy the objective of improving environmental conditions, as well as improving system efficiency, so these are arguably the most desirable of the possible TDM results. However, if travelers adjust their destinations, routes, or departure times to accommodate congestion, this can be considered a 'secondary' desired result of TDM. Whether they drive alone or carpool, this at least allows more efficient use of the existing transportation system and could still have a positive impact on air quality (as was discussed previously in the *Air Quality Analysis* section).

Active peak spreading is the consequence of one of these secondary desired "demand-related" results. If travelers move departure times of trips that would have been made anyway away from the peak period, existing capacity can better accommodate increasing demand. TDM alternatives such as flextime, compressed work schedules, and certain congestion pricing measures are specifically intended to facilitate this exact result. These three strategies can be described as follows (McBryan et al., 1996):

Flextime is a work scheduling technique that, within some parameters, allows employees to set their own work hours on a daily basis. Usually there is a core period of time during which everyone is expected to be on site. The result of flextime in its fullest sense is the ability for employees to shift their work schedules so that their commute avoids all or part of the heaviest peak periods. Their commute could either be drive-alone or via a high-occupancy mode. In its simplest form, flextime can also mean that employees are allowed slight flexibility in their work schedule to accommodate the schedule of a transit or ridesharing mode.

Compressed work schedules usually mean that an employee's regular work week is made up of longer hours over fewer days. For example, rather than the traditional five eight-hour days per week, compressed schedules may consist of four ten-hour days per week, or eight nine-hour days and one eight-hour day over two weeks. The result of compressed work schedules is that longer work days may cause employees to commute outside of the heaviest peak period, either to or from work. Additionally, the commute trip is avoided altogether on the employees' days off.

Congestion pricing is the implementation of pricing measures such as tolls, with the stated purpose of managing the use of a facility to affect congestion. The price for use of a facility can vary throughout the day according to the potential demand on the facility, with higher prices during the peak periods and lower prices during the off-peak. It can also vary by mode, usually to encourage the use

of higher capacity modes. While it is one of the more politically controversial of possible TDM strategies, congestion pricing can result in various types of shifts away from the high priced facility. Commuters may shift their times of travel away from the peak period, shift their modes, or shift their routes to another facility.

Advanced information systems are more commonly associated with Intelligent Transportation Systems (ITS) rather than TDM. However, they may also promote active peak spreading by providing travelers with real-time information about roadway conditions. Some examples of traveler information systems are variable message signs, radio broadcasts, cellular phone numbers, or web sites that inform travelers of current traffic conditions. Travelers who receive this information in a timely manner may be able to adjust their routes, destinations, or departure times accordingly.

Although active peak spreading is a desirable secondary result of TDM, and all of these strategies will encourage active peak spreading to some degree, it is difficult to take that to the analysis level. No standard methods exist to estimate either the magnitude of peak spreading impacts or the type of benefits that can be assigned to changes in traveler behavior. This intangibility is typical of potential TDM impacts and benefits, and it makes it difficult for these strategies to compete on a level playing field with more traditional capacity-oriented strategies for which there are accepted and well-defined benefit analysis methods. The 'competition' between supply-side and demand-side solutions becomes even more lopsided if the estimated benefits of capital construction projects are overestimated as a result of failure to consider capacity constraints under a no-build scenario.

Passive peak spreading can in some cases promote TDM as well. In addition to providing incentive for active peak spreading, longer travel times and greater delay for single-occupant-vehicles (SOVs) may provide incentive for drivers to change their travel mode, route, or destination. A change of mode is only likely, however, if transit and carpools are able to circumvent these conditions, such as through the use of high-

occupancy-vehicle (HOV) or dedicated transit lanes, and SOVs are not. Otherwise, passive peak spreading is likely to affect alternative modes even more adversely than it would the traditional SOV (i.e., it is typically less attractive to be stuck in traffic on a bus than to be stuck in traffic in your car).

ANALYSIS SCENARIOS

To evaluate or predict peak spreading, whether as a desired or simply inevitable traffic phenomenon, one must first understand long-term and short-term transportation planning and programming processes.

LONG-TERM TRANSPORTATION PLANNING AND FOUR-STEP MODELING

Long-term planning generally requires travel demand forecasting, which is traditionally accomplished through the "four-step" travel demand modeling process. The four steps (trip generation, trip distribution, mode choice and transportation network assignment) are four separate mathematical models which, when integrated, form a complete forecasting procedure. Figure 3 illustrates the forecasting process that is employed by the Puget Sound Regional Council (PSRC), which reflects the state-of-the-practice and has at its core the traditional four-step modeling procedure.

Urban travel demand forecasting is a complex process, with its method and results dependent upon current technologies, federal and local government policies, environmental concerns, and transportation system user needs and priorities. Nevertheless, as complex as forecasting methods can be, they still greatly simplify the conditions being modeled. Figure 3 shows that the steps are modeled in a sequential manner (integrated by some feedback loops), even though in actuality travel demand decisions and their implications are not sequential, nor are they independent. These confines make innovative analysis of a phenomenon such as peak spreading difficult because it does not easily fall into one component or another. As travel decisions become more complicated (more congestion, more sprawl, more environmental considerations, more constraints on existing and future transportation systems), the disparity between modeling techniques and actual conditions will become more pronounced.

The traditional modeling approach begins by dividing the area under study into

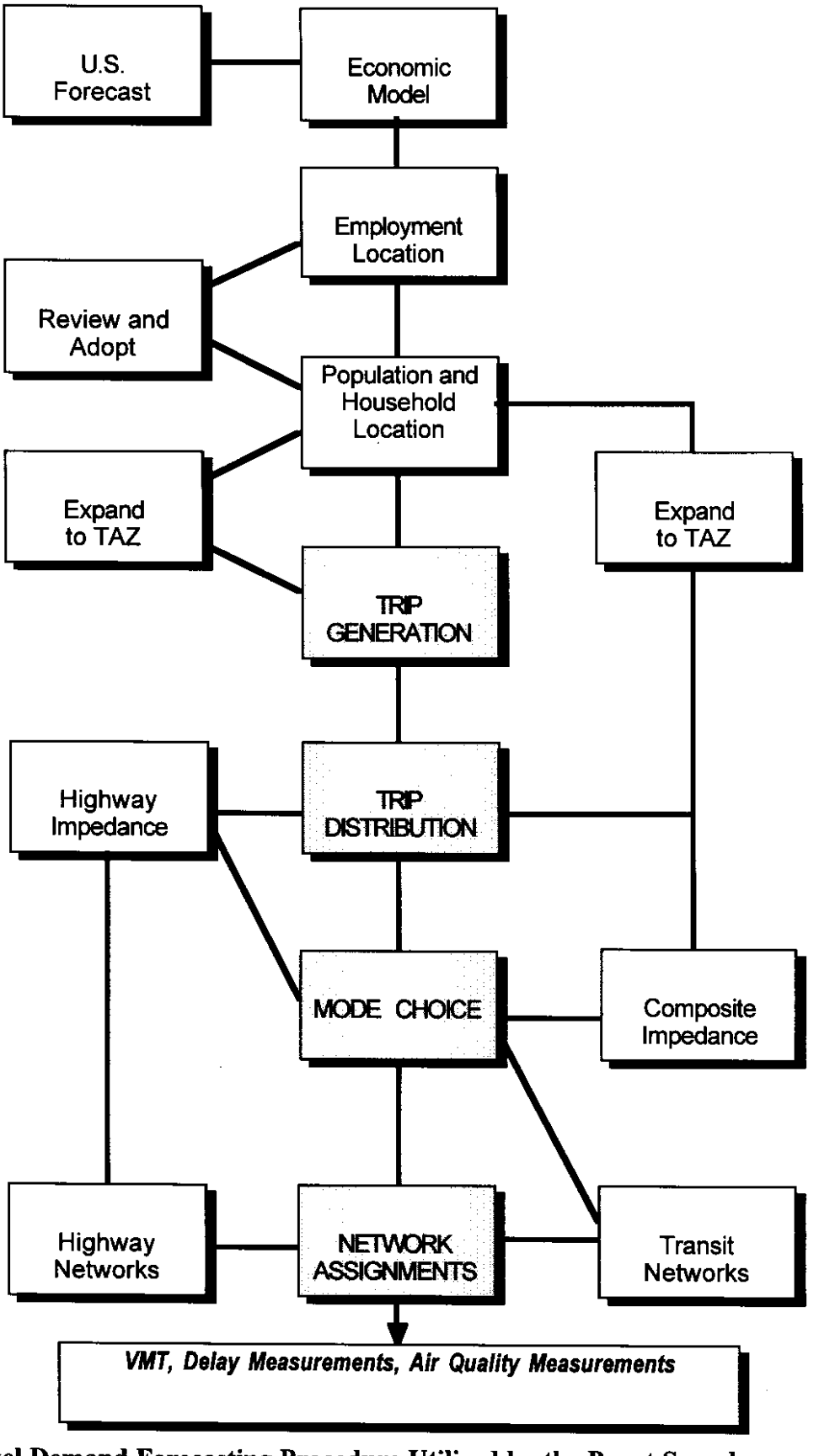

Figure 3: Travel Demand Forecasting Procedure Utilized by the Puget Sound Regional Council

transportation analysis zones (which are usually based on census tract and block boundaries) and developing the transportation network to be modeled. The transportation network is coded by a series of links (that represent roadways or transit lines) and nodes (that represent intersections). The purpose of this report is not to provide extensive explanation of the four-step modeling process, but the following sections explain the key concepts of each of the four steps, particularly those aspects that are pertinent to peak spreading analysis.

Trip Generation

The trip generation model estimates the total number of trips produced by and attracted to each transportation analysis zone in the study area. Inputs into this model include population and household characteristics, employment information, economic model output, and land-use information. Typically, either *regression equations* or *cross classification tables* are used to generate trip rates (daily trips per household) on the basis of independent variables such as household sizes, income groups, and auto availability. Trips generated are categorized by their general purpose. The traditional trip purpose categories are home-based-work (any trip with home as one end and work as the other end), home-based-other (any non-work trip with home as one end), and non-home-based (any trip that does not have home at either end). The trip generation model generally estimates the number of trips that are generated per household per day for each of these purposes. The daily generated trips are not estimated with any type of temporal distribution, which is why time-of-day analysis is particularly difficult.

Trip Distribution

The trip distribution model allocates the trips estimated by the trip generation model to create a specific zonal origin and destination for each trip. The result is a trip matrix (for each of the trip purposes specified in trip generation) that specifies how many trips are traveling from each zone to every other zone. The trips are often referred to as trip interchanges. The most common technique for determining trip distribution is the

gravity model, which distributes trips according to the land use characteristics of the zones and the characteristics of the transportation system that connects them.

The conformity rule requires that the travel times that are used for trip distribution be reasonably close to the travel times that result from trip assignment. The idea is that congestion may cause trips to be sent to closer destinations (DeCorla-Souza et al., 1995). Although in theory this sounds reasonable, two major drawbacks emerge. First, it is most common to model daily trips, so congested travel times that normally occur only during the peak periods, will result in an inaccurate distribution of daily trips. Second, even if peak and off-peak conditions are modeled separately, travel times output by traffic assignment are not true travel times but 'impedance' values that include factors in addition to travel time (this will be discussed in the subsequent *Network Assignment* section). According to DeCorla-Souza, it is more desirable to first estimate "true" congested speeds with a speed post-processor (presumably to perform trip distribution), and then obtain peak and off-peak travel times by hour-of-the-day from the assigned daily traffic volumes.

Mode Choice

The mode choice model is used to predict the share of total trips that will be made by each available mode. Modes that have been traditionally modeled are single-occupant-vehicles, carpools, and transit. However, non-motorized modes such as bicycling and walking are increasingly being included in mode choice models. Varying forms of a *logit model* are most typically utilized for mode choice in the four-step process. Logit models measure the relative attractiveness of the modes on the basis of characteristics such as travel times by mode, travel costs by mode, and the household characteristics of the travelers who make the mode choice. These relative attractiveness measures are used to predict the percentage of trips each mode will make, for each trip purpose. The percentages are applied to the trip matrices that are generated in the trip distribution step. The final result is a series of trip tables that reflect every combination of trip purpose and

available mode. Each trip table specifies how many trips occur from each zone to every other zone, for the mode and trip purpose unique to that table.

Mode choice is not directly linked to the physical characteristics of peak spreading, which are distinguished by the shifting departure or arrival times of individual travelers. Nonetheless, if peak spreading is to be predicted on the basis of traveler behavior, mode choice is relevent because it can be a competing option. For instance, a traveler who has made the choice to avoid driving during the most congested part of the peak hour may choose to depart at a different time. However, that traveler might also have the option to take a different mode (such as a subway) that will avoid congestion, and may choose that instead. This is a good example of the limitations of trying to model traveler behavior within the four-step process. The traveler makes one choice between two options, but these options surface at different times in the modeling sequence and thus cannot be modeled as a single choice.

Network Assignment

The network assignment model assigns the trips by each mode to their corresponding networks. Many methods can be used to perform network assignment, most of which do recognize the effect of traffic congestion on route choice. This is the step most usually linked to peak spreading analysis, and corresponding adjustments to the modeling process usually occur directly before or directly after this step. Network assignment is based on the impedance of the links. Impedance is a measure of time and/or cost, usually expressed in terms of the "generalized cost" of traversing the link. Total impedance is the sum of the impedance of all of the links along a route.

The most basic form of network assignment is the *all-or-nothing* method, which simply assigns all trips to the network simultaneously along the routes that have the least impedance. All other routes are assigned nothing. This method should only be applied alone where no congestion is anticipated because it does not consider the effect that increasing congestion will have on the impedance of a route. Other methods that do account for congestion, namely the *capacity restraint* and *equilibrium* methods, are

iterative and usually begin with an all-or-nothing assignment. The capacity restraint method involves a number of iterations and builds on the original all-or-nothing assignment by incrementally changing link travel time (and thus impedance) as congestion increases. The equilibrium method takes that one step further by applying a linear programming solution and iterating until no vehicle or person can improve its trip impedance by changing paths.

Although these assignment procedures consider the effects of congestion, they do have drawbacks. The interactions between links are not considered, so travel time on one link is independent of the volumes on adjacent links. Also, there is no temporal dimension to the traffic assignment, so fluctuation within an hour, or the effects of queuing are not recognized. Finally, because the trip table is fixed, the entire table must be assigned from origin to destination during the analysis period, regardless of whether sufficient capacity exists (Cambridge Systematics et al, 1996).

INNOVATIONS IN TRAVEL DEMAND FORECASTING

The four-step travel forecasting procedure just described has been generally accepted and widely used throughout industry. It is conceptually straightforward, and therein lies its appeal. However, the simplifying characteristics of the modeling process also lead to some very strong limitations, some of which have been presented and most of which become more pronounced as modeled conditions become more congested. Numerous research efforts are ongoing to improve the modeling process. Three techniques are particularly worth noting, namely (1) activity-based modeling, (2) dynamic network assignment, and (3) Transportation Analysis and Simulation System (TRANSIMS), because they directly address some of the modeling limitations that hinder peak spreading analysis. These are described in the following sections.

Activity-Based Modeling

The conventional approach to transportation modeling has studied travel behavior in terms of the actual trips that are made. However, in recent years this paradigm has

begun to shift from trip-based to activity-based approaches. Activity-based travel analysis is characterized by a more holistic framework, in which travel is analyzed as patterns of behavior dependent on the lifestyles and activities of the members of the population. The traditional focus on the trips themselves is replaced by a focus on the reasons behind the trips. Some of the features unique to activity-based travel analysis include the following (Jones et al, 1990):

- explicit treatment of travel as a derived demand
- focus on the sequence or patterns of behavior rather than discrete trips
- emphasis on decision-making in a household context, taking into account the linkages between members
- emphasis on the detailed timing as well as the duration of activity, rather than the traditional categorization of 'peak' and 'off-peak'
- explicit consideration of spatial, temporal, and inter-personal constraints on travel and location choices
- recognition of the interdependencies among events that occur at different times, involve different people, and occur in different places
- use of household and person classification schemes (such as stage in family life-cycle) based on differences in activity needs, commitments, and constraints.

Many of the limitations of the trip-based approach that discourage inclusion of peak spreading into travel analysis are addressed through the activity-based approach. Namely, (1) its measures directly involve changing time constraints and influence the time of travel, and (2) it is capable of capturing the complex and varied responses of travelers, recognizing that intra-household characteristics are important determinants of travel time flexibility (Jones et al, 1990).

While activity-based modeling theoretically addresses many of the shortcomings of the traditional methods, it also requires a substantially more complex treatment of travel. Thus, so far it has been carried much further in research efforts than in actual practice. Nevertheless, it is emerging as the cutting edge in travel demand forecasting, so it should definitely be considered in any long-term approaches that are developed.

Dynamic Network Assignment

Several research efforts have developed algorithms to perform *dynamic network assignment*, although no urban area in the U.S. is known to use it yet. In dynamic assignment, the analysis period is divided into several time slices, and the trip table is divided into subsets corresponding to the time slices. Trips are assigned during each time slice from origin to destination, traversing the network as far as they can in that time and continuing on in the next time slice until the journey is complete. Flow rates cannot exceed capacity, so any excess demand forms a queue. Advantages of dynamic assignment include the following:

1. modeling of congestion in a more realistic manner than traditional static methods
2. recognition of variation in demand within the analysis period
3. a reduction in one form of aggregation error because of the allowance of demand to vary for every origin-destination pair within the analysis period.

The primary drawbacks of dynamic assignment are that:

1. it models at a level of detail much finer than is assumed in most transportation models
2. it requires substantial amounts of data that far exceed the requirements for typical static methods (Cambridge Systematics et al., 1994).

Nevertheless, the temporal dimension to this assignment method holds some potential with regard to peak spreading analysis.

Transportation Analysis and Simulation System (TRANSIMS)

The TRANSIMS project is a long-term research effort, sponsored under the USDOT Transportation Model Improvement Program (TMIP), that seeks to develop a fundamentally different approach to transportation and land-use forecasting. TRANSIMS breaks the transportation system into three time scales and attempts to simulate traveler behavior within each scale. The time scales are (1) a long-term scale associated with land use and the demographic distribution of travelers, (2) an intermediate scale associated with trip chaining and intermodal route planning, and (3) a short-term scale associated with the execution of trips through various modes in the transportation system. TRANSIMS takes the opposite approach of the traditional four-step process in that it is based on the disaggregate simulation of the behavior of individual travelers, from which it uses a "bottom up" computation to derive the aggregate behavior of the system (Barrett et al., 1995).

The TRANSIMS project has recently completed its first case study of a small area in Dallas, Texas. Work on a case study for Portland, Oregon, is scheduled to begin as soon as the Dallas report is complete (TMIP, 1997). Given the ambitious goals of this project, it is still fairly young. However, any progress that TRANSIMS makes toward accomplishing simulation of individual travel behavior could make great strides toward addressing some of the major drawbacks of the traditional four-step process. Simulation would allow modeled travel behavior sensitive to long-term land use and policy changes, as well as short-term traffic conditions. While the traditional method requires disaggregation of aggregate results to estimate the impacts of a phenomenon such as peak spreading, the results of the micro-simulation that characterizes TRANSIMS would, by definition, already demonstrate those impacts.

WSDOT SHORT-TERM PLANNING AND PROGRAMMING

Almost without exception, increasing levels of detail and model sophistication require increasing amounts of resources and time. Limited resources and time often

necessitate the development of short-term and less complex analysis approaches. This is most definitely the case in the WSDOT Office of Program Management, in the biannual programming of highway mobility improvement projects. 'Mobility' is one of four subprograms in the Highway Improvement program, which is one of four components of the State Highway System Plan, illustrated in Figure 4. The figure shows that in addition to Highway Improvements (I), the other components of the System Plan are Highway Maintenance (M), Traffic Operations (Q), and Highway Preservation (P). The State Highway System Plan is updated every two years, and it provides service objectives and action strategies for maintaining, operating, preserving and improving Washington State highways for a 20-year period. The System Plan identifies all service objective needs, but ultimately it is prioritized and constrained to a reasonable financial level projected over the next 20 years (WSDOT, 1996). The six-year plan and two-year budget are chosen through priority programming to advance the most important projects contained in the 20-year plan.

Currently, the projected revenue scenario in the State of Washington falls far below that required to meet identified transportation needs. As a result, the Washington State Transportation Commission has prioritized the Maintenance, Traffic Operations, and Preservation Programs to be fully funded, since they are essential to prevent degradation of the existing system. In addition, within the Highway Improvement Program, environmental retrofit, safety improvements, most of the economic initiatives, and core HOV and have been identified as top priority. Full funding of these categories and sub-categories allows only 40 percent of the Mobility Program objectives to be met in the financially constrained plan (WSDOT, 1996). This has created a very competitive arena for the capital construction projects that make up the majority of the Mobility Program, as well as increasing the need for demand management and other innovative strategies to address highway deficiencies.

Projects cannot be programmed in the two-year Mobility budget unless they are contained in the financially constrained System Plan. Every biennium, each of the six

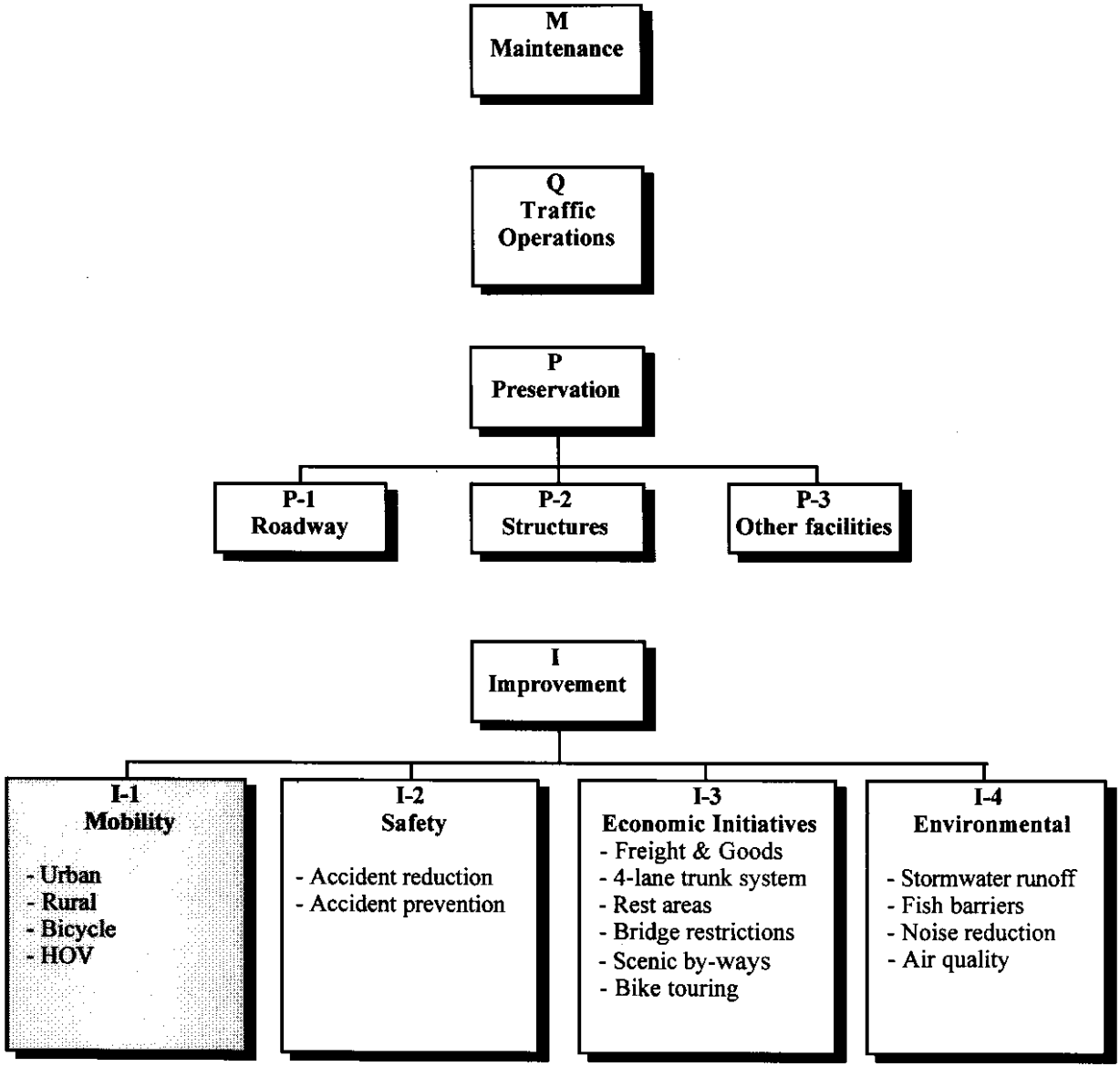

Figure 4
Washington State Highway System Plan

transportation regions in the state submit a list of proposed Mobility projects, with each project quantified in several criteria categories (benefit-cost ratio and six other non-monetary criteria). A prioritization procedure is applied to the lists of projects, and the top ranked projects that fit within available resources are programmed. Analysis must

bedetailed enough to provide a reasonable assessment of the relative benefits and impacts of proposed projects. However, since this is a preliminary process that only determines which projects of many should be further developed, analysis methods utilized by the regions cannot in practicality require excessive resources.

Peak spreading is an important consideration within short-term programming for Mobility, since the majority of projects submitted for programming are large capital construction projects, to which the previously identified analysis issues apply. In particular, if peak spreading is not considered in the baseline 'no-build' scenario, unrealistically high delays may be predicted, thus exaggerating the benefits of any proposed improvements. Because state funding for these types of projects is quite limited and the arena is very competitive, fair competition requires that the return of benefits on investment be estimated as accurately as possible.

Peak spreading issues pertinent to TDM are meaningful as well. WSDOT is sponsoring research at the University of Washington that seeks to develop appropriate methods for including aggressive TDM programs in alternatives analysis, as well as in programming for the Mobility Program. The TDM Resource Center at the WSDOT Office of Urban Mobility has taken the lead, in cooperation with UW, in efforts to include TDM alternatives in Major Investment Studies (MIS). The current emphasis on TDM potential reflects the Washington State Transportation Policy focus on taking a balanced approach to addressing transportation deficiencies.

WASHINGTON TRAVEL DEMAND FORECASTING FRAMEWORK

Traditional forecasting methods are not widely employed by the WSDOT regions, so it is not realistic to expect the WSDOT regions to adopt modeling techniques in the immediate future as part of standard analysis procedures. However, the adaptation of modeling techniques does not seem out of the question in the mid- to long-term future. A major initiative, entitled the Washington Travel Demand Forecasting Framework (WTDFF), is currently under way at WSDOT to promote transportation modeling

throughout the regions. The main functions of the WDTFF are to (1) provide travel forecasting guidance for WSDOT and for public and private partners, (2) establish a common set of assumptions to promote consistent modeling techniques throughout the state, and (3) determine the best technical practices that should be adopted in a statewide modeling initiative (WSDOT, 1997).

WSDOT hired an outside consultant to review forecasting methods currently employed by the metropolitan planning organizations (MPOs) within the state, to review the statewide modeling efforts of other states, and to recommend a statewide modeling framework for the State of Washington. Seven of the 13 MPOs reviewed employ some form of a traditional four-step travel demand forecasting process.

Because forecasting models are not yet in place throughout the state, peak spreading analysis methods that are developed for WSDOT's use in the short-term should be independent of four-step forecasting models. However, the establishment of a common travel demand forecasting framework throughout the state would definitely make longer term modeling approaches more feasible.

STATIC TIME-OF-DAY ANALYSIS

STATIC METHODS FOR ESTIMATING HOURLY VOLUMES FROM DAILY OUTPUT

Forecasting models are often based on daily trips, so if peak period conditions will be analyzed, the peak period volumes must be estimated using the daily output. This is commonly referred to as time-of-day analysis, and it is the most basic approach to estimating volumes for hourly analysis. Three methods are frequently employed to convert daily forecasts into peak hour or peak period traffic forecasts. These methods,

1. post-assignment static technique
2. post-mode choice, time-of-day trip table factoring
3. two-step, time-of-day factoring

are described in the following sections.

Post-Assignment Static technique

This technique begins with an estimated daily traffic on a facility, which is commonly the form of travel forecasting output. Peak hour demand is estimated simply by multiplying the average daily traffic volume by peak hour factors that typically range from 8 to 12 percent. This can be applied to one-directional or two-directional traffic. Note that a low two-directional peak hour factor (say of 8 percent) could be misleading because it could reflect the average of low traffic volumes in one direction and much higher volumes in the other direction. Thus, analysis of traffic by direction of movement will allow the numbers to more accurately reflect actual conditions.

The peak hour factors may be based on observed conditions or historical data. They can be varied by facility type and by area type. Different peak factors may also be established for different times of the day. This technique is very straightforward and may be able to provide a rough estimate of peak hour traffic volumes, particularly under uncongested conditions. However, since it is a static method, it does not allow any type

of consideration of geographical or temporal changes in traffic distribution as a result of future congestion levels. Because of the simplicity of this technique, it is widely used, despite its unsuitability for predicting hourly traffic volumes under congested conditions.

Post-Mode Choice, Time-of-Day Trip Table Factoring

This technique is also known as diurnal-direction split factoring, and it is applied after the mode choice step but before network assignment. With this method, the purpose-specific daily trip tables that are produced by the mode choice model are factored into directional and time-of-day specific trip tables. Then the network assignment model is run for each of the time-specific trip tables. The three time periods typically used are AM peak, PM peak, and off-peak. The diurnal-direction split factors can be derived from household travel surveys, commercial vehicle surveys, and external trip surveys.

Post-mode choice factoring is superior to post-assignment factoring in that it allows different peaking characteristics to be considered for different trip purposes. It is also compatible with equilibrium traffic network assignment. However, it too is typically a static process, so like the post-assignment technique, it is independent of future congestion levels or policy changes. This method also lacks consistency in the modeling process because trip generation, trip distribution, and mode choice are all calculated with daily trips (Cambridge Systematics et al., 1996).

Two-Step, Time-of-Day Factoring

This technique is basically the post-mode choice method described in the previous section with additional adjustments to increase consistency in the overall modeling process. Adjustments that can be applied include the following (Cambridge, 1996):

1. Use peak period impedance for home-based-work trips and off-peak impedance for other trip purposes, for trip distribution and mode split.
2. Apply the diurnal factors before trip distribution has been calculated and convert the resulting production and attraction tables from the mode choice model into origin-destination tables before assignment. This adjustment

will greatly increase the running time of the overall model because the number of trip distribution and mode choice model applications will increase.

REVIEW OF PEAK SPREADING LITERATURE

INTRODUCTION TO PEAK SPREADING ANALYSIS TECHNIQUES

Numerous attempts have been made to incorporate peak spreading into transportation planning and forecasting. These approaches all improve upon the methods summarized in the previous section in that they attempt to specifically model the peak periods and, in all cases, are sensitive to congestion to some degree.

It is worth noting up front, however, that none of the methods presented in this report represents the single answer to peak spreading issues. Most of the more ambitious attempts have relied upon detailed travel surveys and have involved substantial analysis. In addition, the models that have been developed are typically unique to the area they are modeling. While many of the model development methods provide a solid basis for further research, the models themselves are unlikely to be transferable. Finally, no example has been found to date of a peak spreading model that does not have considerable limitations. Nonetheless, many useful examples of analysis methods exist that can provide a foundation for the development of a peak spreading analysis model appropriate for WSDOT analysis needs. Any level of attempt to account for peak spreading, even with limitations, would be an improvement over its current omission from analysis methods.

The peak spreading analysis approaches presented in this report fall into three general categories. The first category consists of methods to adjust the traditional four-step forecasting process to better accommodate the effects of congestion and, consequently, of peak spreading. Some of the approaches require manual adjustments to intermediate output, and others have automatic adjustments built into the modeling procedure. But all of these approaches have the four-step procedure at their core. The second category consists of sub-models that were developed to analyze peak spreading. These would be run independently of the four-step process, but the output of most of

these models could either be used as input for a traditional forecasting model or be used in place of some portion of the output of such a model. The third category consists of peak spreading models that were developed to stand alone, with no connection to a more extensive forecasting model.

PEAK SPREADING ADJUSTMENTS TO THE FOUR-STEP MODELING PROCESS

Two general methods, *link-based* and *trip-based*, implement peak spreading analysis within the steps of a traditional model. Both result in more realistic traffic assignments that are sensitive to congestion. Both methods address the problem of projected demand exceeding the capacity in a given corridor during peak periods, and both attempt more accurate assessments of future travel conditions by considering peak spreading. Link-based measures are applied in the traffic assignment process, diverting trips that exceed link capacity to the shoulders of the peak. Some of the drawbacks of the link-based methods include the following (Cambridge Systematics, 1996):

1. no guarantee of continuity of flow between links, so that the amount of predicted peak spreading could be substantially different between adjacent links
2. failure to account for peak spreading for a specific link that could result from a choke point somewhere else in the system, or from the average level of congestion in the corridor
3. failure to consider peak spreading that may occur outside of the designated peak period
4. no explicit treatment determined for trips that are reduced off of the system.

Methods that focus on trip-based measures reduce the trip table interchanges for those links in which demand exceeds capacity. Many researchers have preferred trip-based methods because they allow continuity of flow between adjacent links. However,

trip-based methods share many of the other limitations of link-based methods. Both methods improve upon post-processing time-of-day analysis in that they result in more reasonable demand forecasts that are capacity constrained.

Examples within both link-based and trip-based methods are presented in the following sections.

Link-Based Method for the Arizona Department of Transportation

The objective of the link-based model developed and implemented in Phoenix was to improve overall modeling of peak-period volumes and speeds by (1) improving the accuracy of modeling of the peak periods, and (2) modeling peak spreading within the peak periods as a facility becomes congested. (Louden et al., 1988).

The underlying assumption of this model was that while trips may shift outside of the peak hour under congested conditions, all trips under consideration will occur in a three-hour peak period. The peak spreading model itself was based on data from 49 corridors in Arizona, Texas, and California that covered a period from five to 20 years. From these data, relationships were defined between the peak-hour and peak-period volume, as a function of facility type and the peak period V/C ratio.

The first step of the procedure was to produce trip tables for each of three time periods: a three-hour AM peak, a three-hour PM peak, and an off-peak that included all other times. The remainder of the method was iterative and used the following steps throughout the equilibrium traffic assignment procedure:

1. Compute the V/C ratio for the *peak period.*
2. Apply the peak spreading model to calculate the peak-hour factor.
3. Determine the revised peak hour volume using the peak-hour factor and the assigned volume.
4. Compute link-level peak-hour V/C ratios.
5. Apply a peak-hour speed model to estimate revised link speeds.

The results were traffic volumes and speeds on congested highways that better reflected realistic conditions (volume did not exceed capacity), thus providing improved

regional VMT measures (Cambridge Systematics, 1996). However, the primary limitations stated for this model were those that were listed as typical for link-based methods.

In spite of its drawbacks, Allen described this project as a "particularly relevant effort" that advanced the state of peak spreading research (Allen, 1991). It provided motivation for the New Jersey model that he developed, which will described later in this report.

Tri-Valley Trip-Based Method

The Tri-Valley Sub-area Model in Alameda and Contra Costa counties (a major sub-area in the San Francisco Bay area) implemented a trip-based peak spreading method that focused on reductions to trip table interchanges for links that were over-assigned (Cambridge et al., 1996). This method constrained the capacity of the future highway network system by time of day. This was accomplished by limiting the assignment of trips to the network on the basis of the overall capacity of the future network at selected gateway links. The V/C ratios at gateway links were constrained to 1.0.

The following steps were used for the trip table reduction and assignment process:

1. Peak-hour volumes were assigned to the highway network and V/Cs were computed.
2. For gateway links with V/C ratios of over 1.0, target volumes were estimated so that the V/C ratio would be 1.0.
3. A mathematical approach was used to adjust the trip tables to reduce the trip interchange volumes on the O-D pairs, based on the gateway links with over-assigned traffic volumes.
4. The revised trip table was assigned and the gateway link V/C ratios were checked for reasonableness.
5. The process was repeated if a close match between the assigned and desired link volumes was not obtained for the gateway links.

By adjusting the trip tables in response to congestion, this method addressed the limitation of link-based methods in that better consistency was achieved from link to link. One major drawback of this process, however, was that excess trips that could not be made within the peak hour were assumed to have been forced to travel outside the peak hour, but they were not explicitly accommodated. So while this method produced reasonable peak-hour traffic volume estimates that were constrained by capacity, it did not account for the overflow vehicles.

Boston Trip-Based Method

Another type of trip-based adjustment method was developed to model conditions in downtown Boston. The motivating factor for the development of this procedure was that base-year peak-hour volumes were already at or near capacity throughout the downtown area. As a result, impossibly high future peak-hour traffic volumes were being estimated (Cambridge Systematics, et al., 1996).

The trip table reduction procedure consisted of five iterative steps:

1. Unconstrained assignment was performed.
2. Key links were selected for examination.
3. Volumes for O-D pairs were adjusted sequentially in the selected link trip tables of congested links.
4. The network was reassigned with adjusted trip tables.
5. Final link volumes were compared with link capacities.

This process was considered complete when the analyst concluded that the overall assignment had converged with the study area network capacity.

Like the Tri-Valley method, a major drawback of the Boston method was that there was no explicit treatment for the trips that were reduced. The analyst had to determine how reduced trips would show up on the transportation system. In addition, neither approach accounted for changes in traveler behavior due to congestion.

Some of the differences between the Tri-Valley and Boston approaches were:

a) Boston employed a manual adjustment based on select link assignments whereas Tri-Valley used travel demand modeling software with capabilities to apply automatic trip table adjustments.

b) The Boston method considered more links and thus was more elaborate.

c) The Boston study created a matrix of interchange-specific peak-hour factors to apply to a daily trip table, whereas the Tri-City study simply adjusted the assignment trip table.

Washington, DC, Trip-Based Method

A trip-based method was developed for Washington, DC, that also relied on the assumption that a three-hour peak period has a fixed travel demand and that trips will spread within that period. This procedure estimated the percentage of peak hour to peak period travel at the vehicle trip interchange level, on the basis of: (1) congested travel time minus free-flow travel time, and (2) trip distance. This was accomplished through the use of a set of curves that relate the percentage share of peak period trips to these two independent variables.

Cambridge Systematics et al. asserts that the Washington procedure appears to be transferable to other areas and requires data that can be obtained from traditional household surveys and travel models (Cambridge Systematics et al., 1996).

Simplified Modeling Approach for Conformity Analysis

DeCorla-Souza et al. presented a simplified approach for adjusting the four-step modeling process to produce results in line with those required for air quality conformity analysis under the 1990 CAAA. The recommended procedures relied heavily on previous Federal Highway Administration (FHWA) research to develop average daily speed determination models for freeways and signalized arterials (DeCorla-Souza et al., 1995). The steps in the procedure developed by this research were as follows:

1. Split daily traffic by hour and direction, using data from automatic traffic recorders to develop time-of-day distribution profiles for various levels of congestion (time of day model).

2. Use a traffic simulation model such as NETSIM or FRESIM, along with estimated hourly directional traffic, to compute the queuing delay effects by hour.

3. Accumulate the delays over all hours and aggregate them with travel times at free-flow speeds to estimate total daily travel times and average daily speeds (weighted by VMT).

Empirical formulas were developed and later refined for both freeways and arterials to estimate hourly link volumes and total daily delay, on the basis of the ratio of average daily traffic to link capacity (ADT/C). The refined freeway equations were

for $AADT/C \leq 8$: $DR = 0.0797\ (AADT/C) + 0.00385\ (AADT/C)^2$ Eq. 1

for $8 < AADT/C \leq 12$: $DR = 12.1 - 2.95\ (AADT/C) + 0.193\ (AADT/C)^2$ Eq. 2

for $AADT/C > 12$: $DR = 19.6 - 5.36\ (AADT/C) + 0.0342\ (AADT/C)^2$ Eq. 3

where, DR = daily vehicle-hours of delay / 1,000 VMT

AADT = average annual daily traffic

C = highway capacity

Zone-to-zone travel times were then developed with the resulting speeds and then compared to the travel times that were input into trip distribution.

The methods presented in this paper were endorsed by the Federal Highway Administration as "simple, but rational, procedures that States and MPOs can use to address many of the modeling requirements in the current conformity requirements." (Heanue, 1995) This approach allowed total delay to be based on hourly volumes, thus accounting for the differences in average peak and off-peak speeds. It also allowed comparison of final estimated travel times to be compared to those used for trip distribution. Both of these considerations are mandated by the CAAA. The authors of this paper also assert that peak spreading effects were implicitly incorporated into this

model because the hourly distribution profiles that were used to split daily traffic into hourly volumes varied by the ADT/C ratio. However, these methods also had some serious limitations.

The procedure was illustrated for a case study in the Baltimore area, but the paper does not specify the source of the data on which the time-of-day model or the ADT/C equations were based, so there is no evidence to confirm that they would be transferable between different urban areas. The authors also recognize that delay functions would vary depending on area type, as well as facility type, to which the model was not sensitive. In addition to insensitivity to urban design and demographics (which is not uncommon), neither was the procedure sensitive to changes in traffic congestion (Replogle, 1995). Finally, the model was not capable of estimating average hourly speeds as it did average daily speeds (although further FHWA research is cited on this point). Explicitly recognizing at least some of these drawbacks, the authors stated that " the main contribution of this effort is the operationalization of simplified procedures for time-of-day analysis and estimation of average daily speeds" (DeCorla-Souza et al, 1995).

Adjustments to SATURN - United Kingdom

Two papers present adjustments that were made to SATURN, an assignment model that seems to be commonly used in Britain, to accommodate the effects of congestion. The first was applied to the Trafford Park SATURN model and employed matrix capping techniques. This is a trip-based method with the following steps (Rogers, 1991):

1. Links were identified in the network where demand exceeded capacity.
2. Volumes were constrained on the identified links to reflect capacity, thereby reducing the traffic demand for those zone pairs using each overloaded link.
3. The assignment/simulation process was reconverged using the revised matrix.
4. Steps 1, 2 and 3 were repeated as necessary.

This matrix capping technique treated the starting matrix as an initial estimate and adapted the starting matrix to retain only those movements that could be accommodated in the modeled hour. The 'lost' trips would theoretically be re-allocated by the assignment, modal split, or distribution models, although they were not in this example.

The second approach also adjusted the trip matrix for the East Anglia SATURN model, given the following four elements (Goodwin and Coombe, 1991):

1. The demand for parking in the central area was controlled to the likely available supply.
2. Low-cost transportation system management (TSM) improvements were identified.
3. The degree to which trips were likely to spread were estimated.
4. Excess trips were suppressed.

Peak spreading was modeled using a simple formula, $R = 1 - (k * V^2)$ Eq. 4

where, R = the ratio of the flows in the adjacent two half-hour periods to the flow in the peak hour (the "peakiness" factor)

V = the average peak hour speed

k = a calibrated coefficient specific to the chosen peak period

This formula was utilized in an iterative process whose end result was a reduction in the AM and PM peak hour trip matrices. Peak spreading could be reflected in the modeling process in another way by using SATURN because traffic that exceeds intersection capacity becomes queued within the network and does not add, unrealistically, to downstream congestion. Queues that exist at the end of the modeled hour represent trips that could not be completed in the assignment hour and, therefore, must continue into the following hour, the shoulder of the peak. The number of vehicles queued represent the degree to which the peak will spread. This is presented as a 'diagnostic' rather something that can be adjusted directly in the modeling process.

PEAK SPREADING SUB-MODELS

Many attempts have been made in the United States and in the United Kingdom to develop more sophisticated peak spreading models. The models presented in this section were all developed as stand-alone, but most could then be used as submodels within the more traditional forecasting process.

New Jersey Interstate-80 Model

One ambitious approach for estimating active peak spreading was a link-based model developed for the Interstate 80 corridor in northern New Jersey (Allen, 1991). This study was based on the presumption that peaking patterns are influenced by (1) the extent of flexibility of employees' working hours, and (2) the level of traffic congestion. Because flextime is dependent upon factors that are outside the realm of transportation planning, the researchers made traffic congestion the key independent variable in the model structure. The dependent variable is the distribution of traffic over the 4-hour AM period (from 6:00 AM to 10:00 AM), by 15-minute intervals. The purpose of the model is to calculate the change in temporal distribution of traffic over a 4-hour AM peak period in response to changes in the total peak period traffic volume and other measurable traffic characteristics: speed difference, downstream delay, average trip time, and average relative location (this was an average measure that reflected whether vehicles on the link were at the beginning, middle, or end of their trip, given relative lengths of the access, line haul, and egress trip segments).

The model utilized the following modified Poisson equation to estimate the proportion of traffic per 15-minute interval:

$$P(s,x) = \left[\frac{z * m^{(x+y)} * e^{-m}}{(x+y)!} \right] + a \qquad \text{Eq. 5}$$

where: s = highway segment

x = 15-minute period

m = primary shape factor (based on a regression function of dependent variables)

a, z, y = other scale coefficients (based on regression functions of dependent variables)

P(s, x) = proportion of 4-hour traffic occurring in period x on link s

Allen showed respectable correlation coefficients for this regression function. Attachment A of this report shows the observed versus estimated traffic distributions. However, in addition to the limitations typical of link-based models that have already been stated, the most obvious drawback of this model was that both its development and its execution required excessive amounts of data. Allen himself described this research effort as "a somewhat awkward attempt to quantify and forecast peaking" and went on to say that "it should be viewed as merely an early step in what should become an expanding area of transportation planning research."

Montgomery County, Maryland

A different approach to peak spreading analysis was taken for a peak spreading model applied in Montgomery County, Maryland (Replogle, 1990). The objective of study was to create a model that could estimate peak-hour congestion and the adequacy of traffic conditions, given certain land-use and network characteristics. The result was a model that estimated peaking patterns in terms of population and employment densities.

The underlying assumptions for this project were that two key factors influence the peaking characteristics of traffic:

1. The land use density and mix associated with the demographic character of an area:

   In small towns, bedroom communities, and isolated office or industrial areas a higher proportion of total trips occur during the AM and PM peak hours (higher peak-hour factors) than they do in heterogeneous, high density urban centers.

2. The amount of peak hour congestion in the transportation system:

In travel corridors and areas with severe peak hour traffic congestion there is a relatively even distribution of daily traffic demand, with low peak-hour factors.

The researchers determined that the traditional peak-hour factors should be altered to reflect urbanization and corridor congestion. Given the thousands of links in the network, a systematic and automated approach would have been needed to establish new factors. However, gaps and inaccuracies in the available traffic count data hindered reliable calibration of such a model. Instead, an alternative and more direct approach was taken in which daily trip tables were split into a peak-hour trip table for assignment. Because of the labor-intensity required for model development, only an AM peak-hour model was created. Since survey data indicated that work trips constituted nearly 80 percent of AM peak-hour traffic (as opposed to a majority of non-work trips in the PM peak), the AM peak was determined to be easier to model and calibrate.

After several tests of alternative model forms, a simple density-based model was produced that simulated vehicle-miles-traveled (VMT) in very close agreement to observed VMT, for two study years. The model adjusted the original trip-table splitting factors that had been developed through traditional methods upward or downward by as much as 20 percent. The output was consistent with the original hypothesis that the lowest trip-table factors would be applied to high-density, mixed land-use areas, and the lowest factors to low-density, homogeneous areas. The model is included with this report as Attachment B.

The peak-hour trip-table splitting model that was developed for Montgomery County provides a means for accounting for changes in peak-hour factors in response to urbanization over time. However, its limitations highlight the difficulty in forecasting peaking due to the variety of possible causal factors. This model did not explicitly account for the impact of congestion on peak spreading. It was not able to differentiate between the extent to which peak spreading occurred because of demographic changes and

the heightened congestion that resulted from increased urbanization. The researchers also identified a weakness in that the model introduced distortions in the relative trip distribution of the final peak-hour trip tables.

Analysis of NPTS Data

Gordon et al conducted a study that also minimized the effect of congestion on peak spreading. The researchers concluded that there is no evidence to support active peak spreading as the consequence of increased congestion in major metropolitan areas (Gordon et al., 1990). Their study was based on the National Personal Transportation Study (NPTS) data for 1977 and 1983. From the NPTS data, the researchers determined that adjustments in locations for both residences and workplaces provided a much more solid explanation for congestion relief than "spontaneous" adjustments to work schedules at an aggregate level. They submitted that potential travel time savings benefits that result from changing departure time may not be enough to offset the costs of adjustment in the activity patterns in non-working hours. Even though the researchers disregarded the effect that voluntary shifts for individuals may have on the peak hour, they did suggest that institutionalized factors that affect a significant number of workers (such as shifts at manufacturing plants or longer hours for retail establishments) do have the potential to affect peak spreading.

Dulles Airport Corridor, Washington, D.C.

A peak spreading model recently developed as part of the Dulles Corridor Transportation Study used an approach similar to that of Montgomery County, but it also expanded on it by (1) stratifying the data by trip purpose, and (2) considering other independent variables beyond the one congestion measure.

This study rejected the link-based approach for two reasons. First, it could not guarantee continuity of flow on the network, which could lead to presentation and analysis problems. Second, because the link-based approach only deals with one link at a time, it cannot measure overall trip congestion. The researchers theorized that total congestion was the reason for peak spreading, so they sought to develop a model based

on that hypothesis. Thus, they formulated a post-mode choice trip interchange approach that considered congestion, trip purpose, and trip distance to estimate peak spreading (Allen and Schultz, 1996).

The model was based on the assumption that the 3-hour peak period remains stable over time. The independent variables used in the model were (1) the distance of the trip measured over the highway network, and (2) the difference between the peak-hour travel time and the off-peak travel time as the measure of congestion. The model was stratified by six trip purposes: (1) home-based–work, (2) home-based–university, (3) home-based–other, (4) non-home-based–journey to/from work, (5) non-home-based–at work, and (6) non-home-based–non-work.

The final model structure was a series of cross-classified curves varied by distance range and by trip purpose. The model's function was defined as follows:

$$\text{Share}_d = \text{Max}\{ [\text{maxshare}_d + \text{slope}_d * \text{Max}(\text{timediff} - \text{limit}_d , 0)], \text{minshare}_d \}$$

where d is the distance range and *timediff* is the difference between congested travel time and freeflow travel time. Attachment C of this report contains the model parameters, the model curves, and a comparison of estimated versus observed vehicle-hours-traveled. The steeper slopes of the non-work curves indicate a higher sensitivity to congestion, which makes intuitive sense.

This model allowed estimated share of peak-hour travel to be modified on the basis of congestion levels and trip distance between zones. The primary stated limitation is the assumption of a constant 3-hour peak period, but the report asserts that a more rigorous 3-hour model requires additional research on trip chaining and trip tours (Allen and Schultz, 1996).

Environmental Protection Agency

A series of methodologies were developed for the U.S. Environmental Protection Agency (EPA) to estimate the effects of individual transportation control measures (TCMs) on travel activity (Austin et al., 1994). This series included procedures for

estimating direct peak and off-peak period trips shifts due to certain TDM measures. The researchers ascertained that a work trip distribution closely resembled a Gaussian (normal) distribution. On the basis of this relationship, a series of equations was developed that produced estimates of the fraction of total trips that would be removed from the peak period as a result of (1) flextime and (2) compressed work weeks. The properties of the normal distribution led to development of the following equations:

$$\delta = 0.475 - F\left(\frac{\phi}{2} - \omega + \mu\right); [for \omega \leq \phi] \qquad \text{Eq. 6}$$

$$\delta = 0.475 + F\left(\frac{\phi}{2} - \omega + \mu\right); [for \omega > \phi] \qquad \text{Eq. 7}$$

where, δ = the fraction of the total trips that will experience a shift from the peak to the off-peak period, either because of flextime or compressed work weeks

ϕ = peak period length

ω = average shift in time the participant is willing to travel

μ = mean value of the peak period

$F(\phi/2 - \omega + \mu)$ can be evaluated using a standard normal table

Note that the equations were identical for calculating the effects of both flextime and compressed work weeks, but they were actually presented in the report as separate procedures.

This is the only method found to date that was developed to evaluate specific TDM measures. However, this model fell short of many of the other submodels reviewed in this report in that it was not sensitive to congestion, traveler characteristics, or land-use characteristics. Its results were based on an assumed number of participants for each of the two strategies, as well as an assumed aggregated value of the time participants are willing to shift.

SATCHMO

The Saturn Travel Choice Model (SATCHMO) was a submodel that was developed to complement the SATURN model (Arezki et al., 1992). It expanded greatly on the issues addressed in the other SATURN papers, and it is unique among all models reviewed in that it included all of the following behavioral responses:

- the route followed to avoid congestion
- the mode used to get there
- the time of departure to avoid the most congested part of the peak
- the destination of the trip to a less congested area
- the frequency of journeys by taking the trip at another day, perhaps combining it with other activities.

SATCHMO's innovative approach to modeling these choices involved elasticity concepts, which expanded on standard methods for mode choice modeling. The most notable module of this program was called SACHAS, which performed *simultaneous* travel choice and assignment. The program used the following generalized logit formulation:

$$P_k = \frac{e^{(-\beta * GC_k)}}{\sum e^{(-\beta * GC_k)}} \qquad \text{Eq. 8}$$

where, P_k = the proportion of travelers choosing alternative k

GC_k = the generalized composite cost of choosing alternative k

The composite costs would be determined with standard utility calculations procedures. However, unlike the traditional mode choice model in which alternative k would be a pure choice of mode, such as auto or bus, this procedure allowed alternative k to be a choice like one of the following:

- a pure mode or a composite mode

- an alternative departure time, such as 30 minutes earlier or later to avoid the worst congestion
- an alternative destination where this was a realistic choice (such as for shopping trips).

Figures 5 and 6 illustrate how these choices could be nested in the logit model. As of this writing, SATCHMO only allowed the nesting of alternatives that could be assumed to have generalized costs that did not depend heavily on the assignment process. In other words, although the mode choice and assignment functions were simultaneous, the utilities were not sensitive to changes in congestion levels. Even so, this approach complemented the other methods that focused on congestion-sensitive assignments.

Transport and Road Research Laboratory, UK

An extensive peak spreading research effort carried out by the Transport and Road Research Laboratory in Britain attempted a utility maximization approach, somewhat similar to that of SATCHMO. The researchers addressed the question of what effect travel retiming had on travel forecasts and on the calculation of benefits for proposed road improvement projects (Johnston, 1991). The project consisted of three components. First, a simple AM peak mathematical model was developed. Second, a stated preference survey was employed to expand on the qualitative conclusions of the AM peak model and to evaluate the numerical tradeoffs travelers were making between travel duration and the deliberate retiming of trips. The results of the survey proved to be insufficient for calculating reliable utilities, but they did appear to provide enough basis for the third component, which was development of a multinomial logit model of traveler adaptation based on utility maximization.

After completing this series of projects, the researchers were able to draw numerous conclusions regarding the value travelers place on journey timing versus journey speed. However, even though fairly rigorous mathematical procedures were used in analysis, the conclusions were presented qualitatively. Also, limited resources caused the

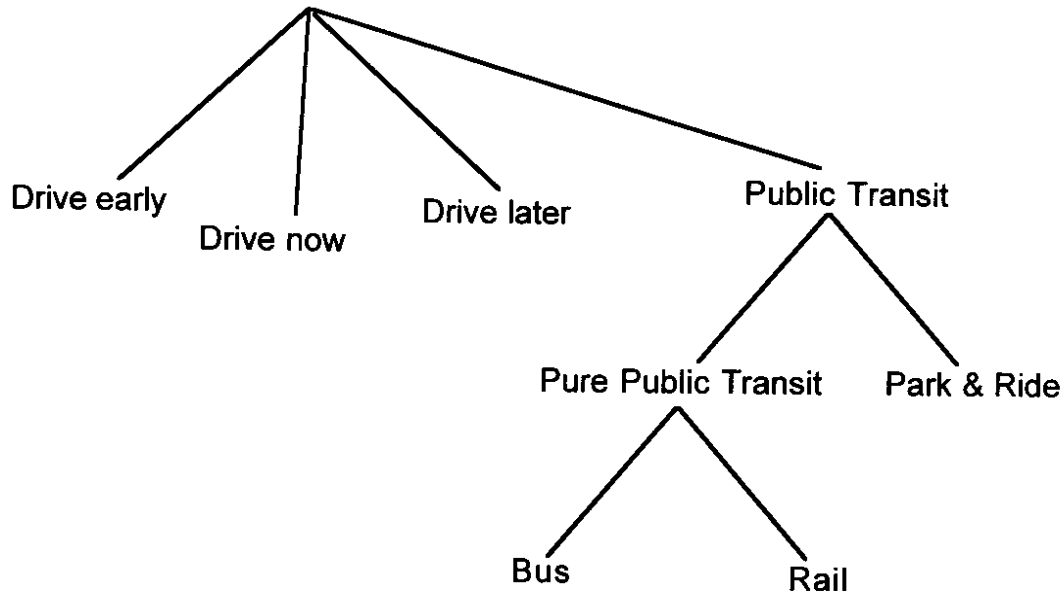

Figure 5: Example of Possible Model Structure for Mode Choice *and* Time-of-Day

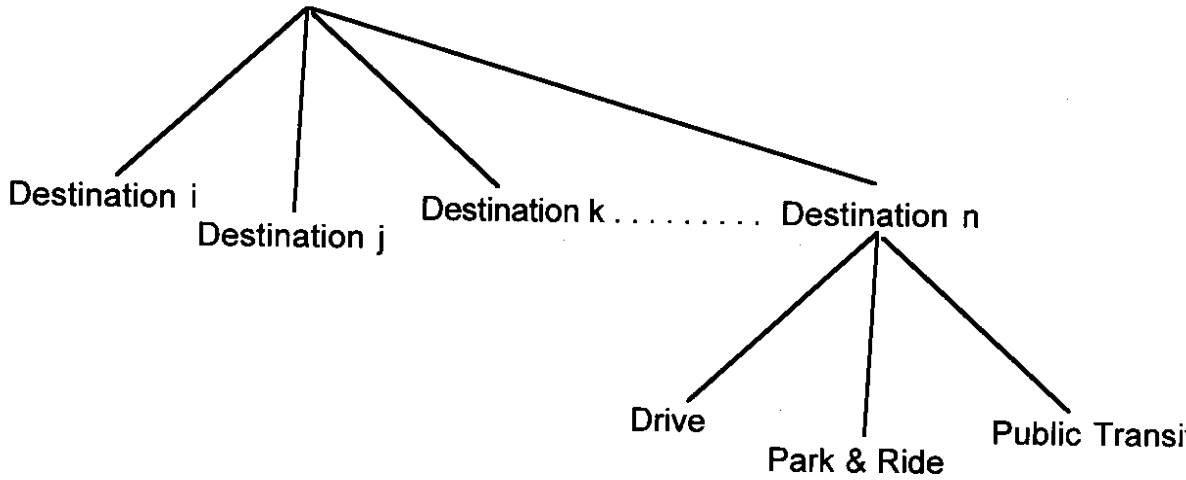

Figure 6: Example of Possible Model Structure for Destination *and* Mode Choice (source: Arezki et al., 1992)

researchers to focus mainly on a fairly select group of commuters who travel to central London. It is questionable whether the findings could even be applied to the general population in London, and it is extremely unlikely that they could be applied to any urban area in the State of Washington. Therefore, the conclusions of this study are not presented in this review. However, the study is noteworthy because the approaches used have many similarities to the approaches we are contemplating for our continuing research in utility calculation. The somewhat marginal success of the methods, as well as the ultimately qualitative nature of the conclusions, could provide some valuable insight as we proceed in this area.

STAND-ALONE PEAK SPREADING MODELS

A few efforts have been made to develop peak spreading models that are completely independent of the four-step forecasting process. Examples of stand-alone peak spreading models are presented in the following sections.

Cross Tyne Study, UK

This project utilized historical traffic data over three bridges across the Tyne River in England to determine whether clear evidence existed of peak spreading. The primary objective of the study was to provide a full understanding of all trip movements by all modes across the Tyne. The limited number of river crossings provide drivers few alternative routes, which simplified the analysis (Ramsey and Hayden, 1995).

Historical data over ten years confirmed that peak spreading was indeed occurring on the bridges crossing the Tyne River. The Peak Spreading Road Efficiency Percentage was derived to provide a single measure of how the total flow in a 2_-hour peak period was related to the maximum possible flow for the reference year. The Efficiency Percentage was calculated as follows:

$$E_i = \frac{100 * \sum_{j=1}^{10} Q_{ij}}{10 * \underset{j \varepsilon [1,10]}{Max} Q_{rj}} \qquad \text{Eq. 9}$$

where, Q_{ij} = the flow in year i during the quarter-hour period j

i = the number of years after the initial year

j = an index, in the range 1 to 10, which identifies each quarter-hour period in the 2_ hour peak period

r = the value of i corresponding to the year being used for reference

E_i = the Peak Spreading Road Efficiency Percentage

The Efficiency Percentage was calculated for each of the three bridges for five consecutive years, the results of which are included in Attachment D of this report. Theoretically, an E_i value of 100 percent would indicate that the capacity limit of the facility has been reached, but Ramsey and Hayden suggested that 95 percent would be a more realistic figure. Two of the three bridges showed increasing values of E_i from year to year, and the third bridge showed nearly constant E_i values of approximately 92 percent, since it was already operating a near-capacity conditions.

The Efficiency Percentage measure provided the basis for the Road Efficiency Percentage Model, which was used to predict traffic growth on the three bridges. The underlying assumption of this model was that, in general, the rate of traffic growth decreases substantially as the flow approaches capacity, which is illustrated in Figure 7. The figure shows that initially, the rate of traffic growth is assumed to be exponential, but over time the growth rate decreases and the capacity limit is approached asymptotically.

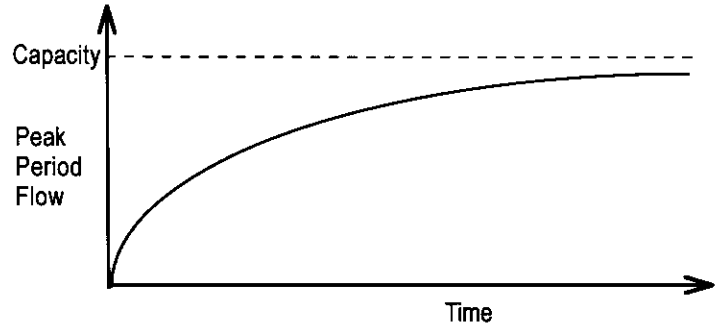

Figure 7: Assumed Form of Traffic Growth Rate Over Time

This relationship was combined with the Efficiency Percentage measure to form the following equation:

$$E_i = \frac{M}{1 + \left(\frac{M}{E_0} - 1\right) e^{-at_i}} \qquad \text{Eq. 10}$$

where, $M =$ the maximum percentage of the capacity limit that is attainable

$a =$ the proportionate growth rate that can be achieved at the lowest levels of E_i

$t_i =$ the time in years measured from the initial base year

$E_0 =$ the Peak Spreading Road Efficiency Percentage for the base year

$E_i =$ the Peak Spreading Road Efficiency Percentage for the future year

Because the objective was to predict future growth, the equation was rearranged to solve for a, giving the model the following final form:

$$a = \frac{1}{t_i} \log_e \left[\frac{E_i (M - E_0)}{E_0 (M - E_i)} \right] \qquad \text{Eq. 11}$$

Attachment D contains the graphs that show predicted growth in Peak Spreading Road Efficiency, projected for 1996 from the reference year of 1991.

This project is particularly worth noting because it compiled readily available historical data for defined corridors and used those data to predict traffic growth in the corridors *without* employing a full-scale forecasting process. Although this model was initially formulated with 15-minute traffic volumes, the final result was simply the total amount of average traffic projected on a facility for a future year. The researchers were only concerned with the composite effect of traffic growth on the bridges over an entire peak period and did not try to predict the temporal distribution within that period. However, it is conceivable that trends in the original historical data could have been used to estimate the temporal distribution of the predicted future volumes.

Peak Spreading Analysis at the Department of Transport, UK

The objective of a study conducted at England's Department of Transport was to identify which explanatory variable (growth or V/C ratio) and which model form (linear or negative exponential) were most appropriate for use in modeling peak spreading (Porter, et al, 1995).

The researchers fit historical traffic count data from 68 highway sites into a linear model of the following form:

$$\frac{PH}{PP} = a + b * Growth \qquad \text{Eq. 12}$$

where, $PP =$ pre-specified 3-hour peak period traffic

$PH =$ peak hour traffic – maximum 1-hour flow within the PP

$Growth =$ growth in traffic since 1981

$a =$ intercept

$b =$ slope

The slope, intercept, and goodness of fit measures were calculated for each site. From this the researchers determined with 95 percent confidence that peak spreading was prevalent at 38 of the sites in the AM and at 22 of the sites in the PM. This analysis was the basis for development of three other model forms

$$\frac{PH}{PP} = 0.333 + Ae^{b*Growth} \quad \text{(negative exponential based on traffic growth)} \qquad \text{Eq. 13}$$

$$\frac{PH}{PP} = a + b * V/C \quad \text{(linear model based on V/C ratio)} \qquad \text{Eq. 14}$$

$$\frac{PH}{PP} = 0.333 + Ae^{b*V/C} \quad \text{(negative exponential model based on V/C ratio)} \qquad \text{Eq. 15}$$

Subsequent analysis showed that of the 38 sites originally determined to exhibit peak spreading, only 14 showed statistically significant results in all four models. These four models were expanded into ten models on the basis of various combinations of

explanatory variables and model forms. Different models included both site-specific and aggregate approaches. One of the models assumed no peak spreading. All models were applied to ten randomly selected locations from the 38 over the period 1981 to 1991. They were evaluated according to the goodness of fit of their output to observed data over the 10-year period, as well as to the PH/PP values at the end of the forecasting period. Root Mean Square Errors were calculated for each of the models and used as the basis of comparison.

The analysis concluded that peak spreading was widespread and that the best fitting model for peak spreading analysis was the negative exponential model, using V/C ratio as the explanatory variable (negative exponential outperformed linear models, and V/C based models outperformed growth based models). Additionally, the study concluded that more years' worth of data provided better models but that *any* peak spreading model forecasts were better than the assumption of no peak spreading. Observations showed that the AM peak period was more pronounced than the PM peak but that peak spreading was still more predominant in the AM period. Finally, the study concluded that site-specific negative exponential models provided the most consistently accurate and statistically sound results of all models tested. The method, observations, and conclusions of this study could prove to be extremely useful in the development of a peak spreading model.

CONCLUSIONS FROM LITERATURE REVIEW

1. The most common simplifying assumption among all of the techniques was to define a peak period (usually 3 or 4 hours) that surrounded the peak hour and assume that all peak spreading would occur within that period.
2. Many of the models were developed for the AM peak only. The AM peak is easier to model because the majority of the trips are work trips (unlike in the PM peak).

3. Adjusting the four-step modeling process was the most frequently employed technique found for recognizing the effects of congestion on peak period traffic conditions, and the most common of these adjustments was to simply constrain the trip matrix so that demand could not exceed capacity. The number of 'overflow' trips could be quantified, but in all examples found for this report, these trips were not explicitly accommodated. Instead it was assumed that they would be accommodated 'somewhere else,' either through retiming their trips, by mode change, or to a reasonable extent, through queuing to get into the system.

4. Examples do exist of choice-based analysis in innovative peak spreading approaches. Several possible traveler responses to congestion might be expected, made more difficult by the fact that these choices are not independent. Some responses may be to

   a) seek an alternative route

   b) switch modes from auto to transit or carpool

   c) change destination choice

   d) stop making the trip

   e) make the trip at a different time of day.

5. There is not as much evidence to support the potentially significant capture of TDM benefits of peak spreading as there is evidence that ignoring peak spreading will exaggerate the benefits of capital improvements. However, there is potential for further research in this area.

6. It does not appear that peak spreading treatments require activity-based modeling or detail beyond that which is already included in most urban area models. However, a model that is developed independent of a forecasting model is likely to require a substantial amount of data, time, and effort

RECOMMENDED APPROACH FOR MODEL DEVELOPMENT

The overall goal of any further research efforts regarding peak spreading would be to actually develop a peak spreading model for the Seattle metropolitan area. Because WSDOT does not utilize a statewide four-step modeling process, and because these methods have numerous inherent limitations, development of any peak spreading analysis methods that simply adjust the traditional four-step model is not recommended. Instead, it is recommended that further research be divided into short- and long-term efforts. In the short-term, it is most realistic to work toward developing a stand-alone static model that would allow the estimation of more realistic traffic profiles for congested conditions on the basis of historical trends, but would not be sensitive to factors that affect traveler behavior. Research toward an approach that would reflect traveler choices fits with long-term research that is already occurring at the University of Washington. The recommended short-term and long-term approaches to further research are described in the following sections.

RECOMMENDED SHORT-TERM APPROACH

In the short- to mid-term, it is recommended that directional historical traffic data that WSDOT has collected be compiled for key freeway locations that represent a rich variety of freeways and area types. The result would be historical trends in traffic profiles, by direction, for representative locations throughout the Seattle metropolitan area. The historical trends could be used to formulate simple models (either graphical or mathematical) to predict traffic conditions, on the basis of future estimated growth rates. The following approach is recommended for the short-term:

1. Collect Historical Traffic Data

a. Select key freeway locations on the basis of the locations of traffic counters. Other considerations in location selection are that all freeways be represented, as well as a variety of area types. In addition, locations

with the oldest traffic counters should be chosen to the greatest extent possible because they will yield the most historical data.

b. Choose the representative years by which to calculate historical trends, given the traffic count data that are available through WSDOT.

c. Determine what portion of annual data should be aggregated to represent an average day, and determine what, if any, screening measures should be used to ensure that the data are reasonable.

d. Compile WSDOT traffic count data from selected locations to create average daily traffic profiles, by direction, for each representative year

e. The result will be examples of historical trends in traffic profiles for representative locations throughout the Seattle metropolitan area

2. Determine Model Form

Once the historical data have been compiled, the next step is to determine how that information can be used to create a model that will predict peak spreading trends. Some considerations in model development that have been highlighted in the literature include the following:

- A variety of possibilities exist for model form, so it is beneficial to maintain an open mind.
- Active peak spreading is recognized as a different phenomenon than passive peak spreading.
- Sites with different characteristics may require different model variables or coefficients.
- The AM peak period is often more straightforward to model than the PM peak period.
- Examples of model input include congestion levels, trip purpose, land use, and area type.

- An example of model output includes estimated daily trip distributions by hour.

The drawback of this type of approach is that predicted results would not be sensitive to policy changes or to strategies that resulted in anything different than traditional traveler behavior. It would be a static process that did not attempt to model behavioral responses to changing traffic conditions. However, this type of model could provide a means by which forecasts of traffic conditions would reflect capacity constraints at congested conditions, which at the very least would avoid exaggerated estimated benefits for capital improvements.

RECOMMENDED LONG-TERM APPROACH

In the longer term, it is recommended that a departure time element be included in the ongoing research at the University of Washington (UW), the goal of which is to include a more robust variety of traveler choices in travel demand forecasting. This research is directed generally toward TDM strategies and not specifically toward peak spreading analysis, but it is applicable because it is attempting to address the same question that hinders analysis of future *active* peak spreading trends: *how does one predict the travel choices people will make, given circumstances or conditions that do not yet exist?*

The objective of the research project is to calculate utilities for alternative travel choices travelers may make as a result of increasing congestion levels and TDM strategies. Utility is an empirical measure of the relative attractiveness of different choices and has traditionally been used for mode choice modeling. However, if empirical data are collected for other types of choices, it should be possible to model them as well. Utility functions in travel demand models have traditionally been calculated from the preferences of travelers, given their actual behavior as revealed in travel surveys. Although revealed preference methods have traditionally been appropriate for deriving travel utilities, they have limitations that restrict the inclusion of non-traditional choices, namely (1) they

cannot be used directly to evaluate demand under conditions that do not yet exist, and (2) it can be difficult to obtain sufficient variation in data to evaluate a wide range of choices.

Therefore, researchers at the UW are examining the use of stated preference surveys to address these drawbacks. Stated preference methods consist of a series of techniques to estimate relative utility functions, on the basis of survey respondents' statements about their preferences in a set of transportation alternatives (actual or hypothetical). The major drawback (and criticism) of stated preference is that respondents may not do in reality what they say given hypothetical situations. However, a carefully crafted research method and statistically solid interpretation of stated preference data could enrich revealed preference data to allow estimation of a wider variety of traveler choices than has traditionally been modeled.

This is a long-term research project that at this time is only beginning at the UW. It is not peak spreading research per say. However, the inclusion of a "departure flexibility" element in the stated preference survey could allow departure time to be included in utility calculations so that ultimately the behavioral aspect behind active peak spreading might be modeled. This is not a realistic goal in the short-term, but it fits in well with some of the other long-term goals of WSDOT-sponsored research.

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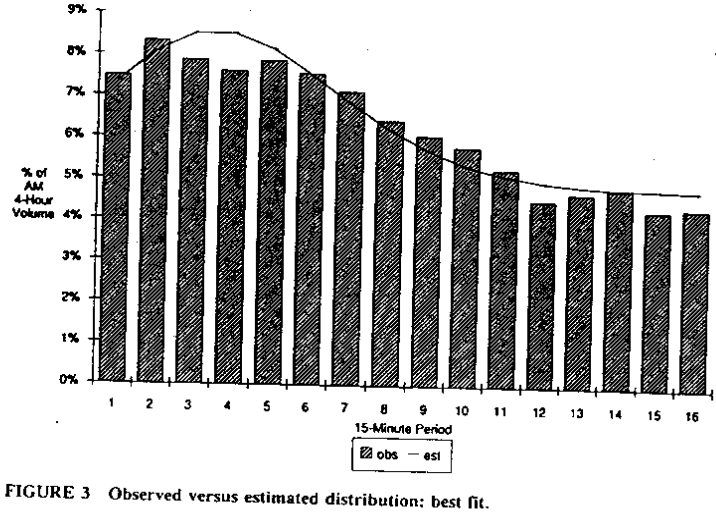


FIGURE 3 Observed versus estimated distribution: best fit.

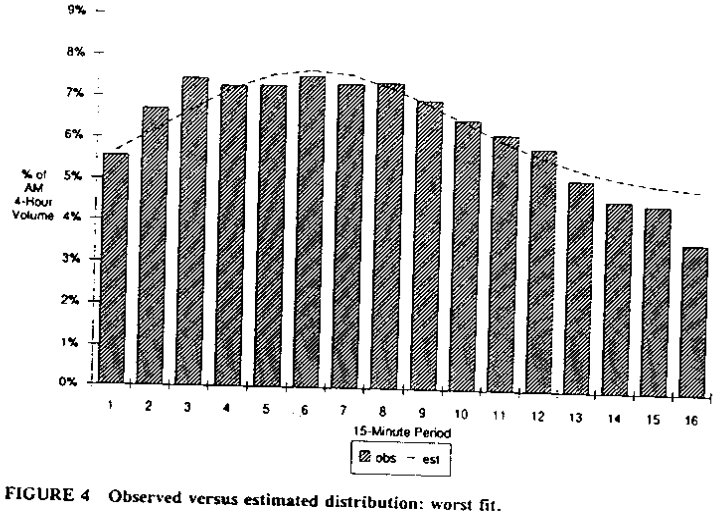


FIGURE 4 Observed versus estimated distribution: worst fit.

Attachment A-1
Observed versus estimated traffic volumes for the New Jersey Interstate-80 model (Allen, 1991)

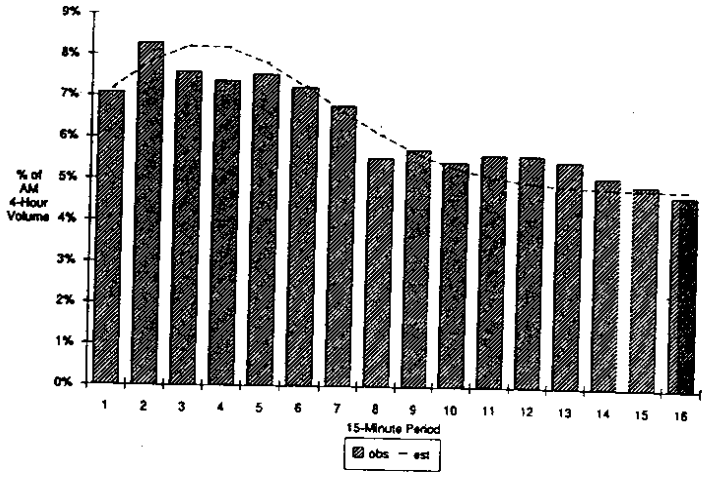


FIGURE 5 Observed versus estimated distribution: average fit.

TABLE 3 OBSERVED AND ESTIMATED PEAK-HOUR VOLUMES

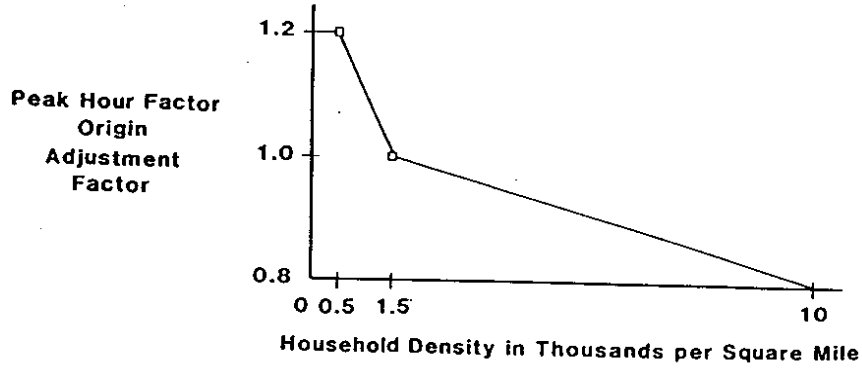
Segment (Entry - Exit Milepost)	Observed	Estimated	Percent Difference
0 - 4	1,405	1,454	4%
4 - 12	1,303	1,332	2%
12 - 19	1,616	1,694	5%
19 - 25	2,019	2,119	5%
25 - 26	2,595	2,689	4%
26 - 27	3,497	3,570	2%
27 - 28	3,301	3,435	4%
28 - 30	3,258	3,277	1%
30 - 34	3,250	3,381	4%
34 - 35	4,299	4,443	3%
35 - 37	4,678	4,507	-4%
37 - 38	5,652	5,740	2%
38 - 39	5,091	4,939	-3%

TABLE 4 OBSERVED AND ESTIMATED START OF A.M. PEAK 60-min PERIOD

Segment (Entry - Exit Milepost)	Observed	Estimated	Difference
0 - 4	6:00	6:15	:15
4 - 12	6:00	6:15	:15
12 - 19	6:00	6:15	:15
19 - 25	6:15	6:15	0
25 - 26	6:15	6:30	:15
26 - 27	6:15	6:30	:15
27 - 28	6:15	6:30	:15
28 - 30	6:15	6:15	0
30 - 34	6:15	6:15	0
34 - 35	6:15	6:15	0
35 - 37	6:15	6:30	:15
37 - 38	6:30	7:00	:30
38 - 39	6:30	6:45	:15

Attachment A-2

Observed versus estimated traffic volumes for the New Jersey Interstate-80 model (Allen, 1991)



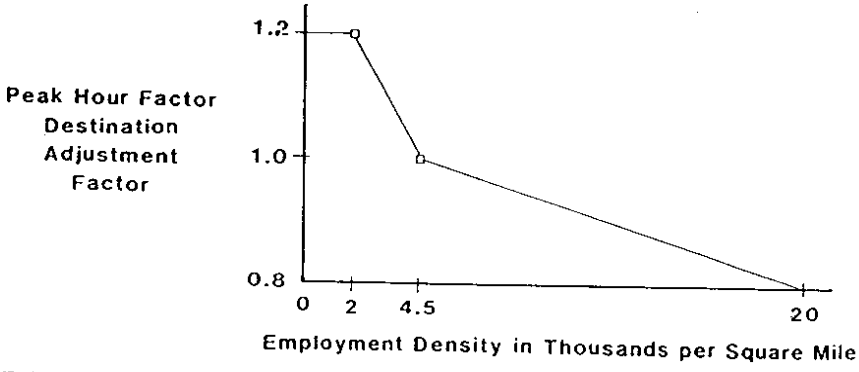


FIGURE 1 AM peak-hour trip-table splitting using density-based adjustment factors to account for effects of sprawl-clustering on peaking of trips.

Attachment B
Montgomery County, Maryland, peak spreading model (Replogle, 1990)

TABLE 4 A.M. Peak-Hour Model Parameters

Purpose	Distance Range (km)	Maximum Share	Slope	Limit	Minimum Share
HBW					
	0 - 6.4	0.481	-0.0200	10	0.100
	6.5 - 14.5	0.465	-0.0075	10	0.333
	14.6 - 22.5	0.456	-0.0060	10	0.333
	22.6 - 30.6	0.427	-0.0035	10	0.333
	30.7 +	0.365	-0.0025	10	0.333
HBU					
	all	0.460	-0.0295	15	0.000
HBO					
	0 - 6.4	0.336	-0.0660	10	0.000
	6.5 - 22.5	0.368	-0.0370	10	0.000
	22.6 +	0.430	-0.0155	10	0.200
NHB JTW					
	0 - 6.4	0.420	-0.0840	5	0.000
	6.5 - 22.5	0.437	-0.0225	10	0.100
	22.6 +	0.490	-0.0260	10	0.100
NHB WRK					
	0 - 6.4	0.275	-0.0275	5	0.000
	6.5 - 22.5	0.430	-0.0290	5	0.000
	22.6 +	0.480	-0.0180	10	0.300
NHB NWK					
	0 - 14.5	0.325	-0.0325	10	0.000
	14.6 +	0.130	-0.0130	10	0.000

Note: 1 km = 0.6 mi

Attachment C-1
Model Parameters for Dulles Corridor Transportation Study
(Allen and Schultz, 1996)

TABLE 5 Estimated Versus Observed A.M. Peak-Hour VHT by Jurisdiction

Purpose: HBW			
Production Jurisdiction	Observed Peak Hour VHT	Estimated Peak Hour VHT	Estimated/Observed Percent Difference
D.C.	17,897	17,295	-3.4%
Montgomery	36,279	34,498	-4.9
Prince George's	26,345	27,149	3.1
Arlington	6,632	7,328	10.5
Alexandria	6,272	6,135	-2.2
Fairfax	43,000	42,817	-0.4
Loudoun	4,783	4,300	-10.1
Prince William	10,843	12,781	17.9

All Purposes			
Production Jurisdiction	Observed Peak Hour VHT	Estimated Peak Hour VHT	Estimated/Observed Percent Difference
D.C.	26,331	25,780	-2.1%
Montgomery	49,694	48,160	-3.1%
Prince George's	35,722	37,138	4.0%
Arlington	10,135	10,750	6.1%
Alexandria	7,716	8,004	3.7%
Fairfax	57,429	56,423	-1.8%
Loudoun	6,761	6,043	-10.6%
Prince William	14,740	16,329	10.8%

Attachment C-2
Observed versus estimated VHT for Dulles Corridor Transportation Study
(Allen and Schultz, 1996)

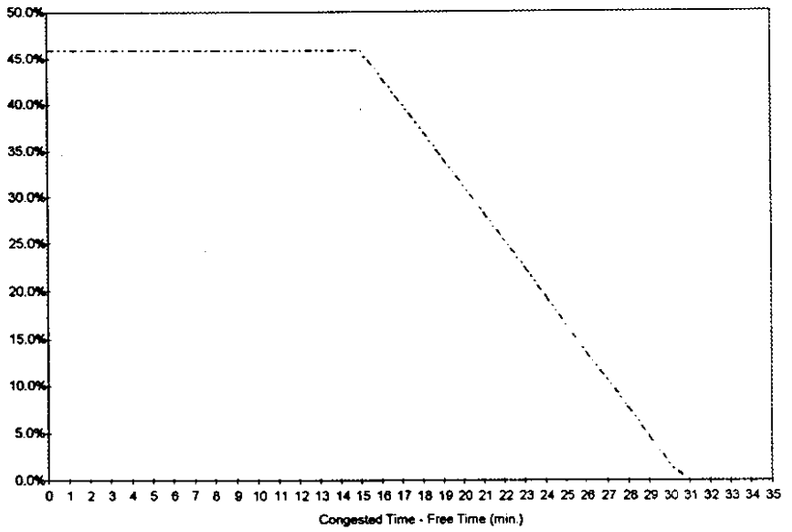


FIGURE 4 HBU automobile drivers: a.m. peak hour/a.m. peak period model.

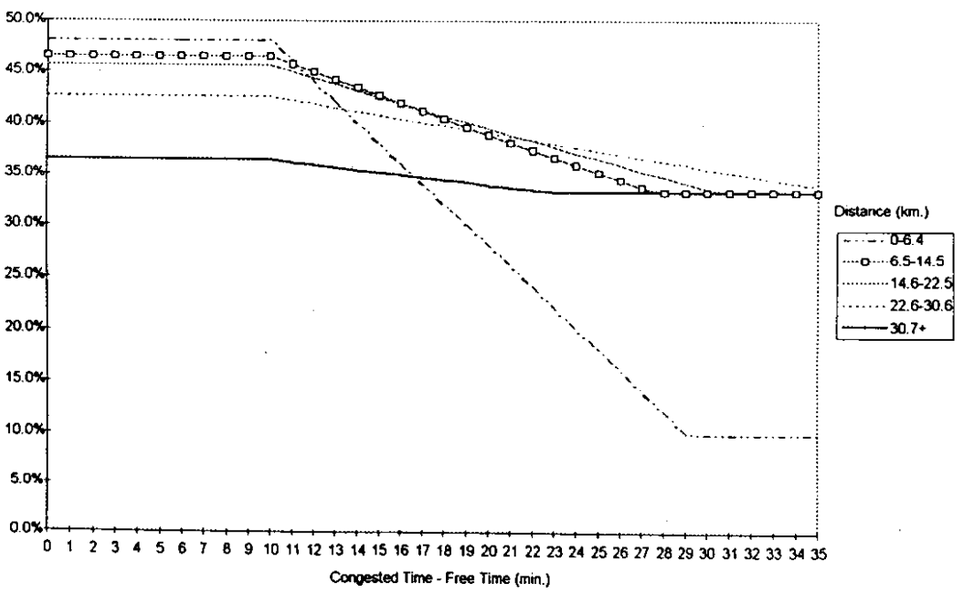


FIGURE 3 HBW automobile drivers: a.m. peak hour/a.m. peak period model.

Attachment C-3
Model Curves for Dulles Corridor Transportation Study
(Allen and Schultz, 1996)